Impact of Fiber Optics on Photometry - Design of two High-Speed Multichannel Instruments

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1 Introduction

The use of optical fibers as a link between spectrograph and telescope focus has become more and more common. It is not only to avoid the variation of gravitational forces which attack the stiffness of Cassegrain instruments but it also allows one to provide a constant environment for the spectrograph thus yielding high spectroscopic stability. Furthermore, for the purpose of multi-object or two-dimensional spectroscopy the application of fiber bundels are essential for an effectiv optical design.

Applications of optical fibers for aperture photometry are comparably rare. Unlike for spectroscopy, varying transparency (or vignetting) of the light path between telescope and detector provides the most serious instrumental constraint to the photometric accuracy. In general, geometrical changes of (long) fiber links e.g. due to the telescope tracking motion cause changes of the light throughput and of the amount of degradation at the fiber exit. Another problem of using fibers as photometer input channels arises from the uneven flatfield characteristic when using the fiber entrance window as measuring diaphragm: Any dust particle on the fiber surface, which is then identical to the focal plane of the telescope, would cause considerable flux variations even if the seeing disk is moving within the boundary of the fiber core.

Our experiments with fiber coupled photometers started more than 10 years ago when we initialized a research program to analyse eclipsing cataclysmic variables. These stellar systems consist of a late type secondary that fills its Roche lobe and transfers mass via an accretion disk to a white dwarf (WD) primary. Due to the geometry of the systems and the orbital periods of the order of some hours, sufficiently high inclined systems give rise to different high speed eclipse phaenomena. For example: the eclipse ingrees or egress of the WD of the cataclysmic system OY Carinae with an orbital period of appr. 100 minutes lasts only 20 seconds.

In oder to monitor such fast events, the method of classical photometry i.e. to measure iteratively object, comparison star and sky background is no longer feasible. If additionally 5 colours are needed, the serial measuring mode yields a time efficiency of less than 7%, which means, that only a small fraction of the observing time is allocated to a specific filter. It is clear that only simultaneous high-speed monitoring of the program star, a nearby comparison star and the background radiation simultaneously in different filters provides uninterupted reliable observations of short time events.

2 MCCP - The first-generation fiber-fed photometer

The prototype of a 3-channel UBVRI fiber-fed photometer (the socalled "MCCP" = Multi-Channel multi-Colour Photometer) fitting these requirements had been developed at the Universitäts-Sternwarte München (Barwig et al. 1987). As displayed in the schematic diagram of Fig.1. the instrument comprises 4 basic units: a) Fiber input and positioning device, b) Prism spectrograph, c) Detector unit e) Data acquisition and control.

In the frame of this conference we will mainly focus on a description of the first two units:

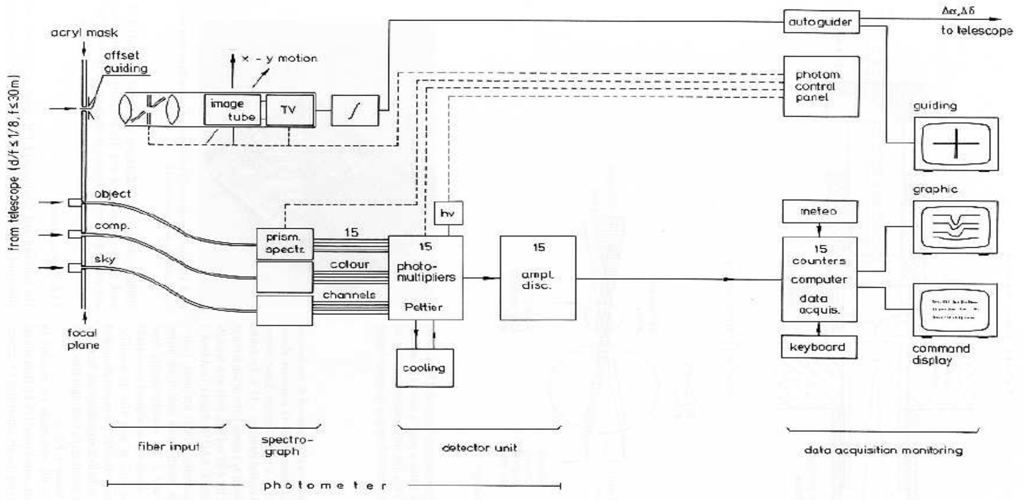

Figure 1: Schematic diagram of the MCCP

2.1 Fiber input channels

In order to obtain lightcurves simultaneously in different filters e.g. similar to the Kron-Cousins UBVRI system, the use of a prism spectrograph for the separation of colours from a large wavelength-range turned out to be most convenient. Since the spectral resolution of a (mono)fiber-fed instrument depends on the fiber core diameter, even for a resolution of 5 a transfer optic has to be applied to reduce the measuring diaphragm diameter to the smaller fiber dimensions. As a feasible solution the following input device was chosen: Diaphragms of typically $\leq$ 1mm (corresponding to $\leq 26''$ at a 1m f/8 telescope) are imaged onto quartz mono fibers (QSF 400 W) with $400 \mu m$ core diameter by means of two ball lenses with diameters of 3mm (BK10) and 1mm (BK7) respectively. The lenses are arranged to match a confocal system that makes the light beam enter the fiber nearly symmetrically with respect to the fiber axis (Fig.2). This in turn yields a constant light cone (f/2.8) at the fiber exit end independently of the star's position in the diaphragm. However, due to different reflections on the surface of the ball lenses, the flatfield is distorted towards the edges of the diaphragm. Another disadvantage of this device turned out to be the inhomogeneities (dust particles and/or air bubbles) within the epoxy adhesive which fixed the 1mm lens to the polished $400\mu m$ fiber core and give rise to high frequency flatfield distortions. We therefore replaced the two lenses device by a single Fabry lens between diaphragm and fiber entrance, which projects the pupil of the telescope onto the fiber core resulting in a more homogeneous flatfield without any higher frequency distortions.

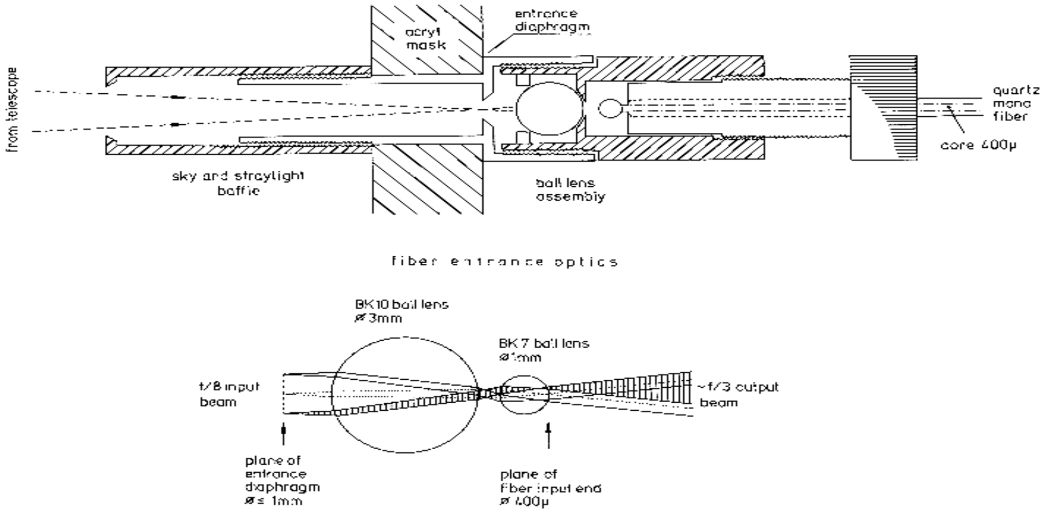

Figure 2: Layout of fiber channel input (2 lenses system)

2.2 Fiber positioning

In the first version of the MCCP the 3 fibers were positiond in the focal plane of the telescope by means of a mask, which could be prepared on the telescope itself just prior to observation. For mask preparation an acryl plate was fixed in the photometer beside the focal plane of the telescope beneath an automatic drilling machine that was connected to a CCD guiding camera which could be set remote controlled to different star positions. Whenever centered on an object, a hole was drilled at the concerning position on the plate. Finally the mask was inserted in the focal plane and the fibers fixed in the holes.

This economical fiber positioning device was replaced later by 3 stepper-motor driven computer controlled X-Y positioning units holding the individual fibers. (It seems interesting to note, that this upgrade became necessary when we intended to participate in monitoring the rather spectacular events of the predicted impact of comet Shoemaker-Levy (SL-9) on the backside of Jupiter. Our aim was to search for light echoes which might have been reflected from the Jovian satellites facing the impact sites. We therefore had to center the fibers on the concerning moons which in turn were relatively fast moving thus preventing the use of fixed holes in a mask.)

2.3 Spectrograph unit

The end faces of the 3 input fibers form the circular entrance pupils of 3 small f/2.2 prism spectrographs. Each of the resulting spectra (linear dimensions 10x0.4 mm^2) covering the wavelengths region 340-900 nm is imaged onto an array of mono fibers. This array was designed to approximately match the edges of the UBVRI filters. Due to the strong non-linearity of the dispersion of the prisms, 5 quartz-fibers with core diameter of 1 mm were packed in a row for the U-channel. The other colour bands are defined by plastic fibers. Their originally circular faces (1-1.5 mm diameter) were reformed to a nearly rectangular shape. The width of each individual fiber at the spectrograph exit window was adjusted according to its position in the spectrum and the desired filter band-width. The required overlap of the filter regions is achieved by the size of the entrance pupil which limits the spectral resolution. To obtain identical colour bands for all 3 spectrographs the respective relative positions of the fiber array and the spectrum were adjusted by means of a monochromator.
The 15 spectrograph output fibers are connected to the detector unit. It consists of a close arrangement of 15 HAMAMATSU miniature photomultipliers encapsuled in a single housing and thermoelectrically cooled down to -20^{o}C. The individual photon counts are processed by a realtime multi-tasking VME-Bus computer system which enables a time resolution of the order of a few milli-seconds. All observing parameters can be defined via different menus. The observer can select which of the 15 channels will be subject to on-line graphics and statistical analysis.

2.4 Data Reduction

The primary aim is the determination of time resolved intensities of the object (reduced to airmass X=0) relative to a comparison star in the instrumental filter system. Since the MCCP provides data from simultaneous measurements of object, comparison star and sky in five colours, variable atmospheric transparency and wavelength dependent extiction effects (of first order) can be compensated using the so called standard reduction procedure (Barwig et al. 1987). Any instrumental changes during observation, for example transmission changes of the individual fiber channels e.g. due to their changing geometry, can only be checked and compensated by performing frequent calibration measurements. For this we need 3 measuring procedures: - measurement of a constant point light source (e.g. a "normal" star during photometric conditions) in the object- and comparison-channel respectively, - measurement of a homogeneous field light source (eg. sky background) with all three channels and - the dark current of all detectors.

2.5 Performance

From our long time experiences the MCCP can be charaterized as follows:
- Apart from the Poisson noise limit the photometric accuracy of the relative intensity for a single uninterrupted run is better than 1 %. On the other hand the absolute intensities over many observing runs are subject to larger errors due to

uncertainties in the calibration to be performed for each run.
- One of the most important advantage of the fiber coupled multi-object photometer is the fact, that due to the differential measuring methods useful data can be obtained even if the atmosperic transparency decreases down to less than 10% (Fig.3).

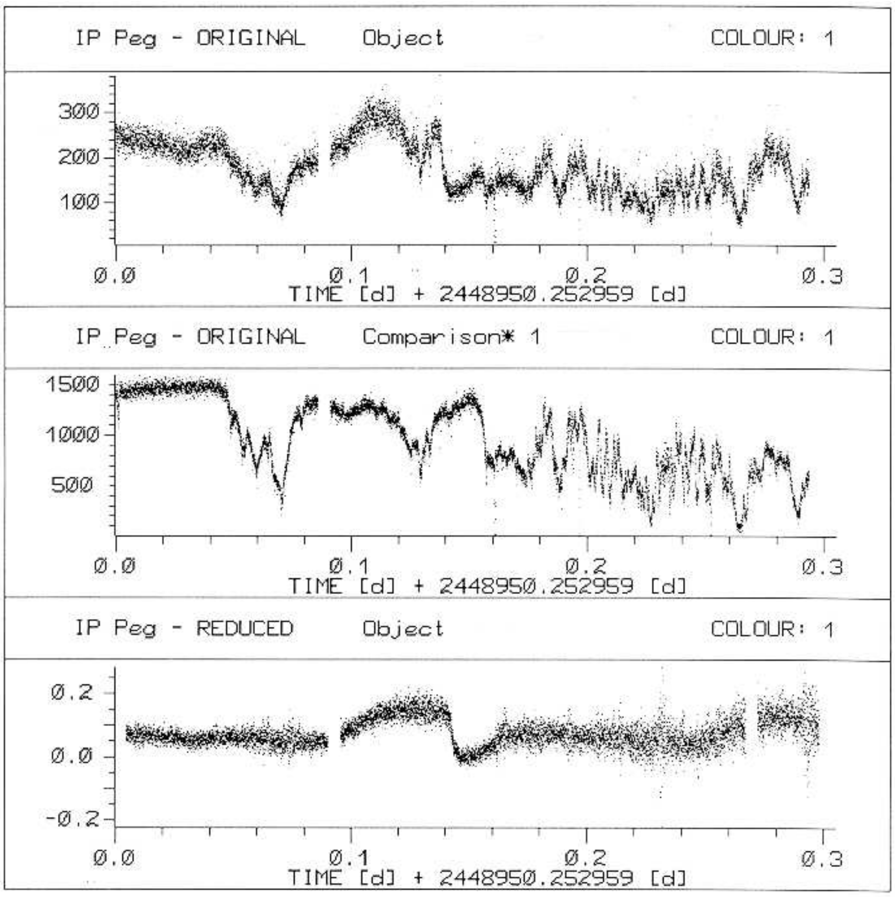

Figure 3: Standard reduction applied to object data obtained during strong transparency variations. Original data of object and comparison star are shown in the upper and mid panel respectively. In the lower panel the reduced eclipse light curve of IP Peg is displayed (from Wolf and Mantel, 1994)

3 MEKASPEK - The 2nd-generation spectrophotometer

After all the experiences gathered with the MCCP, a more general question arose concerning the photometric accuracy which in principle can be reached using terrestrial broadband photometry. We learned that this task is hampered by problems associated with the elimination of atmospheric extinction and the colour transformation from the instrumental to a standard photometric system. Careful analysis show that these problems can be attributed to an insufficient description of atmospheric extinction effects and to a poor knowledge of the spectral flux distribution of the objects observed (Mantel 1993). Therefore high photometric accuracy requires an optimized instrument with respect to obtaining the utmost spectral and temporal information about atmospheric extinction effects and the program star observed.

In order to meet these requirements the new 4-channel fiber-fed spectrophotometer MEKASPEK was developed at the Universitäts-Sternwarte München (Kiesewetter 1992). Compared to the MCCP the new design (Fig.4) uses a fourth fiber channel which allows one to measure a second comparison star to check the stability of both reference sources. However, most important is the increased spectral resolution $R = \lambda/\Delta\lambda \approx 50$ of the new instrument, which allows second order extinction effects to be eliminated and different photometric systems to be synthesized at a sufficient high accuracy. Furthermore, a time resolution of up to 5 ms that could be achieved using a photon counting 2-dim. detector (MEPSICRON) and data-compression algorithms, covers the whole frequency domain of variable stellar objects.

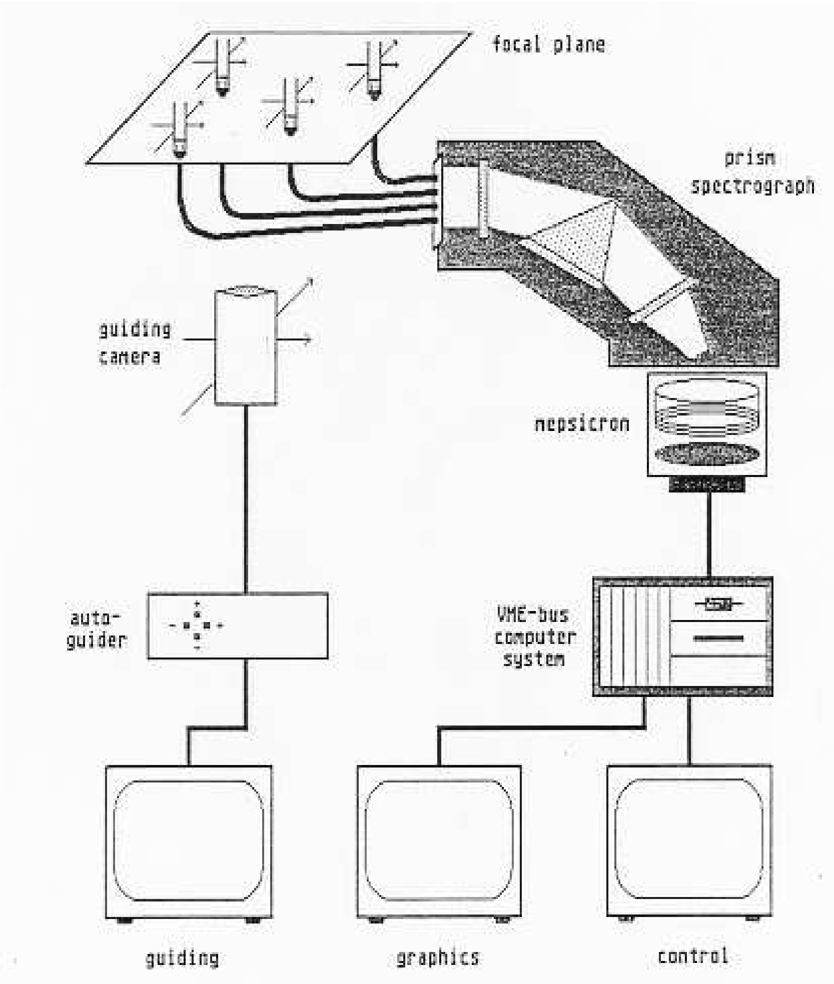

Figure 4: Schematic diagram of MEKASPEK

3.1 Design details

For the scope of this conference two details of MEKASPEK shall be discussed:

1) In order to reach a sufficient spectral resolution 4 fiber bundles each consisting of 130 individual fibers are used as image slicers. Each input channel consists of a electromagnetically interchangeable measuring diaphragm with diameters up to 2 mm. A Fabry lens mounted behind projects the telescope pupil onto the circular fiber bundle entrance window (diameter = 0.8 mm). At the double beam - prism spectrograph the individual fibers (core diameter $70\mu m$) of the 4 bundles are arranged in two rows forming a long slit of 250μ width. Taking into account the instrumental profile together with the pixel size of the MEPSICRON detector in the focal plane of the camera lens a spectral resolution of 50 is achieved within the wavelength region 340-900 nm.

2) Since the 4 fiber bundels should be simultaneously and independantly movable in the focal plane of the telescope (e.g. to follow different planetary satellites) a special fiber positioning unit had been developed. As displayed in Fig.5 each fiber bundle is attached to the link of two steel bands which are winded onto two steel drums. By rotating the drums via stepper motors which are connected to a reduction gear, the length of the steel bands can be changed and thereby the position of the fiber bundle in the focal plane. This device provides a positional accuracy of 10 μm and a reproducebility of $2\mu m$.

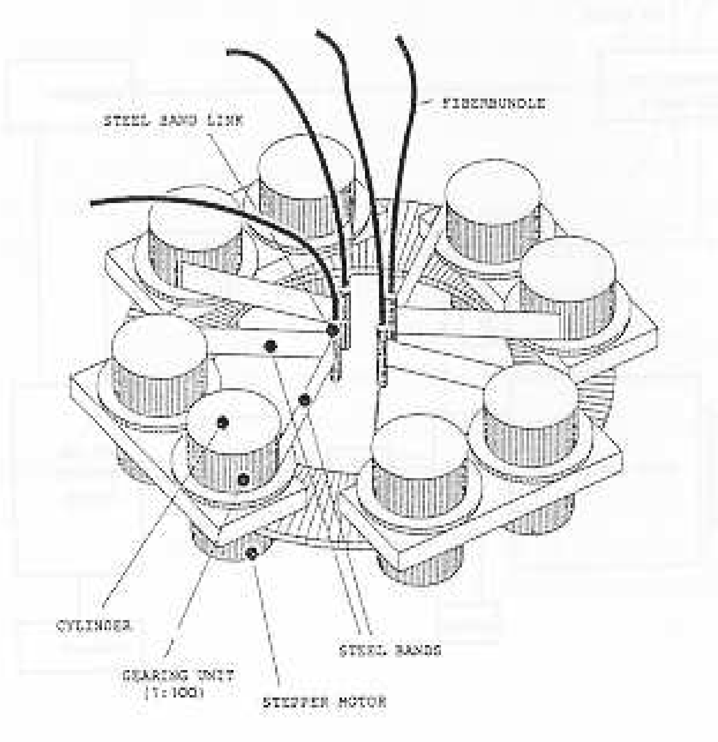

Figure 5: Fiber positioning unit

4 Concluding remarks

The development of the high-speed multi-channel spectrophotometer MEKASPEK was an important step towards the utmost photometric accuracy which can be reached with earth bound telescopes. The application of optical fibers has turned out to be essential to realize the differential measuring principle, which, together with sufficient spectral resolution provides the highest possible accuracy for terrestrial photometry. Since the completion of MEKASPEK in 1993 numerous scientific observing programs have been performed with this instrument mounted at the 3.5m telescopes at La Silla and Calar Alto observatories:

Key projects were:
- Eclipse spectrophotometry of cataclysmic variables (CV)
- Flux calibration of spectroscopic data for Doppler-tomography of CVs
- Spectral eclipse-mapping of accretion disks in CVs
- Simultaneous optical and X-ray high-speed monitoring of flare stars
- Phase resolved spectrophotometry of the Crab-pulsar
- Light echo mapping in X-ray binaries

Though still being a powerful tool for the investigation of high speed phaenomena in astrophysics, MEKASPEK will presumably be replaced in a future not too far from now by focal reducer instruments like e.g. CAFOSC. They will be equipped with star plates, grisms and CCD-detectors with fast readout facilities and high quantum efficiency covering a broad wavelength region. Adaptiv optics then may even make obsolete the application of fibers for light scrambling and image slicing.

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