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ORIGINAL ARTICLE

High speed photon-counting imager using a position sensitive diode

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Abstract A new use for a 2-dimensional position sensitive diode (PSD) is described. A duolateral PSD was used with a microchannel plate image intensifier as a proof-of-concept photon counting (event driven) imager for astronomical imaging and photometry. This produced an imager capable of counting 25–30 kcps over the astronomical bands B, V & R, with an overall efficiency of ∼19%.

Keywords Detectors · Position sensitive diode · Microchannel plate intensifier · Avalanche photodiode · High time resolution · Imaging

1. Introduction

The concept of two dimensional photon counting imaging is not new, as shown by the consistent use of, for example, multianode microchannel array (MAMA) cameras [12], intensified CCDs [3] and the development of low light level CCDs (L3CCDs) [2]. The duolateral effect photodiode was chosen as the imager for this photon counting system on the basis of it having extremely low image distortion levels – despite edge effects, there are no barrel nor pincushion distortions as can be present in other types of diode, and its lateral response is inherently linear. It is background insensitive (since the ratio of output signals is used to produce positional information), has low noise levels capable of producing a high signal-to-noise ratio, and no detector gaps. This duolateral diode is indifferent to spot size in determining the incident spot location (which only depends on collected spot intensity). Due to the continuous structure, its accuracy is not affected by spot truncation or non-optimal spatial sampling, as may be the case with devices composed of discrete photodetectors.

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The reason behind wanting a photon counting imager is that such a device makes it possible to define a software-based aperture in post exposure analysis that will allow the creation of a size-variable, but optimised, aperture giving maximum target signal-to-noise throughout all the collected data. This has been investigated before by members of our group [5]. Unlike a fixed physical aperture the centroid of the software-based aperture can track the target, which would move due to telescope vibrations and atmospheric seeing, throughout the data and be constantly repositioned, ensuring the collection of all the available photons from the target. The aperture size can be matched to the instantaneous seeing conditions. The sky background can also be sampled close to the aperture to acheive accurate photometry.

In this layout target flux, sky background, and a reference star flux can also be independently and simultaneously sampled by three avalanche photodiodes (APDs). The use of fibres and APDs has been used previously in TRIFFID [12], and in the OPTIMA system [14] without a photometer viewer.

2. Detector unit

A collimated beam design is used which allows the easy insertion of optical components (e.g. dichroic mirrors, filters, etc.) into the beam path without disturbing the other elements. A schematic of the optical layout of the detector unit is given in Figure 1 and a physical layout is depicted in Figure 2. A collimated beam assembly allows for light to be split off easily from the main beam without a complicated lens configuration, and leads to a compact design as infinite conjugates are used. This is further helped by using high quality commercial camera lenses which have short back focal distances, further reducing the overall optical path length. Adaptability to telescope scales and f-ratios is achieved through the choices of the collimating and refocussing lenses, (B and G, respectively, Figure 1), which allow the magnification or minification of the input focal plane.

The photocathode of the MCP intensifier is positioned in an image plane (H), and the fibres leading to the APDs are positioned in another image plane (F). The B and V bands are transmitted and reflected by the dichroic mirrors C and D respectively, and brought to a focus by the lens G. The R band is passed to a focus at F for the APDs. One or two PSDs can be mounted behind the MCP output phosphor to capture the B and V images through imaging fibre rods. Camera lenses manufactured by Mamiya [7] are used for the collimating and focussing lenses (B and G respectively) and one of a selection of standard biconvex lenses is used at position E for the APD fibres. Through matching the focal lengths of these three lenses to the telescope plate scale, size of target, and the sizes of the PSD and APDs, an optical system is created with the desired detector spatial resolution and field of view coverage on the sky.

3. Design of the PSD device

3.1. PSD description

The photodiode is a dual axis, duo-lateral PIN photodiode, has a 4 mm $\times$ 4 mm active area and is a continuous single element with no gaps or dead areas, highly important for a full field imaging device. It is operated in the photoconductive (reverse-biased) mode and converts an incident light spot into continuous positional data.

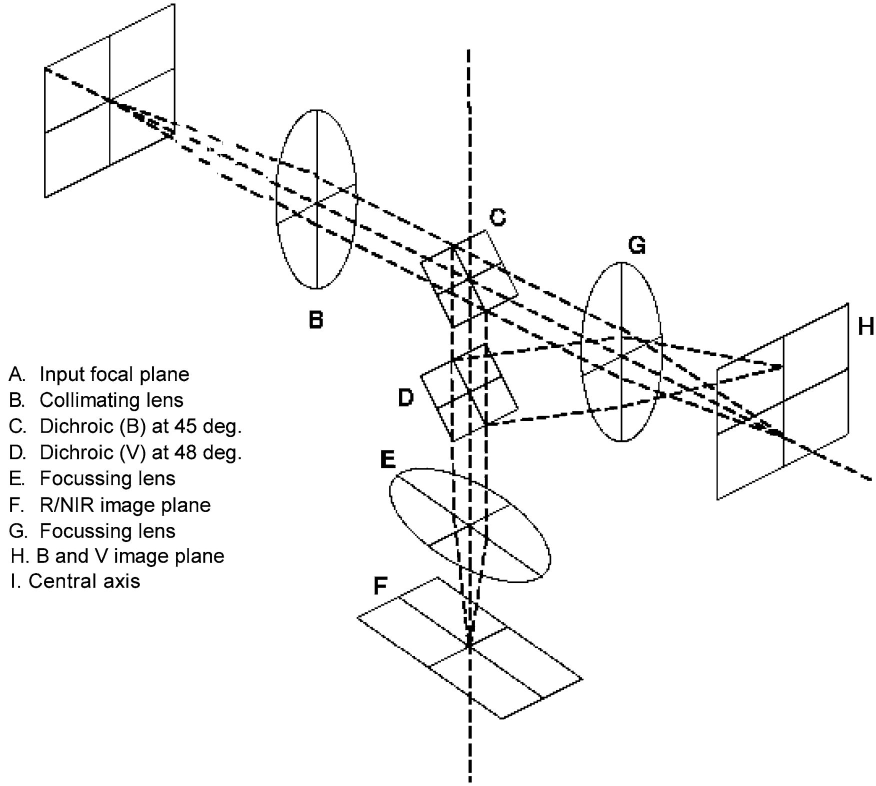


Fig. 1 The optical layout of the PSD and APD photometer system

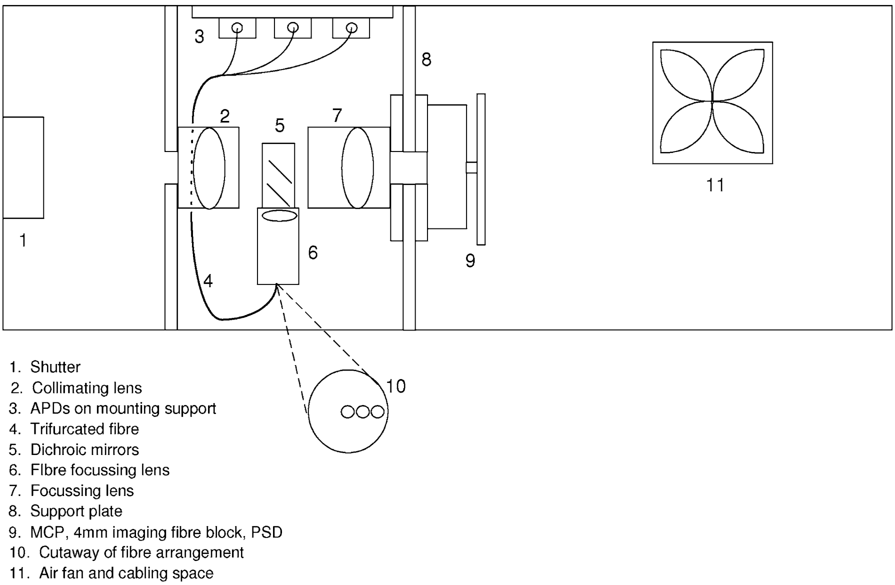


Fig. 2 The physical layout of the PSD and APD photometer system

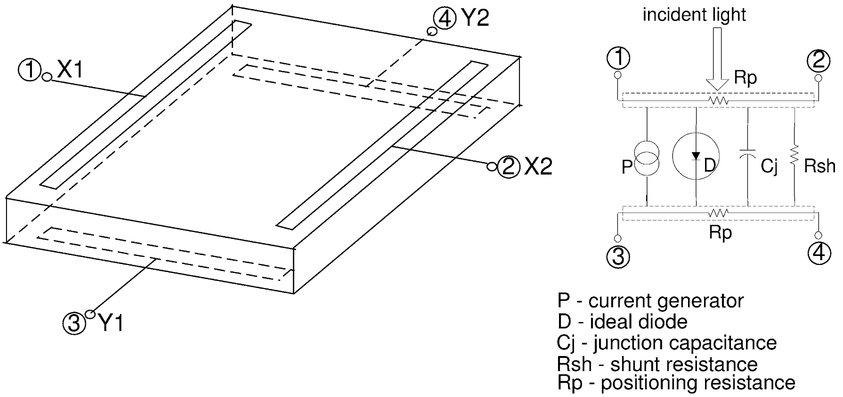


Fig. 3 Schematic of a two dimensional PSD structure and equivalent circuit

The two dimensional position sensitive diode has four terminals, two on both the front and back (P and N) surfaces, but orthogonal to each other (Figure 3). Light pulses absorbed by the diode produce electron-hole pairs which, if produced in, or within a diffusion length of, the diode junction, get separated by the high electric field (the naturally produced field plus the applied reverse bias) present across the junction. The two currents now meet the resistive face on either side of the diode and are divided to the two contacts as dictated by the resistance within the layer to both contacts from where the current meets the layer initially. This division of the photoelectric current on each face will yield an X and Y positional coordinate through ratioing of the pulse heights.

Figure 3 shows the layout of a duolateral PSD with an equivalent circuit. The PSD is represented as an ideal diode with a current source and shunt resistance in parallel, and a positioning resistance connected in series. The series positioning resistance is the resistance of the contacts and the undepleted bulk of the substrate. The boundaries of the depletion region act as two plates of a parallel plate capacitor giving the diode the capacitance C_j. The current source represents the photoelectric current produced by the absorption of incident photons.

The actual duolateral photodiode used was purchased from Silicon Sensor GmbH, Berlin [13].

3.2. Microchannel plate intensifier

The MCP was manufactured by Photek Ltd [10] and is a three plate, 25 mm tube, with S20 photocathode, P20 phosphor and expected spatial resolution of up to 16–18 lp/mm [10]. The pores are 10 μm in diameter on 12 μm centres, with a length to diameter ratio of 40:1, set on a 12° bias angle. The light output from the MCP phosphor is coupled to the PSD through a 1:1 imaging fibre bundle, with a 4 mm × 4 mm face, matching the dimensions of the PSD chip. The gain of the MCP is controlled by a high voltage power supply using four user controlled settings.

4. PSD data collection

4.1. PSD pulse conversion and amplification

The PSD is mounted in the centre of a printed circuit board containing the relevant circuitry, Figure 4, for amplifying the four current pulses produced in response to an absorbed pulse of light.

Each of the four arms contain a current-to-voltage converter followed by two gain amplifier stages. The current pulses coming from the p-side of the diode (A1 and A2 inputs) are positive and the accompanying pulses from the n-side (K1 and K2 inputs) are negative, all on the nanoamp scale. All the gain amplifiers have approximately the same 30× gain, to maintain pulse height ratio, ensuring that there are four positive, simultaneous, and easily sampled pulses as an end result. The final outputs 1–4 are terminated and are physically represented

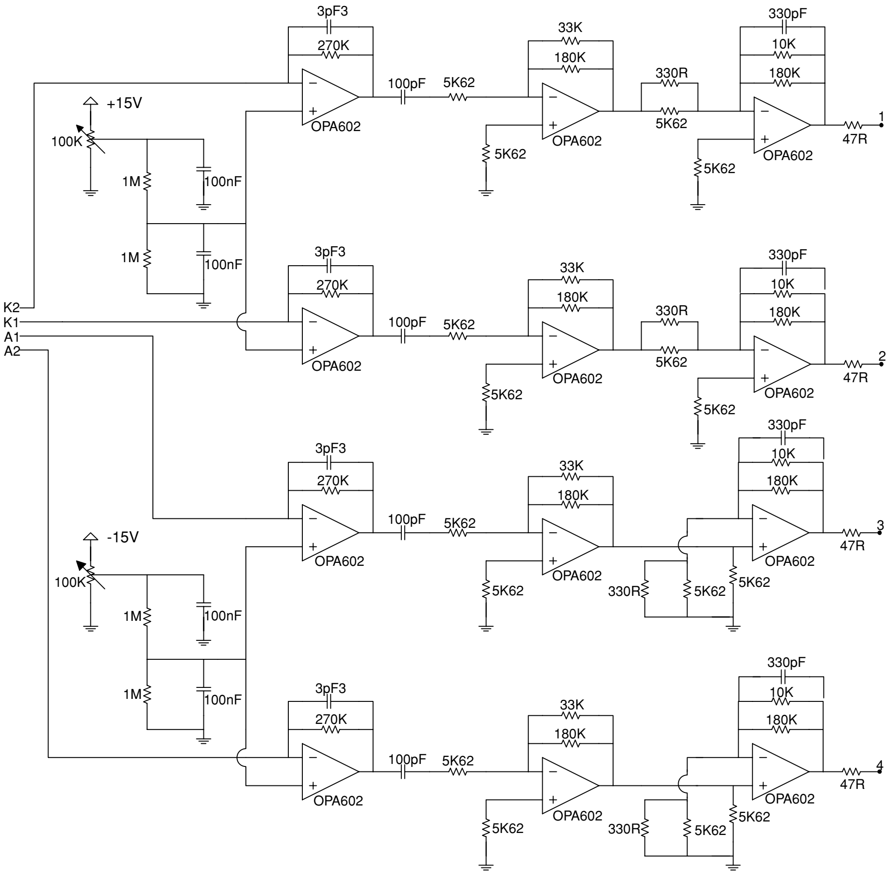


Fig. 4 The circuit branches used to pickup and amplify the PSD current pulses. Each leg contains a current-to-voltage converter followed by two op-amp gain amplifiers. A1 and A2 are two positive pulse inputs from the p-side of the PSD, K1 and K2 are the complementary negative pulse inputs from the diode's n-side. Outputs 1 and 2 are preceded by inverting amplifiers, while 3 and 4 use non-inverting amplifiers. The final output is four positive, simultaneous, easily sampled pulses produced with the same gain, and presented at terminated SMB contacts

by four SMB contacts. The signals are then transmitted via coaxial cable to a custom made pulse digitiser card for the next stage of data collection and interpretation.

4.2. PSD pulse digitisation

Three digitiser cards were custom built, each capable of accepting the four analogue amplified voltage pulses from two PSDs simultaneously, giving an option of using up to six devices, at a rate of up to 1 M pulses per second each. The four PSD outputs are digitised to ten bits and each is simultaneously sampled at selectable high resolution rates of either 200 ns, 100 ns, or 50 ns sampling intervals. The four digitised channel values are summed together to 12 bits for peak detection. When a peak is detected the four 10 bits values along with the twenty-three least significant bits from a 24 bit local timer (counting clock ticks from an oscillator on the card), with the use of one bit to identify from which of the two possible PSDs the inputs originated. The peak data and timestamp are saved to disk and also are multicast as two thirty-two bit words onto the local Ethernet network for realtime processing.

There is provision for a time event, based on the one pulse per second (PPS) sent by a GPS receiver. At every PPS the current UTC is added into the output peak data stream along with the contents of the local timer previously mentioned. In post-processing of the data the time of arrival of each detected peak can then be calculated in UTC, and separately the stability of the internal clock oscillator can be monitored.

The centroiding of the peak data is performed in software with the Equations (1) and (2), referring to Figure 4.2.

$$X = ((x_1 - x_2)/(x_1 + x_2)K) + K \tag{1}$$

$$Y = ((y_1 - y_2)/(y_1 + y_2)K) + K \tag{2}$$

where x_1 and x_2 are the pulse heights of the two current components given out by the PSD along its x-axis, and y_1 and y_2 on its axis (Figure 5). K is a multiplicative factor which governs the number of logic image pixels created, equal to half the number of image pixels wanted per axis on the 4 mm PSD, e.g. for 256 15.6 μm logic image pixels per axis, $K = 128$.

There is a fixed pattern present in the PSD images, apparent in Figure 6a. This pattern is created by the analogue to digital converters used to digitise the incoming pulses from the PSD. Since the pattern is fixed and unchanging it can be removed from any images by flatfielding, as demonstrated by Figure 6b. This is a flatfielded image of a resolution bar chart. Figure 6c is an image of HD1326B (saturated due to lack of colour depth) taken during a test observation run on the 60 cm telescope at the Loiano Observatory, Italy [6]. It shows the principle, in post exposure analysis, of background correcting the target flux. All detected photons are timestamped and their spatial coordinates recorded. The target flux is taken, second by second, from an area around the target. The sky background is taken at the same intervals from an area of sky which is then scaled by the ratio of the two sampling areas. Figure 6c also shows a profile of the target across the image.

5. Fibre-fed APD modules

Three optic fibres each lead to an APD module. The three fibres are joined at one end in an FC connector (one fibre in the geometrical centre of the housing, the second to one side and

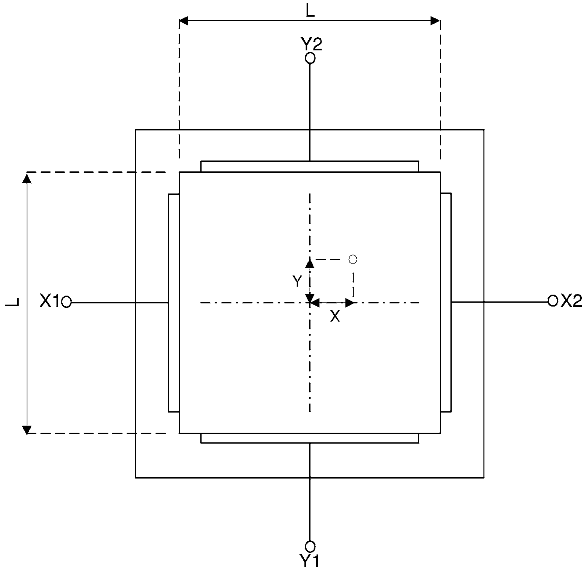
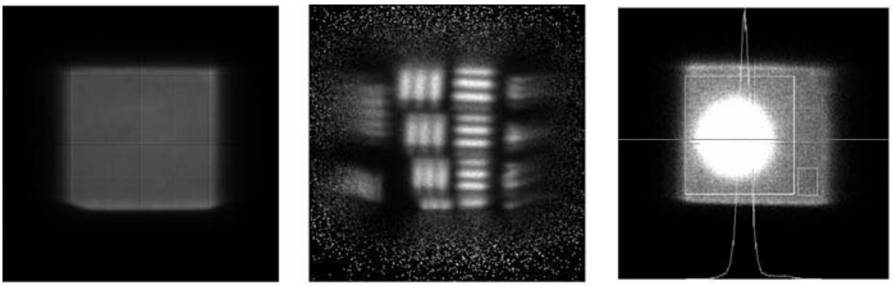


Fig. 5 Schematic showing position determination with a two dimensional PSD. See Equations (1) and (2)



a. MCP-PSD flatfield. b. Lab image. c. Stellar target.

Fig. 6 Three MCP-PSD images, *a* is a flatfield of the MCP-PSD from lab characterisation tests; *b* shows an image of a resolution bar chart flatfielded by *a*; *c* is a flatfielded image of HB1326B

the third beside this again, see Figure 2) and each of the three free ends are housed in separate FC connectors. The package was manufactured to specification by Multimode Fibre Optics Inc. [8].

The cores are pure fused silica of 200 μm diameter on 240 μm centre-centre spacings. The free end of each fibre is mounted to a lens on an XYZ stage to allow independent and controlled focussing onto each APD. Figure 7 shows the arrangement of the fibres, focussing lenses in brass blocks on XYZ stages, and the APDs, all mounted on a perspex plate for electrical insulation from the rest of the system housing.

The three APDs used in the photometer system are from PerkinElmer [9] and are all active quench single photon counting modules with extremely low dark counts (two with dark counts typically 150–250 counts per second, the third with typically 250–500 counts per second). Each has an active area of 180 μm. The theoretical maximum count rate for the APD modules is 15 Mcps [9] although the detected rate is highly non-linear at this stage due to diode overheating.

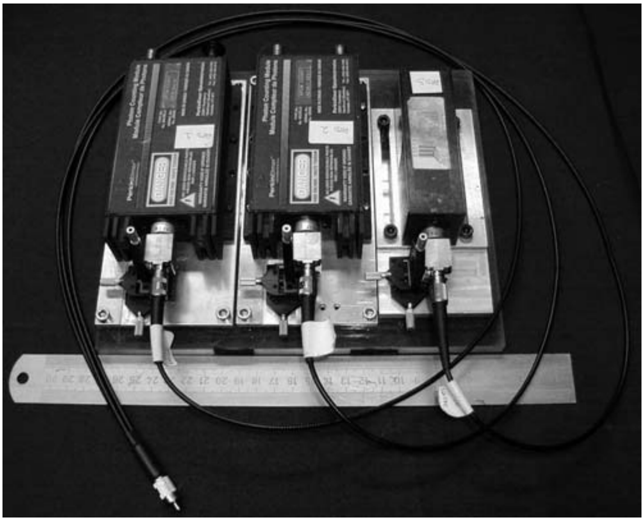


Fig. 7 The three APDs and the 1 metre long trifurcated fibre. Brass blocks mounted on XYZ stages each contain a doublet lens to focus light from the fibres onto the APDs

One APD is used to measure the target flux, while the other two sample the near-object sky background. Alternatively the second APD can monitor a suitably nearby reference star while the third samples the nearby sky background. As the APD data is taken simultaneously with the PSD data, the APDs give contemporary scintillation and guide measurements. Also as the sky background is separately sampled by either one or two APDs there is no need for chopping.

6. APD data collection

A data acquisition system based on TTL I.C. logic devices was created to collect data from the three APDs [4]. The modular nature of the design electronics allows the addition and removal of the three detectors without limiting the performance of other elements within the system. The data path is designed so that archiving integrity is maintained while data is simultaneously used for realtime analysis and display. The data is archived to disk as well as transmitted over Ethernet as a multicast stream (as for the PSD data). This allows real-time display and analysis programs to be located anywhere on the local network without disturbing the integrity of the archiving process. The dedicated electronics for the APD detectors were designed to incorporate timing information and buffer the incoming data.

The absolute time of arrival of each detected photon is known to one microsecond, achieved by using an oven-stabilised 10 MHz oscillator and the GPS receiver system that provides UTC time and a 1 pulse per second (PPS) signal that is accurate to better than 0.1 μs (the same PPS that is used to stamp the PSD data flow). By connecting a 24-bit counter to the oscillator output, sub-microsecond timing accuracy can be assured. Every second the UTC time from the GPS receiver is inserted into the data stream to ensure absolute timing accuracy (as for the PSD data flow).

Table 1 System characterisation details, resulting from in-house testing and an observation run. APD detection efficiency is as per manufacturer's datasheet [9]

Component parameters and efficiencies	
MCP efficiency	~20%, (400−500 nm)
PSD efficiency	~99%
MCP and PSD combined efficiency	~19% (400−500 nm)
Overall PSD system efficiency (detector and optics)	~1.4% (400−500 nm)
PSD active area	4 mm × 4 mm
Imaged Spot size, X	6 pixels (93.6 μm) − best
Imaged Spot size, Y	4 pixels (62.4 μm) − best
Image Spatial resolution, X	125 μm − max.
Image Spatial resolution, Y	88.34 μm − max.
MTF resolution	~40 μm − best
MCP global rate	131 kcps (2 cps per pixel) − linear limit
PSD global rate	25−30 kcps, pulse pile-up limit
PSD interpulse dead-time	30 μs
Detected photon timestamping resolution	1 μs
APD detection efficiency	up to 70%
Fibre transmission efficiency	~30−40%
Collimating lens transmission efficiency	53.22% (400−500 nm)
Refocussing lens transmission efficiency	53.22% (400−500 nm)
Dichroic transmission efficiency	83.16% (400−500 nm)

7. System characteristics

A series of characterisation experiments were performed in order to determine the sensitivities and throughputs of individual system components, thereby leading to overall efficiencies of the system. This lab characterisation combined with an observation run carried out at the 60 cm telescope of the "Osservatorio Astronomico di Bologna" in Loiano, Italy [6] determined the characteristics of the system. The telescope has a focal ratio of f/20 and a plate scale of 17 arcsec/mm. Lenses of focal lengths 80 mm and 150 mm were chosen for the collimating and refocussing lenses, respectively (B and G in Figure 1), giving an imaging scale on the MCP-PSD imager of 0.54 arcsec per pixel. A 75 mm focal length lens was used for E of Figure 1 giving the APD fibre a field of view of 3.63 arcsec and a fibre-to-fibre separation of 4.35 arcsec. Further details are summarised in Table I, with the experiments and observation run described by Ryan [11].

8. Conclusion

A proof-of-concept system was developed to ascertain the validity of use of a two dimensional position sensitive diode (PSD) as a viewer coupled to a microchannel plate intensifier (MCP) in a photon counting and imaging capacity. The MCP-PSD viewer is capable of counting up to 25–30 kcps in the B and V bands with a spatial resolution of $\sim$100 μm, and used with a GPS controlled timing system exhibits a time resolution of 1 μs. It is adaptable to most telescopes' plate scales and f-ratios. Dichroic mirrors allow light to be focussed onto three optical fibres each leading to a high efficiency photon counting avalanche photodiode (APD). Target flux, sky background, and a reference star flux can each be independently sampled by the APDs and imaged simultaneously by the system. The adaptability of the system is such that it is hoped to incorporate up to six PSD detectors into the system, after further work to improve on the 19% efficiency of the MCP-PSD viewer.

References

1. Adlink Technology Inc.: http://www.adlinktech.com
2. Basden, A., Haniff, C., Mackay, C.: Monthly notices of the royal astronomical society, 345(Nov.), 985–991 (2003)
3. Bergamini, P., Bonelli, G., Paizis, A., Tommasi, L., Uslenghi, M., Falomo, R., Tondello, G.: Exp. Astron. **10**, 457–471 (2000)
4. Buckton, D., Ryan, O., Shearer, A., Redfern, M., Butler, R.: Proc. SPIE **4876**, 1037 (2003)
5. Golden, A., Shearer, A., Redfern, R.M., Beskin, G.M., Neizvestny, S.L., Neustroev, V.V., Plokhotnichenko, V. L., Cullum, M.: Astron. Astrophys. **363**, 617 (2000)
6. Loiano Observatory: http://www.bo.astro.it/loiano/index.htm (2003)
7. Mamiya America Corporation: http://www.mamiya.com
8. Multimode Fiber Optics Inc.: 9A Great Meadow Lane, East Hanover, New Jersey 07936, USA. http://www.multimodefo.com
9. PerkinElmer Inc.: APD Based SPCM-AQR Series Datasheet, http://optoelectronics.perkinelmer.com/content/Datasheets/SPCM-AQR.pdf
10. Photek Ltd.: 26 Castleham Road, St. Leonards on Sea, East Sussex TN38 9NS, UK. http://www.photek.co.uk
11. Ryan, O.: Ph.D. Thesis, National University of Ireland, Galway, Galway, Ireland (2004)
12. Shearer, A., Stappers, B., O'Connor, P., Golden, A., Strom, R., Redfern, M., Ryan, O.: Science **301**, 493–495 (2003)
13. Silicon Sensor GmbH: Position Sensing Photodiodes datasheet, http://www.silicon-sensor.com
14. Straubmeier, C., Kanbach, G., Schrey, F.: Exp. Astron. **11**, 157–170 (2001)