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GASP: High Speed Optical Detectors for Polarimetric Observations

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We present an overview of the work currently ongoing into the detector system used on the Galway Astronomical Stokes Polarimeter (GASP). GASP is based upon a Division of Amplitude Polarimeter and has no moving parts or modulated components. The complete Stokes vector is measured from just one exposure. This means that the timing resolution depends only on the frame rate of the detector system. GASP has been used on the 2.2 m Telescope at Calar Altro (2009) and on 4.2 m WHT (2010). The system consists of the instrument box to which either an L3Camera system or an APD detector system is attached. A GPS Time and Frequency system controls all timing aspects for both detector systems. The choice of detector depends on the science target and objectives. For frame rates up to 650 Hz the L3Camera system can be used, but for faster varying targets, the system must be used with APD detectors. The latter can operate at resolutions of < 1 μsec with a timing accuracy of 25 nsec. Data loads for the L3Camera system are typically 86 GB per Hr per camera (for full frame). The APD system only stores data if a photon is detected and each photon event is individually time tagged to a 40 MHz clock (25 nsec). For the APDs, 1TB of disc space would provide a minimum of 8.5 hours recording time.

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1. Introduction

Since its introduction into astronomy in the 1970s [1], the CCD detector has become the main stay of imaging devices. It provides astronomers with a robust imaging device that has a linear and wide spectral response which extends from the blue to the near infra-red. One of the only draw backs to using a CCD based detector system is the slow readout rates, which can result in readout times of anything up to a minute or more. The primary reason for the slow readout stems from the fact that the faster you read out a CCD, the greater the readout noise. This in essence makes them unsuitable for low light level applications or for the photon counting regime.

To address this problem, the Low Light Level or L3CCD was developed by E2V Technologies in 2000 [2]. It employs electron-multiplication to increase the signal so that it is above the noise floor of the readout electronics. Now instead of reading out at KHz rates, the L3CCD detectors can be readout at MHz rates [3]. The amplification process introduces a noise factor of $\sqrt{2}$ to the output signal, but with suitable thresholding schemes, the original photon count may be extracted [9]. Apart from increasing the readout rate, the readout mode can be optimised. Firstly the CCD sensor is broken into two parts; imaging and storage sections. This allows the CCD to be exposed to light, while the previous image data is been readout from the storage area. This reduces the dead-time between frames to approximately 2 ms. This is known as Frame Transfer and coupled with electron-multiplication, it allows for frame rates up 500-600 Hz. To date a number of research groups have successfully used some or all of these methods for there high speed observing campaigns e.g. UltraCam [4], LuckyCam [5], GUFI [6], POETS [7], TOφCAM [8].

The use of CCD technology above 1KHz becomes somewhat tricky. To achieve such high frame rates, one would have to generally window down so a size where you may only get a single star in the frame (depended on instrument platescale). An alternative would be to use avalanche photodiodes or APD detectors. These are single channel devices where the star light is typically fibre fed. Apart from dark count and minor non-linearity effects, these devices can be thought of as been true photon counting devices. Commercial APD modules have peak quantum efficiencies of 65% at 650nm and can count up to 2 to 5 Mc/s [10]. These devices have been used by TRIFFID [11, 12] and OPTIMA [13] for high speed photometry.

The Galway Astronomical Stokes Polarimeter or GASP is based on a Division of Amplitude Polarimeter. It uses a modified Fresnel rhomb to act as a highly achromatic 1/4 wave plate and beam-splitter. The unique feature of this instrument is that it contains no moving parts or modulated components and the complete Stokes vector can be measured from just one exposure - making it unique to astronomy. This means that determination of the Stokes vector is limited only by the speed of the detectors and the incident photon flux. GASP is currently equipped with L3CCDs and was used on the 2.2 m Telescope in Calar Altro in 2009 and on the 4.2 m WHT in 2010. In this paper we describe the particulars of the detector system for GASP and discuss the performance metrics for L3CCDs and the newly proposed GASP APD detector system.

2. Scientific Motivation

Polarisation studies are important part of HTRA as many objects which exhibit behaviour on short timescales also result from the interaction of relativistic plasmas and magnetic fields where the radiation is expected to polarised. The classic example of this is the optical emission from pulsars where a time resolved linear polarisation signal from the Crab pulsar has been observed by many groups [14, 15, 16]. These observations highlight the need for a high-throughput polarimeter with a time resolution down to a few microseconds. Furthermore, if stochastic events are to be observed then the polarimeter should be able to measure the Stokes parameters instantaneously without the need for either rotating wave-plates or retarders. An ideal polarimeter should also return all Stokes parameters to enable a determination of both linear and circular polarisation. Although GASP is planned to observed across the full gamut of HTRA targets it is its ability to study optical counterparts [17] of giant radio pulses from pulsars and rotating radio transients (RRATs) [18] which were the main science drivers behind GASP. In both these examples we require the ability to observe the polarisation from on either short timescales (for the Crab pulsar) and on random time scales (RRATs). These criteria introduce distinct instrument design parameters. But essentially they both require low-noise high quantum efficiency systems which pointed to the use of either electron multiplying CCDs or avalanche photo-diodes. In this paper we describe the characteristics of the EMCCDs used in GASP.

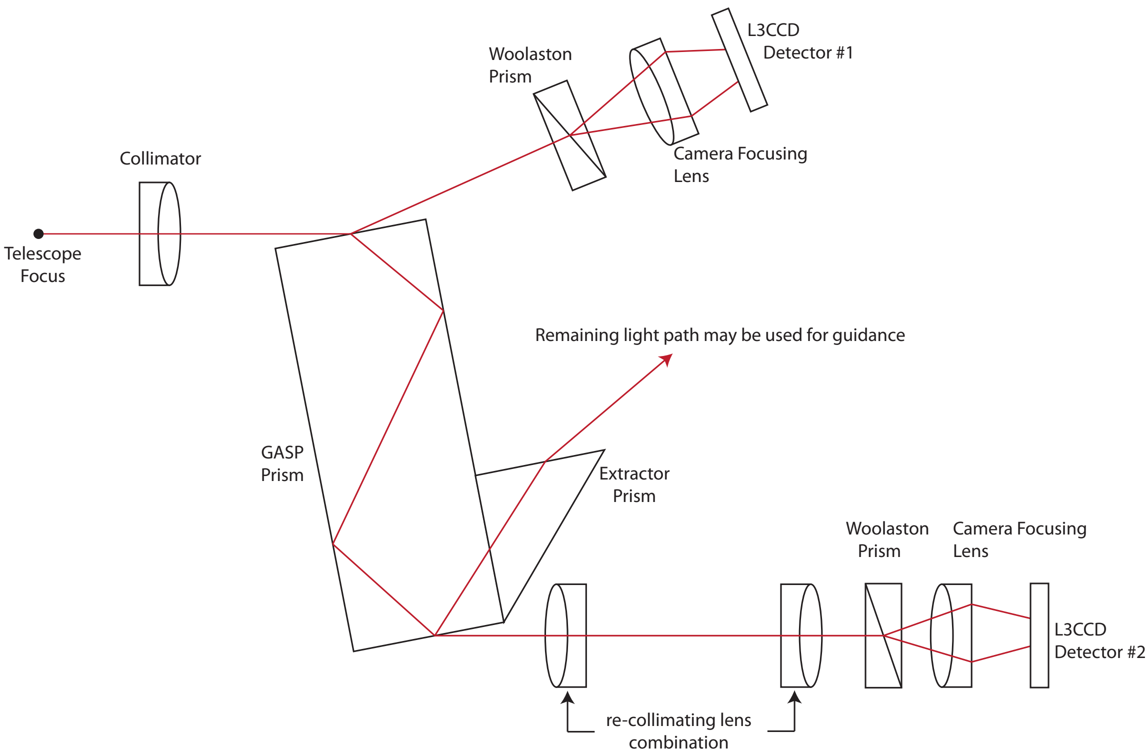

Figure 1: Schematic showing the optical components of GASP. Detector #1 receives linear polarised light while detector #2 receives the circular polarised light. For 100% unpolarised light, both detectors will receive equal amounts of light. The GASP filter wheel (fitted with a Sloan filter set) is placed between the Prism and the Collimator.

3. The GASP Detector System

GASP currently uses two E2V CCD97 camera systems acquired from *PixCellent Imaging Limited* [20]. The CCD97 comes with a native resolution of 512 x 512, 16 um^2 pixels and is operated at a pixel rate of 15 MHz. This allows a frame rate of 45 Hz for full frame, and by reducing the number of rows in the frame, frame rates of 650 Hz may be achieved. The sensors are housed in a hermetically sealed vacuum head and are cooled to $-120\,^{\circ}$C using liquid nitrogen. The vacuum unit is designed to operate at 10^{-5} Torr and is assisted by a charcoal pump. This allows the cameras to remain chilled for at least 8 hours. The CCD97 is thinned and back illuminated to give it both an improved blue response and a peak quantum efficiency of $\approx$ 90% at 575 nm.

3.1 Low Light Level Detection

For L3CCD sensors electron-multiplication or EM-gain is used to elevate the problems of readout noise. However EM-gain also adds its own noise elements, the most problematic of which is Clock Induced Charge or CIC. This is the random generation of electrons from the clocking out process and occurs randomly within an image frame. This would not normally be a problem as they would have been lost in the readout noise. Now however, they are amplified to a level where they can be mistaken for real photon events. The rate of CIC generation increases with EM-gain.

CIC events may however be distinguished from genuine photon events. The majority of CIC is generated partway along the multiplication register and thus on average experiences less amplification than real photon events. By comparing the distributions for both *CIC* and *Photon + CIC* a gap is observed that separates the incident photons from CIC (figure 2). Here one may threshold the data to remove the CIC and noise components.

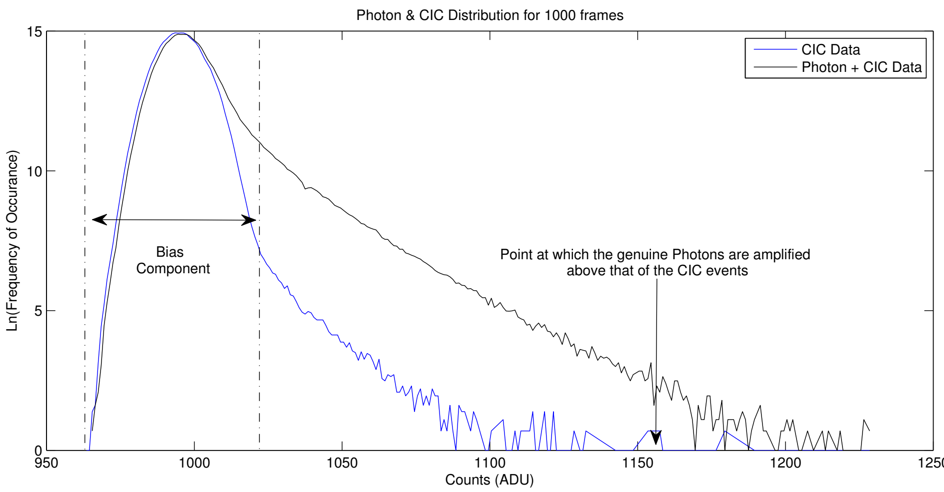

Figure 2: Clock Induced Charge & Photon distributions (Flux rate $<$ 1 photon/pixel)

To successfully extract the genuine photons and recover full quantum efficiency, the detectors must be operated in photon counting mode (i.e. $<$1 photon/pixel). This means that all counts above the bias are photon counts, but intermixed with these are the CIC events. The CCD97 detectors in the GASP cameras have been specially designed to operate in this regime. To this end, they have been tuned to work with relatively low saturation levels but at an extremely low CIC level.

Figure 3 illustrates how the applied threshold might work for a dataset. The scheme works where the detector is operated in photon counting mode (i.e. 1 photon/pixel). It is assumed that every count registered by the camera is a photon, but intermixed are the CIC events. It is taken that every pixel with a count above the chosen threshold is a pixel with one genuine photon. The plot shows that for an increasing threshold level the number of detected photons decrease, but at the same time the number of CIC events decrease. At some stage just before the cutoff for the CIC distribution, the ratio of detected Photons to CIC events reaches optimum. Increasing the threshold any further will reduce CIC even more, but one loses more photons due to reaching the end of the photon distribution.

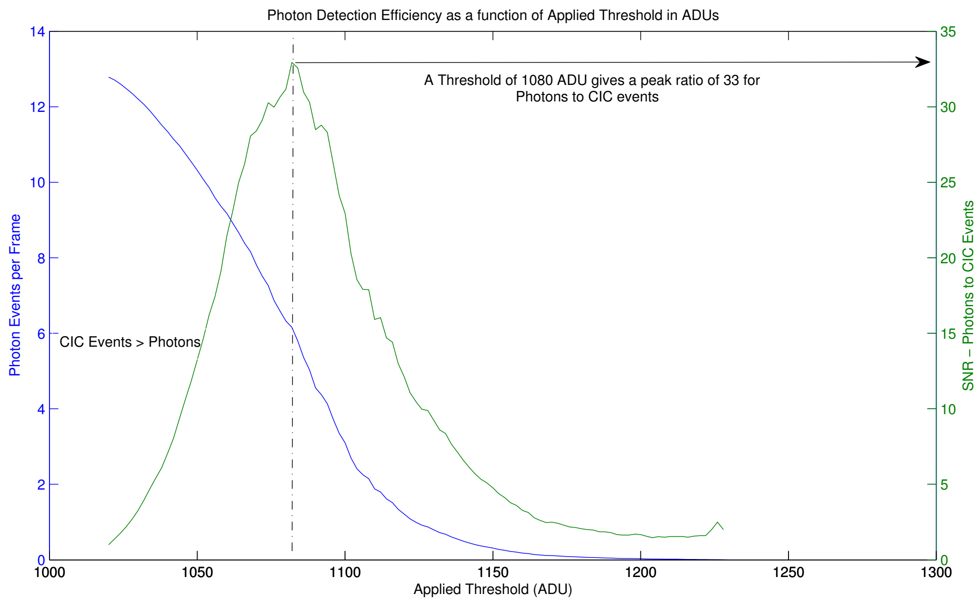

Figure 3: How applied the threshold affects the ratio of detected Photons to Clock Induced Charge

Figure 4 demonstrates the application of thresholding for a calibration test target. The left most image is the raw frame where the EM-gain is set to a level where the photons are just about visible; it was 1000 of these frames that produced the photon distribution in figure 2. The center is the same frame but that is thresholded to 1020 ADUs. The calibration plot of figure 3 shows that this level of thresholding would result, on average, a ratio of near 1:1 for CIC and Photon events. The right most image shows the resultant image if the 1000 images are thresholded to the optimum level as suggested by figure 3, at 1080 ADUs.

3.2 L3Camera Operation & Time-Stamping

During operation, the two L3CCD cameras are configured to work synchronously to a GPS timing signal. One of the detectors receives a 20 MHz external clock, that drives all sensor clocking functions, and also a external TTL trigger signal. The external trigger either initiates each

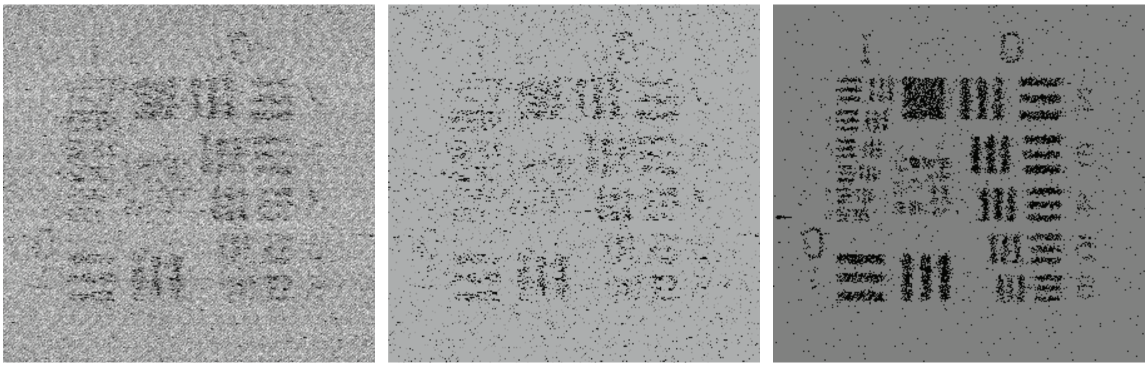

Figure 4: Applying various thresholding levels to a calibration test target

individual frame readout or just the first frame in the sequence. The second camera is linked to the first by means of a *multi-camera sync cable* which shares all timing and clocking waveforms. This essentially makes the two cameras work as one.

Time-stamping of the data is achieved through the use of the external trigger signal. The cameras clock (20 MHz) is a stable TTL signal derived from a GPS receiver - Symmetricom Time & Frequency unit [19]. This GPS system has a 10 MHz crystal which is phase locked to the GPS 1PPS and its on-board frequency synthesiser produces the 20 MHz system clock. This means that the 20 MHz is frequency locked (at an arbitrary phase) to GPS for the duration of the observations. The fact that the camera clock runs at an arbitrary phase does not matter. The trigger that initiates the readout process is a known absolute GPS time. It is produced by the Symmetricom Time & Frequency unit via a *programmable pulse output* which has a resolution of 1 μs and is accurate to GPS to 100 ns. This sets the accuracy of the data collection system and this time-stamp is recorded by the system during observations. By having all timing aspects controlled by hardware, it elevates the need for super-accurate OS controlled timing and possible issues with software interrupts.

4. Future Plans - APD Detectors

To operate GASP at higher frame rates, >1 KHz, (e.g. study of pulsars) it would be more desirable to use an APD detector system. This comes with a number of advantages:

- Direct photon counting (after quantum efficiency & dark count correction)
- No Amplification or threshold calibrations, Readout Noise or Clock Induced Charge
- Achieve full quantum efficiency for the selected pass-band
- Less data storage required
- Achieve a resolution of < 1 μs

For GASP, a minimum of 8 APD channels is required; 4 for science and 4 for sky background/field star. One of the main differences between using the L3CCD system and the APD system will be the characterisation of the relative gain in each of the APD channels. Also, each APDs is fibre fed and hence each optical path for the 8 APDs will have associated transmission efficiencies. These effects, the relative gain and its stability is currently been investigated in the laboratory.

4.1 APD Operation & Time-Stamping

The system comprises of the APDs, a custom built data logger (PixCellent Imaging) and a computer running MS Windows Xp. The core of the detector system is the data logger. This has 15 input channels (8 ST-Fibre ports and 7 TTL BNC ports) and are all sampled at the rate determined by the external clock. For GASP, the system is designed to operate at 40 MHz, which is provided by the Symmetricon Time & Frequency unit. All the data logging functions, control and recording, are carried out by a PLD chip. The system operates as follows:

1. Time is measured by a 48-bit counter (clocked at 40 MHz).
2. The rising edge of a trigger pulse (TTL, BNC Input) resets and starts the 48-bit counter.
3. APD events are logged whenever a rising edge is detected at one of the loggers inputs.
4. The events that occur within each clock period are recorded in a bit-mask.
5. The PLD encodes the data into frames.
6. Each frame contains the 48-bit counter value of the first period for that frame, and each consecutive bit-mask.
7. The computer software writes the frames as event files.
8. Events files contain a series of 64-bit events records. The low 48-bits contains the counter value, next 15-bits is the bit-mask defining which data logger channel registered an event from an APD during that clock cycle. The last bit is a parity bit for system checks.

The event files are recorded as binary files and can be set by the user to have a maximum size; default is 24 MB. In-house software decodes the data for analysis and display. The system currently runs on a quad-core computer and uses an Adlink data card (PCIe7300A) to read the data from the data logger. The data logger software currently runs on a MS Windows OS but there are plans to transfer it across to a LINUX platform also. Under typical data loads, a 1 TB disk would provide a minimum of 8.5 hours recording time

The main advantage of this system is the time-stamping capability. The resolution of the system depends on the external clock and all timing functions are carried out in hardware. The trigger pulse used to start the acquisition is sent from the Symmetricon Time & Frequency unit. This is a programmable pulse output and is a known absolute GPS time with a resolution of 1 μs and accurate to GPS to 100 ns.

5. Data Acquisition System

The two L3CCD cameras are fitted externally to the instrument box and optically aligned to the polarimeter prior to mounting on the telescope. Each L3CCD camera system made up of the

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camera head, power supply unit, interface adaptor box, interface card and rack mounted computer. The Symmetricom Time & Frequency unit which is used for time stamping the data can be either mounted with the computers in the telescope rack or in the control room with the operator. GASP operates as a stand-alone system and as such all communications and control of GASP is carried out on its own private LAN. Over the LAN all computers are synchronised using NTP (typical offset 10 ms from GPS), and remote control/live video feed is facilitated by a remote desktop server/client. Figure 5 shows how the GASP detector system is setup at a telescope site.

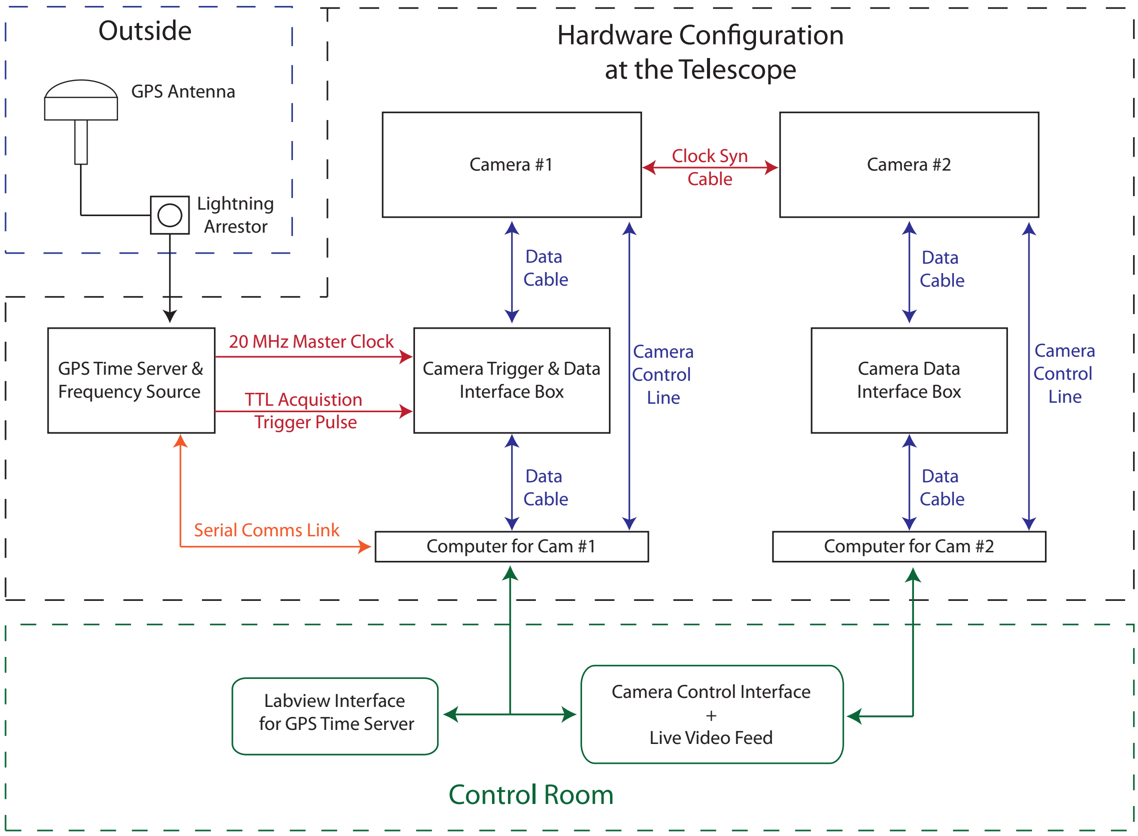

Figure 5: Schematic illustrating the layout of the GASP detector System

Each computer is fitted with a 1 TB, 7200 rpm harddrive and at max data load of 70 GB/hr, it provides the user with approximately 12 hours recording time. The harddrives are accessible from the front of the computer and can be pulled out and replaced when necessary.

With plans to operate GASP using APDs, the system will be re-configured by removing one of the cameras with the APD data logger and the APD modules. One L3CCD detector will remain for guidance and star alignment with the APD fibre tips. Currently with the L3CCD detector system, GASP uses a removable fold-mirror which gives a larger field of view (4 x 4 arcmins) on the finder camera (Starlight Express SXVF-M5 SuperHAD CCD camera). Due to optical nature of the GASP prism, the extractor beam will only provide a limited field of view for which to verify the star field. This means, for the APD system, the star acquisition will work in two steps. The first, to locate the desired target within the finder camera, and then switch over to the remaining L3CCD detector for final APD alignment. The location of the fibre tips will have been mapped on this camera for final placement of the target star. This method has been found to work well in the past, and does not require much time; fold mirror moves in and out of position in a matter of seconds.

6. Final Comments

We have described the application of Low Light Level CCD detectors for high speed polarimetry. Given the unique design of GASP and its ability to yield a complete measure of the Stokes vector, the challenge is to maximise both the speed and sensitivity of the detector system. Currently the L3CCD detectors can provide frame rates up to 650 Hz and calibrated to operate in photon counting mode. For each observing run, the detector system is dark room calibrated with a number of known EM-gain levels. This allows the operator to select a suitable amplification factor so that the measured target flux is above the background noise, but at the same time minimising the contribution from CIC events. To further reduce the contribution of CIC events to the final measurement, the data will have to be thresholded during analysis.

By using the L3CCD detectors, the polarimeter is suitable for observing targets with millisecond timing resolution. Current work is concentrating on replacing the L3CCD detectors with APD sensors. This will allow the polarimeter to push into the microsecond resolution, which is required for observing targets such as the Crab pulsar. For this to successfully work, the polarimeter will have to fitted with extra APDs to monitor the polarimetric signature from suitable nearby field stars. The hardware for data logging and recording the data is already in place and darkroom tested. The remaining concern for the APD detector system is the optical coupling and maximising system throughput. It is planned to have this system completed by the end of 2010 and ready for observing in early 2011.

Acknowledgments

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