Southern Africa Large Telescope

Prime Focus Imaging Spectrograph

SAAO Detector Subsystem:

Design Study

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1 Scope
This document reports a design study for the Detector Subsystem of the University of Wisconsin-Madison's Prime Focus Imaging Spectrograph (PFIS). It specifies the performance that the Detector Subsystem could meet to satisfy the overall performance goals of the spectrograph.

2 Overview
The detector subsystem will comprise a cryostat containing a 3x1 mini-mosaic of CCD chips. These chips shall be Marconi Applied Technologies 44-82 CCDs with 2k x 4k x 15 micron pixels. They shall be mounted on an invar cold plate and it is planned that Marconi will do the butting in order to achieve co-planarity of the devices. The mosaic shall be housed in an evacuated cryostat and thermally connected to the cold end of a Cryotiger, which shall cool the chips sufficiently to render dark current insignificant, whilst at the same time reducing QE by the smallest extent possible. The detectors shall be managed by an SDSU II CCD controller, which will in turn be controlled by a PC.

3 The CCDs
Marconi Applied Technologies CCD 44-82 chips will be used as the PFIS detectors. Marconi currently offer the best performance in astronomy grade devices of any commercial manufacturer. We are aware that possibly better performance at cheaper cost is available from Lincoln Lab/MIT chips, but these devices are supplied to consortia and not routinely available commercially. As a result, delivery is too risky.

3.1 Basic Parameters
The CCD characteristics may be obtained from the Marconi data sheets, the most important details of which are reproduced below. In this list, guaranteed (min or max as appropriate) as well as (more generous) typical figures are quoted:
- 2048 x 4096 x 15 micron square pixels
- 30.7 x 61.4 mm² imaging area
- Thinned and back-illuminated
- 3-side buttable
- 2 output amplifiers
- Charge transfer efficiency: min: 99.999 per cent, typical 99.9995 per cent
- Pixel readout frequency 20-1000 kHz
- Peak signal (full well): min: 150 k e⁻/pix, typical: 200 k e⁻/pix
- Readout noise (at 188 K, 20 kHz): max: 4.0 e⁻/pix, typical: 2.5 e⁻/pix
• QE at 500 nm: 80 per cent
• Spectral range: 200-1060 nm
• Dark current (at 153 K): max: 4, typical: 0.1 e⁻/pix/hr

### 3.2 Sensitivity

Typical sensitivity for the chips is shown in the following table (using the Astronomy Broad-Band Anti-reflection coating):

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Spectral Response (QE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
</tr>
<tr>
<td>350</td>
<td>40</td>
</tr>
<tr>
<td>400</td>
<td>70</td>
</tr>
<tr>
<td>500</td>
<td>75</td>
</tr>
<tr>
<td>650</td>
<td>70</td>
</tr>
<tr>
<td>900</td>
<td>45</td>
</tr>
</tbody>
</table>
We are also in discussion with Dr. Paul Jorden at Marconi. He provided the above plot which he used for discussion with the UK Vista Survey telescope project. In the legend, BB denotes Broad Band coating and D-D denotes deep depletion silicon, which extends red response without compromising the blue. We propose to select D-D silicon and the Astro BB type of anti-reflection coating.

For the present, therefore, we propose to guarantee the minimum sensitivity as specified in the above table but naturally we will be negotiating with Marconi in an attempt to increase these figures.

### 3.3 Frame Transfer Architecture

In order to enable rapid spectroscopy, FT operation is essential. None of the large format devices made by Marconi Applied Technologies are available off the shelf in Frame Transfer (FT) Mode. Additionally, the acquisition camera SALTICAM also desires FT chips, so we are negotiating with Marconi to supply FT chips. This requires a redesign of the clock lines of the chip and therefore a special production run from Marconi. Whereas the cost of 1 off would essentially double the price of the chip, an order for 4 or more would result in an additional cost of 10 per cent, possibly less, per chip. The delivery time to complete the order may be as long as a year.

### 3.4 Mini-Mosaic

A mini-mosaic of 3x1 CCDs will be used. Butting will probably be carried out by Marconi who offer co-planarity of the devices to 20 microns, possibly as low as 15 microns. Costs of this are still awaited.

### 3.5 Dark Current and Operating Temperature

The performance goal for dark current is to ensure that noise on the dark current pedestal generated during the longest exposure is small compared to the readout noise. We estimate that, with minimum readout noise of 2.5 e-/pix, a dark current rate of 1 e-/pix/longest exposure will fulfill this satisfactorily. The longest exposure is expected to be about 1 hr. So dark current rate of 1 e-/pix/hr is proposed. From the typical dark current rate on the Marconi data sheet (0.1 e-/pix/hr at 153 K) and the T^3 e^-6400/7 scaling with temperature specified by Marconi, this implies an operating temperature of 163 K or less.

### 3.6 Readout Noise

Marconi guarantee a readout noise from the on-chip amplifier of 4.0 e-/pix at a readout speed of 20 kHz. 2.5 e-/pix is typical. A plot in the data sheet shows this typical figure rising to 5.5 e-/pix at the maximum certified speed of 1000 kHz. It might be expected that the maximum readout noise from the on-chip amplifier at 1000 kHz would be 4.0/2.5 x
5.5 = 8.8 e⁻/pix. We expect the SDSU II controller and additional electronics to add 1.5 e⁻/pix (assuming a gain of 1 e⁻/ADU). We thus propose the following readout noise performance:

- 3.0 e⁻/pix at 100 kHz (10.0 µsec/pix)
- 5.0 e⁻/pix at 380 kHz (2.6 µsec/pix)

These values are TBC1.

4 CCD Controller

The CCD controller will be an SDSU II (Leach) controller from Astronomical Research Cameras (San Diego). The controller will have 6 video channels allowing the use of two outputs per CCD chip.

4.1 Readout Speed

Marconi certify performance in the range 20-1000 kHz. The SDSU II controller allows readout rates of no more than 1000 kHz.

Due to difficulties with getting the SDSU controller working with a PCI card running in a PC, we have to use performance estimates from Guy Woodhouse, a CCD engineer we know well who worked on La Palma. Guy has solid experience with the same kind of Marconi chips and SDSU controllers. For the present, we thus aim to match the performance he reports.

Correlated Double Sampling (CDS) speeds of 2.6 µsec/pix (at 5 e⁻/pix readout noise) or 4.6 µsec/pix (at 3.5 e⁻/pix readout noise) have been achieved with the proposed chips and SDSU controllers by Guy. It may be possible to reduce the 2.6 µsec/pix (with readout noise penalty) but this remains to be investigated. Prebinning and/or windowing causes the figures to increase somewhat (TBC2) (from 2.6 and 4.6 to 2.9 or more and 4.9 or more µsec/pix respectively).

We therefore propose a discrete set of normal pixel readout rates in the range 100-380 kHz (TBC3) and software selectable (slower readout rates would result in unacceptably long readout times). In addition, drift scan and charge shuffling during exposure will require special control of the vertical clocks which will be synchronized at a software selectable rate.

Overheads are also associated with row transfers, 50 µsec per row, and pixel skips (discards) of 0.8 µsec/pix (TBC4).

Each CCD has 4096 rows, 2048 columns and 2 readout amplifiers. There are an additional 50 pixels at the end of each readout register but before the readout amplifier. Thus, readout requires feeding 4096 rows of (1024+50) columns, or a total of 4399104 pixels, through each readout amplifier.
4.2 Lowest Noise Full Frame Readout

Lowest readout noise is expected at the slowest readout rate of 100 kHz (10 µsec/pix). Readout times at this rate would be:

- Time to clear the chip prior to exposure or time for vertical transfers during readout: \(4096 \times 50 \, \mu\text{sec} = 0.205 \, \text{sec}\)
- Time to read out the full chip (without prebinning):
  \(0.205 \, \text{sec} + 4399104 \times 10.0 \, \mu\text{sec} = 44.196 \, \text{sec} \) (readout noise of 3 e-/pix: TBC1)

4.3 Rapid Full Frame Readout

The above timing considerations give rise to the following expected performance when high time resolution is desired:

- Minimum time to read out the full chip (without prebinning):
  \(0.205 \, \text{sec} + 4399104 \times 2.6 \, \mu\text{sec} = 11.643 \, \text{sec} \) (readout noise of 5 e-/pix)

Readout time can be decreased further by any one of (or combinations thereof):

- Frame transfer operation so that only half the detector is used. There is no readout dead time as the next exposure is accumulating during the readout.
- Prebinning (see next section)
- Windowing of the chip either in the spatial or wavelength direction or both

4.4 Prebinning

Software-selectable prebinning of 1x1 to 9x9 (independent in each dimension) will be offered. It is expected that at least 1x2 prebinning will be used as standard where the 2 refers to the spatial direction. For all but the highest resolution observations, 2x2 prebinning will be used. Such prebinning will then result in minimum readout times of:

- 1x2 prebinning: \(0.205 \, \text{sec} + 2199552 \times 10.0 \, \mu\text{sec} = 22.201 \, \text{sec} \) (3 e-/pix readout noise: TBC1)
- 2x2 prebinning: \(0.205 \, \text{sec} + 1099776 \times 10.0 \, \mu\text{sec} = 11.203 \, \text{sec} \) (3 e-/pix readout noise: TBC1)
- 1x2 prebinning: \(0.205 \, \text{sec} + 2199552 \times 2.9 \, \mu\text{sec} = 6.584 \, \text{sec} \) (5 e-/pix readout noise)
- 2x2 prebinning: \(0.205 \, \text{sec} + 1099776 \times 2.9 \, \mu\text{sec} = 3.394 \, \text{sec} \) (5 e-/pix readout noise)

We believe that there will be increased overhead with increasing prebinning so readout rates for higher than 2x2 prebinning are currently unknown. Naïve interpretation of the difference of 0.3 µsec between pixel read times for prebinned and non-prebinned readout suggests that this is the overhead for each prebinning increment (essentially the time to combine pixels during readout). However, this is TBC5.
4.5 Frame Transfer Operation

Frame Transfer capability will be provided by the CCD controller. In this mode, at the end of an exposure of the half of the chip furthest from the readout register (the image section of the chip), the data are rapidly shifted (in 0.102 sec) into the half of the chip next to the readout register (the store section). Readout of the store section then takes place. Naturally, the store section of the chip must be masked from light so that half the science FoV must be sacrificed. The shutter is open throughout the sequence of operations.

Minimum readout times are (with 4096 vertical transfers required because although only 2048 are required to move the image into the store area, vertical transfers in the store area are still required):

- **No prebinning**: $4096 \times 50 \mu \text{sec} + (1074 \times 2048 \times 10.0) \mu \text{sec} = 22.200 \text{ sec} (3 \text{ e}^{-}/\text{pix} \text{ readout noise})$
- **1x2 prebinning**: $4096 \times 50 \mu \text{sec} + (1074 \times 1024 \times 10.0) \mu \text{sec} = 11.203 \text{ sec} (3 \text{ e}^{-}/\text{pix} \text{ readout noise})$.
- **2x2 prebinning**: $4096 \times 50 \mu \text{sec} + (537 \times 1024 \times 10.0) \mu \text{sec} = 5.704 \text{ sec} (3 \text{ e}^{-}/\text{pix} \text{ readout noise})$.
- **No prebinning**: $4096 \times 50 \mu \text{sec} + (1074 \times 2048 \times 2.9) \mu \text{sec} = 6.584 \text{ sec} (5 \text{ e}^{-}/\text{pix} \text{ readout noise})$
- **1x2 prebinning**: $4096 \times 50 \mu \text{sec} + (1074 \times 1024 \times 2.9) \mu \text{sec} = 3.394 \text{ sec} (5 \text{ e}^{-}/\text{pix} \text{ readout noise})$.
- **2x2 prebinning**: $4096 \times 50 \mu \text{sec} + (537 \times 1024 \times 2.9) \mu \text{sec} = 1.799 \text{ sec} (5 \text{ e}^{-}/\text{pix} \text{ readout noise})$.

Thus, a continuous sequence of images with 1.8 sec sampling and no dead time can thus be obtained. Image smearing will occur during the 0.102 sec needed for frame transfer.

4.6 Windowing

Readout of up to 20 windows (TBC6) of rectangular shape and arbitrary size (Dave?) will be offered by the CCD controller. Note that a window defined on one half of one CCD chip is also applied to the other half, as well as replicated twice on each of the other two chips. This is because the readout through each amplifier must use the same clocking scheme. The implication of this for spectroscopy is that windowing in the dispersion direction will result in 6 discrete wavelength intervals being readout. The scientific value of windowing in the dispersion direction in spectroscopy seems limited (but perhaps not zero).

Two examples will illustrate the readout rate possible with windowed operation. The performance in these examples must certainly be confirmed (TBC7).

In the first, a spectrum is to be obtained of a point source located near the middle of the chip, just above the frame transfer boundary, with wavelength range spanning the full
width of the detector in dispersion, and 8.64 arcsec (64 pixels) in the cross dispersion direction. Assuming frame transfer operation and 2x2 prebinning, the minimum readout time would be:

$$0.205 \text{ sec} + (32*537*2.9) \mu\text{sec} = 0.255 \text{ sec}$$

Where the first contribution (0.205 sec) is the time taken to shift the spectrum down by roughly half a frame (to the readout register) and the time needed for vertical transfers in the store section of the chip. The second contribution (0.050 sec) is the time taken to read out the 32 x 537 pixels. However, the image would be exposed for only 0.050 sec and there would be 0.205 sec of dead time, so unacceptable smearing would result.

The 0.205 sec contribution could be eliminated, thereby yielding spectroscopy at a speed of faster than 10 Hz, if the spectrum is shifted just over the frame transfer boundary, rather than all the way down to the readout register. The minimum readout time would then be:

$$(64*50) \mu\text{sec} + (64*50) \mu\text{sec} + (32*537*2.9) \mu\text{sec}$$

$$= 0.0032 \text{ sec} + 0.0032 \text{ sec} + 0.050 \text{ sec}$$

$$= 0.056 \text{ sec}$$

A sequence of such spectra could then be obtained with a cycle time of 0.070 sec (allowing 0.014 seconds for safety) and image smearing over a 0.0032 sec interval.

The second example is an imaging example in which a target and two comparison stars are to be sampled rapidly by reading out three 128x128 boxes of pixels centred on the three objects. In full frame mode (i.e. shuttered), but 2x2 prebinning, the minimum readout time would involve 0.205 sec for vertical transfers, (3*64*(537-64)*0.8) $\mu$sec for pixel skipping and (3*64*64*2.9) $\mu$sec for pixel reads. These contributions are:

$$0.205 \text{ sec} + 0.073 \text{ sec} + 0.036 \text{ sec} = 0.314 \text{ sec}$$

once again dominated by the time for vertical transfers. Frame transfer operation would cut this time in half.

### 4.7 Gain

The SDSU controller allows the gain to be scaled by one of four preset factors: x1; x2; x4.75; x9.5. The base gain can be set by adjusting the electronics and this is still to be decided: TBD1.

### 5 Software

It is planned to provide a user interface for the detector control software in LabVIEW running on a Real Time Linux PC. This LabVIEW program will receive instructions (either via mouse/keyboard input on the screen, or via communication protocol) to set up the CCD for the next exposure, specifying the exposure time, gain (?), prebinning, frame transfer mode (or not), windowing (if any), readout speed. These parameters will then be transmitted to a Real Time Linux Module (RTLM) written in C. This is necessary
because the high time resolution modes of the instrument require no latency in the detector control and readout. The RTLM will then communicate with the SDSU CCD controller and ensure the integrity of the exposure times and time stamping of the data, handling the readout and return of the data.

6 List of TBC Issues

TBC1 - Readout noise of 3 and 5 e^-/pix at readout rates of 100 and 380 kHz
TBC2 - Pixel readout overhead for 2x2 compared with 1x1 prebinned readout
TBC3 - Readout rates in the range 100-380 kHz
TBC4 - Pixel skip times are 0.8 µsec/pix
TBC5 - Additional overhead for each increment in prebinning is 0.3 µsec
TBC6 - Number of windows allowed
TBC7 - Very high speed spectroscopic performance

TBD1 - Base gain of electrons/ADU