Proposed sCMOS Guide Camera System

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The telescope autoguider system is based around an ageing iCCD camera with a deteriorating detector efficiency. It is suggested to replace this camera with a modern sCMOS camera. To this end a cheap ZWO ASI290 Mini mono camera has been purchased for test purposes.

Described here are various aspects of a possible project to be able to use such a sCMOS camera with the existing guide-probe autoguider system. First the operation and control of the camera is considered then the performance and analysis of the camera is given.

Camera Operation

To get images out of the ASI290 camera and check its performance there are two free image display programs, '*ASICAP*' from the manufacturer ZWO of the camera and the third party '*Planatary Imager*' program. With either of these programs it is possible to take and display images in real-time and save the images in FITS format so can be used to check operation and get familiar with the camera. Both programs use GUI's for control of the camera and run under Linux.

Neither of the above programs are suitable for operation as part of a guide system as they provide no remote interface. For controlling the camera from a remote application (API) a free Software Development Kit (SDK) from the manufacture can be used. This SDK provides a library of C language functions for reading and displaying images. In conjunction with the SDK it is necessary to also install three other free packages, *Qt*, *OpenGL* and *OpenCV*. The later *OpenCV* (Open Computer Vision) is the one that puts the image on the screen and provides facilities for graphics overlays, e.g. rectangular box for guide area etc.

As part of the manufacturer's SDK a pair of demo[stration] (sample) programs are supplied. These demo programs give an idea on how to use the C library functions, giving an example on how to separate the reading and displaying of frames in separate threads (processes/cores). This demonstrates the clear need to partition the reading and displaying operations due to the relatively high data rate.

The ASI290 camera comes with an USB2 interface so limiting the distance to a computer to less than 5m. One way to operate this camera would be to have a small computer mounted on the adapter that reads the camera and transmits the frames via Gigabit Ethernet to a second computer down stairs that would do the displaying of pictures, image analysis (find guide star) and send commands to the camera control computer.

An alternative to this, eliminating the need for an adapter computer, would be to purchase a camera with a Gigabit Ethernet interface (GigE Vision) and transmit the frames down on a dedicated line to a single mult-core computer to do everything.

With the ZWO camera it should be possible to do some tests on the telescope by mounting it at Cassegrain via a suitable mechanical adapter and taking imaging with one of the two display programs mentioned above. One of the main parameters to be determined is the dimmest guide star magnitude that can be achieved.

Telescope Tests

The first task would be to check the performance of the ASI290 camera on the telescope and verify its capabilities. A mechanical adapter has be manufactured. The camera can be operated with a computer attached to the telescope similar to the FastCam set up, desktop computer mounted on a frame with dedicated Ethernet cable to the control room. It is believe this should take less than half a night and would ideally be shared with a FIES run to remove the requirement of mounting instruments in the middle of the night.

The main parameters to establish on the telescope for this type of sCMOS camera are the sensitivity and noise performance down to a 15 magnitude star and determine the signal to noise ratio.

One problem that may be found is that because the pixels of these cameras are typically small, 2.9 μm for the ASI290, then a star image will cover a significant number of pixels which all contribute dark current signal and readout noise. To reduce the size of the star image an optical camera in front may be necessary, see *Performance and Analysis* section.

Camera Control Software

As mentioned already a combination of the manufacturer's supplied SDK library for reading the camera and *OpenCV* for displaying the images can be used. Once an image is acquired then probably the existing autoguider code could be used to do the analysis, i.e. find the star in the field, centroid and calculate the corrections, though more sophisticated algorithms could also be tried such as polynomial (Gaussian) profile fit and cross-correlation or moments estimation made.

If the ASI290 camera is used then a two computer solution is required. A computer on the adapter for reading the camera and a second down stairs for displaying and analysis. The camera control needs to be written in C using the SDK library. Language options are available for the displaying since *OpenCV* supports C, C++ and Python. If the existing TCS code for analysis can be used, which is written in C, then it would make sense for the whole package to use the same C programming language.

The image acquisition uses just a handful of library functions that basically, identify the attached camera, open it, initialise it and then loop, asking for new data frames. A separate thread in the same program can then display the image and add graphics or alternatively the image data can be transmitted to a different computer for displaying, analysis etc.

It is necessary to have an understanding of the *OpenCV* package to be able to get and display the image data.

As previously mentioned an option would be to use a camera with a Gigabit Ethernet interface. Many companies make such cameras, one, *IDL*, also provide a sample Python project that could possibly be adapted for our use. They also have there own SDK for C language development.

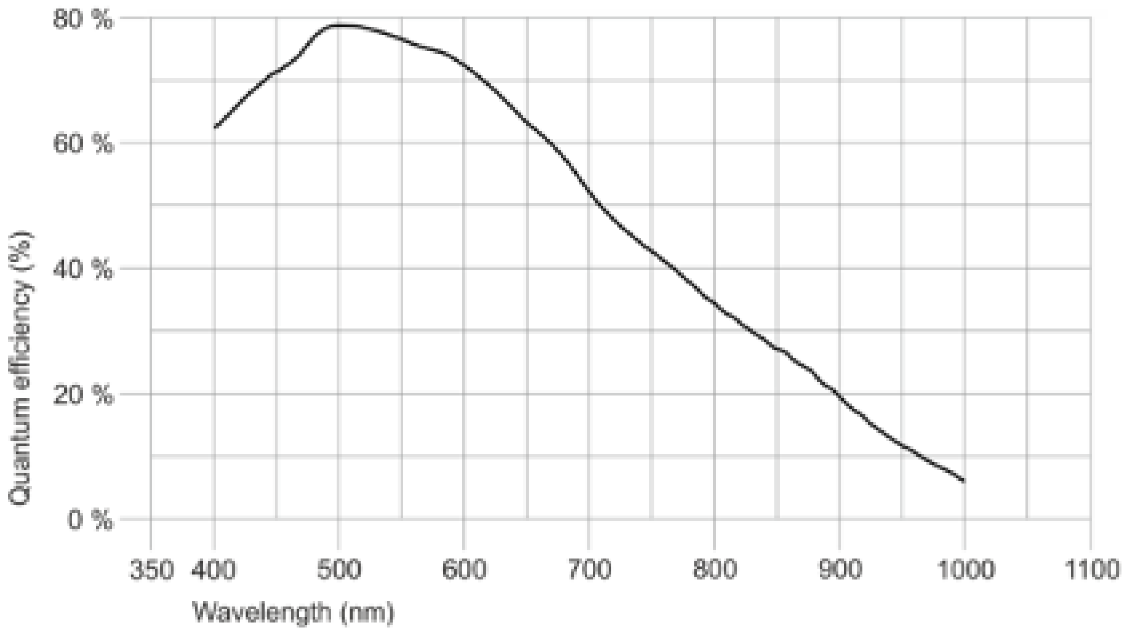
To help with the software development it has been suggested that we could again request the help of Sandro. The main effort for him would be to learn how to manipulate the various packages necessary for the camera control and image data handling and develop a program to do this, though not write image analysis software. Alternatively we do have in-house expertise in C programming who can do the software development.

Performance Analysis of the ASI290 Camera

The performance of a ZWO model ASI290 sCMOS camera has been made for the proposed application as a guide camera. The detector parameters of readout noise (RON), conversion gain, full-well and dark current have been measured. Also simulations have been made to determine the potential as a guide camera, specifically can it return enough signal to noise ratio (SNR) from a suitably dim guide star. One significant issue, as already mentioned, with these sCMOS detectors is the very small pixel size, the ASI290 camera has pixels of only 2.9 µm square.

Detector Parameters

The detector used in the ASI290 camera is a Sony IMX290 back illuminated CMOS device with 1945 (H) × 1097 (V) 2.9 µm square pixels. The device has a rolling shutter using 12 bit ADCs and can be read at up to 60 frames/s at full resolution and dynamic range, though in the ASI290 camera the maximum speed is around 20 frames/s.



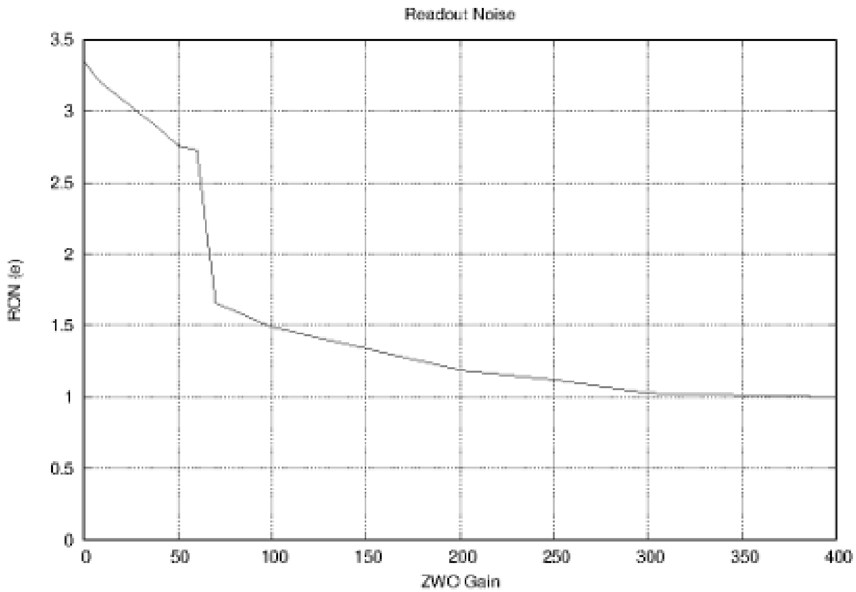
Quantum Efficiency of the Sony IMX290 CMOS detector

The quantum efficiency peaks at around 78 % at 500 nm and has a relatively poor red response.

Four detector parameters were measured, readout noise, conversion gain, full-well, all these against the *ZWO camera gain* value. Also determined was the dark current at a selected *ZWO camera gain* value.

The *ZWO camera gain* is a parameter a user can select which determines the desired performance of the detector. To obtain the RON in electrons and conversion gain, ADUs to electrons, the *ZWO camera gain* was adjusted through its range and for every setting two bias and two flats were taken. Using the standard *Janesick* method the conversion gain and RON were found. Given that the camera has a 12 bit dynamic (0 - 4095) the full-well could be evaluated.

The obtained plot of RON matched the one given in the data sheet, including the discontinuity at *ZWO camera gain* at around 60.

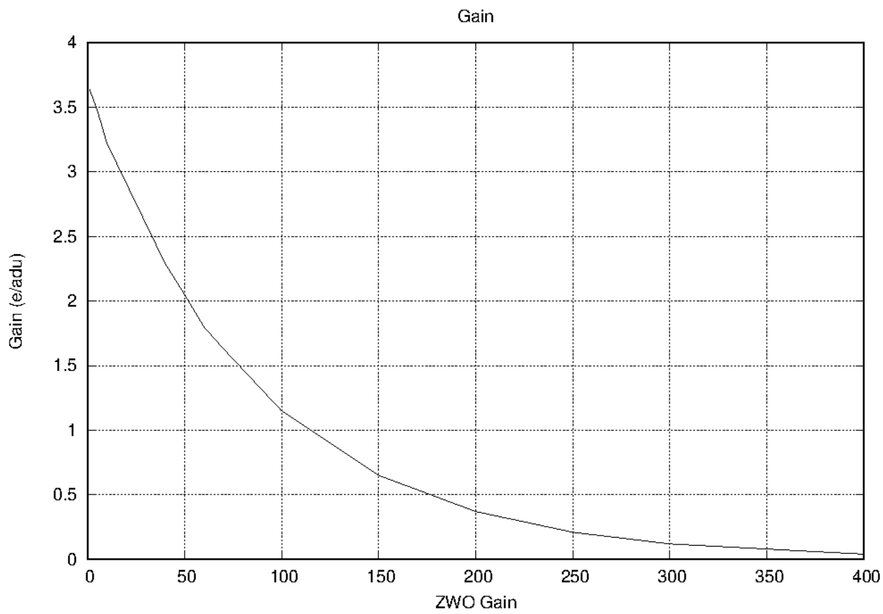


Read-Out-Noise v ZWO Camera Gain

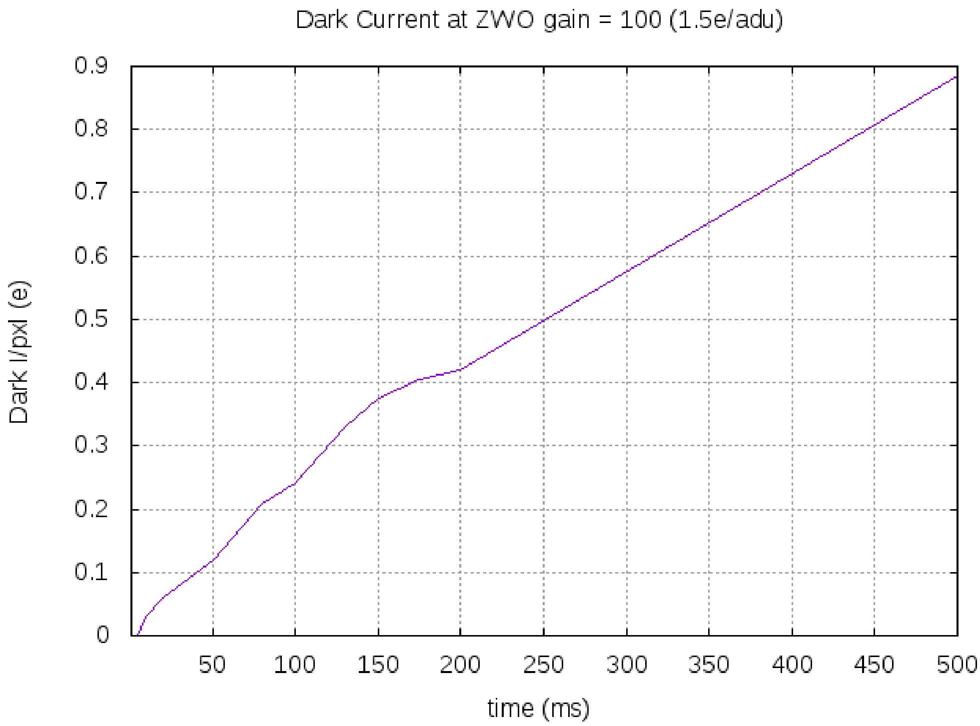
From the same data the conversion gain was found. Finally the full-well for all the *ZWO camera gain* was plotted.

Using the detector performance curves it was decided that the best operating point was at a *ZWO camera gain* of 100. This gives a RON of 1.5 e with the full dynamic range.

For the *ZWO camera gain* of 100 the dark current was measured against exposure time. To operate the camera in a guide system a frequency of about 10 Hz, or 100 ms exposure time, was chosen. At this point the dark current is about 0.24 e/pxl/s. In poorer seeing a longer exposure time can be used with the consequence of a slightly large dark current of 0.42 e/pxl/s.



Conversion Gain v ZWO Camera Gain



Guide Camera Detection Performance

The most important criteria for a guide camera is to be able to detect the dimmest required star with a good signal to noise ratio (SNR). It has been stated in the literature that a minimum SNR required to obtain a 10% centroid accuracy is 10, but preferably 20.

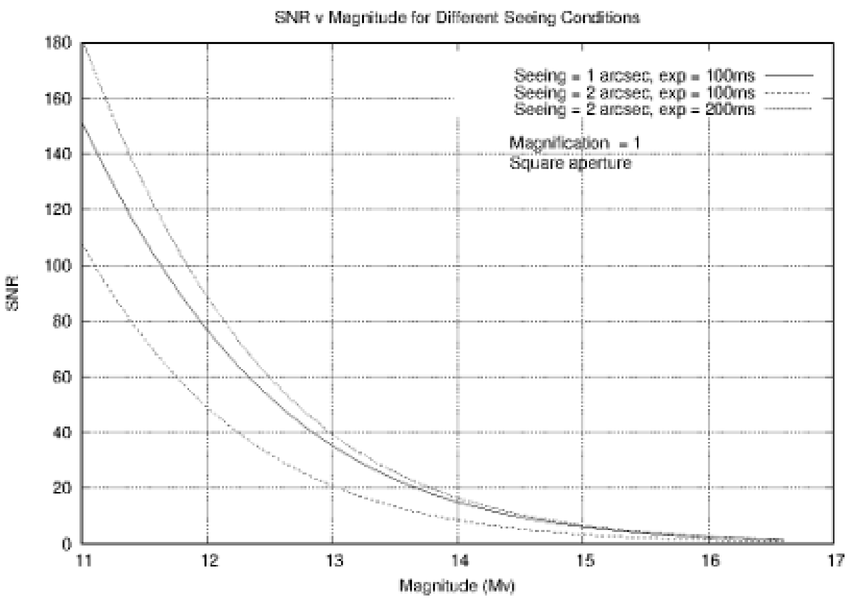
To evaluate this, simulations have been run for the given camera parameters to see if it is possible to achieve the desired SNR. It is known from the NOT database that since data has been available the dimmest guide star ever used was Mv = 15, so this is the target magnitude to get a SNR of at least 10 and preferably 20.

The image scale of the NOT is 7.33 arcsec/mm or 136 μm/arcsec. To enclose a star image with 1 arcsec seeing requires a guide box of around 2 arcsecs square or with 2.9 μm square pixels almost 9000 pixels.

The arrival flux estimate used in the analysis takes into the account the losses due to the atmosphere and the telescope optics, and agrees with value estimates returned from the *signal* program.

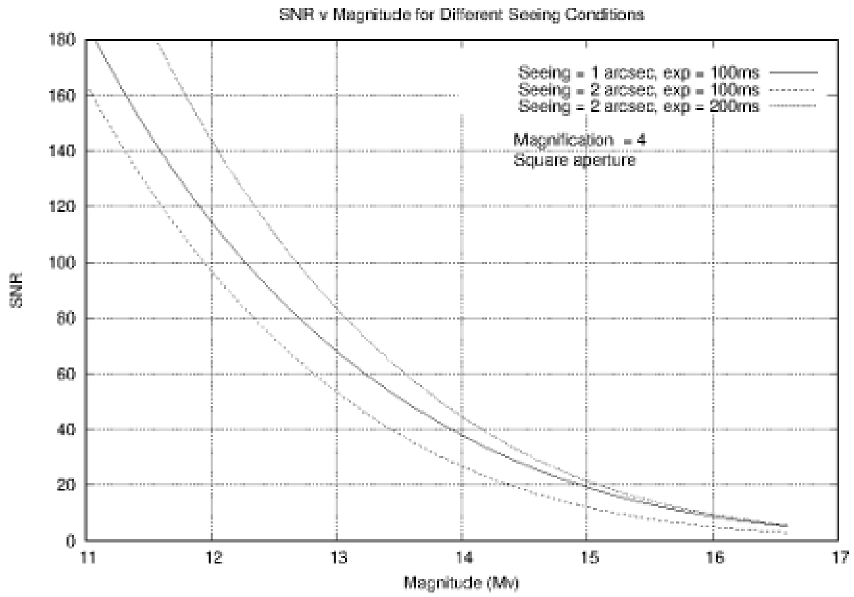
A simulation of star V magnitude for seeings of 1 arcsec and 2 arcsec was done, assuming direct imaging on to the detector. The plot below shows it is impossible to get the desired SNR of 20 in an exposure time of 100 ms even with a seeing of 1 arcsec for a Mv = 15 star. When the seeing was 2 arcsecs a doubling of the exposure time to 200 ms still could not achieve the SNR of 20.

One parameter that was investigated was the guide box size to determine what would be the optimum size to get the best SNR. It was found that having a guide box 1.5 x seeing was best, which agrees with literature values. Possibly dynamically changing the size of the guide box to match the seeing conditions could be implemented, optimising the performance of the guide system. The plot below used a guide box of 2 arcsecs for the 1 arcsec seeing and 3 arcsecs for the 2 arcsec seeing simulations. Note the default guide box at the moment is about 5 x 3 arcsecs. It was also checked if changing the guide box to a round aperture would help, though this only gave a slight improvement of typically 1 to the SNR.



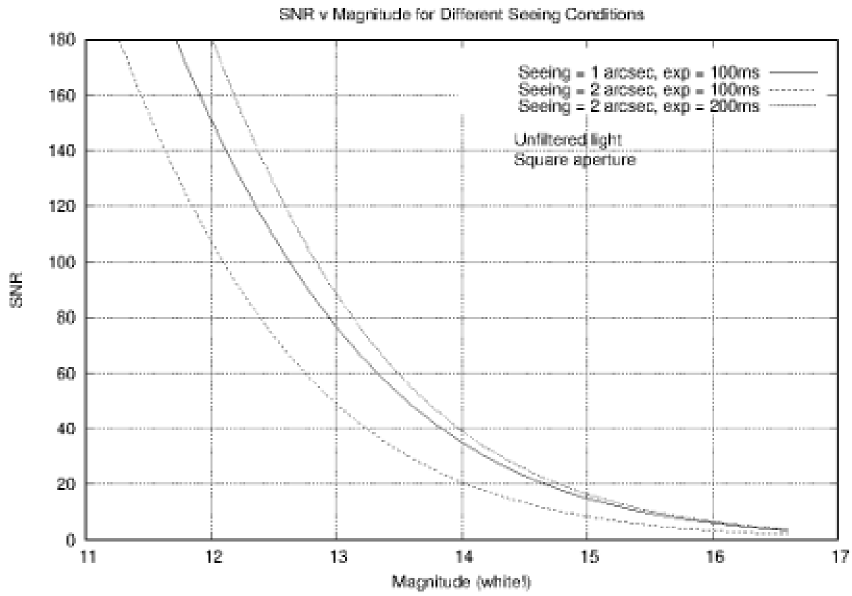
Signal-to-Noise Ratio v Star V Magnitude, direct imaging

The only reasonable way to obtaining the desired SNR at a V magnitude of 15 is to reduce the star image size on the detector so using less pixels. It was found with a magnification of four with 1 arcsec seeing a SNR of about 20 can be obtained with an integration of 100 ms. For 2 arcsec seeing using an exposure time of 200 ms gives a SNR of about 20. Of course having extra optics in the path will reduce the signal, though this has not been taken in to account here.



Signal-to-Noise Ratio v Star Magnitude, with a magnification of 4

Alternatively if unfiltered light is used then approximately 2.5 times more flux (one magnitude brighter) would be expected to be detected based on the QE curve. Assume this is a correct assumption then the SNR v unfiltered magnitudes suggests we should be able to obtain SNR of about 15 for a magnitude 15 star for both a 1 arcsec seeing with an exposure of 100 ms or similarly for a 2 arcsec image and an exposure time of 200 ms.



SNR v unfiltered ("white light") star magnitudes

Discussion

It is believed from the analysis and available software it should be possible to use a sCMOS type camera as a replacement for the old iCCD detector. Significant software development will be required to get a working system, though using available software packages.

It has been shown, in simulation, that to get the desired SNR for a Mv = 15 an optical camera is necessary to reduce the image size by a factor of four on the detector. If unfiltered light is used then an estimated SNR of 15 can be obtained for a 15^{th} Magnitude star with direct imaging.

Since it is expected that a significant effort would be required to develop the software it is proposed to make some tests first with the ASI290 camera mounted at the Cassegrain focus of the telescope.