ULTRASPEC – An Electron Multiplication CCD camera for very low light level high speed astronomical spectrometry

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ABSTARCT

We present the design, characteristics and astronomical results for ULTRASPEC, a high speed Electron Multiplication CCD (EMCCD) camera using an E2VCCD201 (1K frame transfer device), developed to prove the performance of this new optical detector technology in astronomical spectrometry, particularly in the high speed, low light level regime. We present both modelled and real data for these detectors with particular regard to avalanche gain and clock induced charge (CIC). We present first light results from the camera as used on the EFOSC-2 instrument at the ESO 3.6 metre telescope in La Silla. We also present the design for a proposed new 4Kx2K frame transfer EMCCD.

Keywords: ULTRASPEC, EMCCD, Clock induced charge

1. INTRODUCTION

Conventional CCD detectors as used in the very best astronomical instruments are almost the perfect detector. However they still suffer from two issues in that they are slow to readout and they are readout noise limited, typically 3e- rms for the latest devices. These issues combine to make high speed astronomical spectroscopy of faint targets the most demanding of observations, whereby ‘high speed’ is meant on timescales of a few seconds or less. It is possible to overcome the problem of slow frame speed by using *frame transfer CCDs* and detector limited electronics and data acquisition systems. Such an approach has been adopted for ULTRACAM[1], the high-speed, triple-beam CCD imager. However reducing the readout noise in CCDs to negligible levels is more difficult since it is an inherent feature of the devices themselves. The development of electron multiplication CCD*s* has come about specifically to address this read noise issue. These electron multiplication devices are in fact conventional CCDs, but with an additional extended serial register to which a gain structure has been added. This gain structure is similar to the standard serial shift register except that one of the three clocks of the extended serial section is replaced with two electrodes. The first electrode is held at a fixed potential and the second is clocked as normal, except, that a much higher voltage amplitude is applied, typically between 35V and 40V. Compare this with a standard CCD where a clock swing of 10V is usually all that is necessary for charge transfer alone. The design of the fixed voltage electrode and the clocked electrode, and the relatively large voltage difference between them, results in an intense electric field that is sufficiently high for the transferring electrons to cause impact ionization through each single transfer in the multiplication register. This process is summarized as follows. If the electric field strength is increased to a certain level then the electron is more likely to collide with the crystal lattice so that the drift speed becomes saturated at an average speed. This phenomenon begins to occur when the electric field is about 10^4 V/cm and the average drift speed is about 10^7 cm/s. If the clock voltage is increased further, then some of the electrons which escaped collision with the crystal lattice will have a great deal of energy. If they now collide with the crystal lattice, ionization takes place and newly released electrons are produced. These newly generated electrons then create further electrons in the same manner in a process similar to a chain reaction. This phenomenon is referred to as avalanche multiplication. Avalanche multiplication has temperature dependence such that as the temperature increases then the lattice scattering increases which makes the impact ionization less probable because there is less likelihood of an electron colliding with the constantly moving lattice. Electron gains of many thousands are possible in the avalanche gain process described. The avalanche gain is adjustable in these CCDs by changing the upper clock voltage level. EMCCDs have generated a great deal of interest in the high spatial resolution astronomical community, but have received much less attention for other astronomical applications. To address this problem, a consortium from the Universities of Sheffield, Warwick, the UK Astronomy Technology Centre and ESO, were awarded funding under

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OPTICON Joint Research Activity 3: *Fast read-out, high-performance optical detectors* to investigate the use of EMCCDs for high-speed spectroscopy. The resulting camera that has been developed is called *ULTRASPEC*, since it is essentially a spectroscopic version of ULTRACAM.

2. ULTRASPEC SYSTEM DESCRIPTION

At the heart of ULTRASPEC is an EMCCD, the E2V CCD201-20 device, which has an imaging area of 1024 × 1024 pixels (each of 13 microns square). The CCD201 is also a frame transfer device, thereby offering high frame rates (up to hundreds of Hertz) with negligible dead time, as well as essentially zero readout noise through the electron multiplication process as described. The chip is mounted in a modified ESO cryostat, cooled by liquid nitrogen and temperature regulated by a Lakeshore controller. For our science runs the CCD camera was mounted on the *ESO Faint Object Spectrograph and Camera*[2] *(EFOSC2)* instrument which is itself mounted on the ESO 3.6 metre telescope in La Silla, Chile. EFOSC2 is an astronomical instrument for low resolution spectroscopy and direct imaging. It is a focal reducer, multi-mode instrument, using multi-layer coated all-transmission optics. The wavelength range of operation is between 305 nm and 1100 nm and the field of view is 5.2 x 5.2 arc-minutes. Typically a 4k x 2k CCD is fitted to EFOSC2 to sample the available field. Since our EMCCD has only a 1k x 1k imaging area which is the largest EMCCD commercially available then only one quarter of the dispersion direction is sampled in any one exposure. This is the main limitation of our ULTRASPEC camera system.

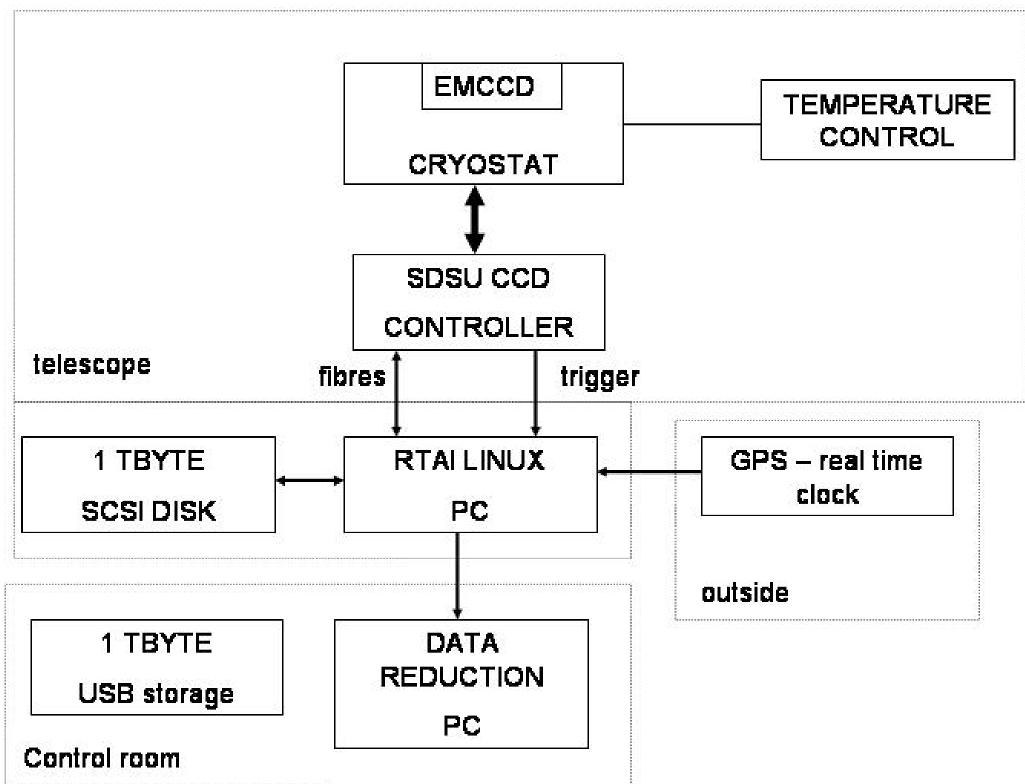

Figure 1 : ULTRASPEC system block diagram

The CCD clocking, readout and digitization is controlled by a Generation III ASTRO-CAM controller, using our own data control and acquisition system, developed for ULTRACAM and shown in Figure 1. A new high voltage clock board has been developed to operate with this controller. This board allows exact clock synchronization and software control of the high voltage clock levels required for electron multiplication.

3. HIGH VOLTAGE CLOCK BOARD DESCRIPTION

The EMCCD requires that the high voltage clock electrode of the avalanche gain register has a peak to peak swing of -5V to a maximum of 40V at the same rate as and synchronised to all the other clocks used with the CCD; the clock rate being set by the maximum clocking speed of this controller which is approximately 2 MHz. Such large voltage swings are required to ensure a high enough electric field to cause impact ionisation and thus electron multiplication within the silicon of the CCD as described previously. The clock high level also needs to be user adjustable and stable since it is this level that determines the gain of the avalanche stages of the CCD. To ensure simple synchronisation with all the CCD clocks then it seemed sensible to use a spare clock from the controller's standard clock board as the input clock pulse to the high voltage clock circuit. In our system, a block diagram of which is given in Figure 2, the input upper clock level from the controller clock board is fixed at 5V. A user adjustable bias level can be taken from the controller clock board or more typically from the video board and used as the control input to set the high voltage clock level. In our setup this bias is adjustable between 0 to 5V in 6 mV steps since the bias source is the 12 bit DAC8420 device used on the 2 channel CCD video board of the ASTROCAM controller.

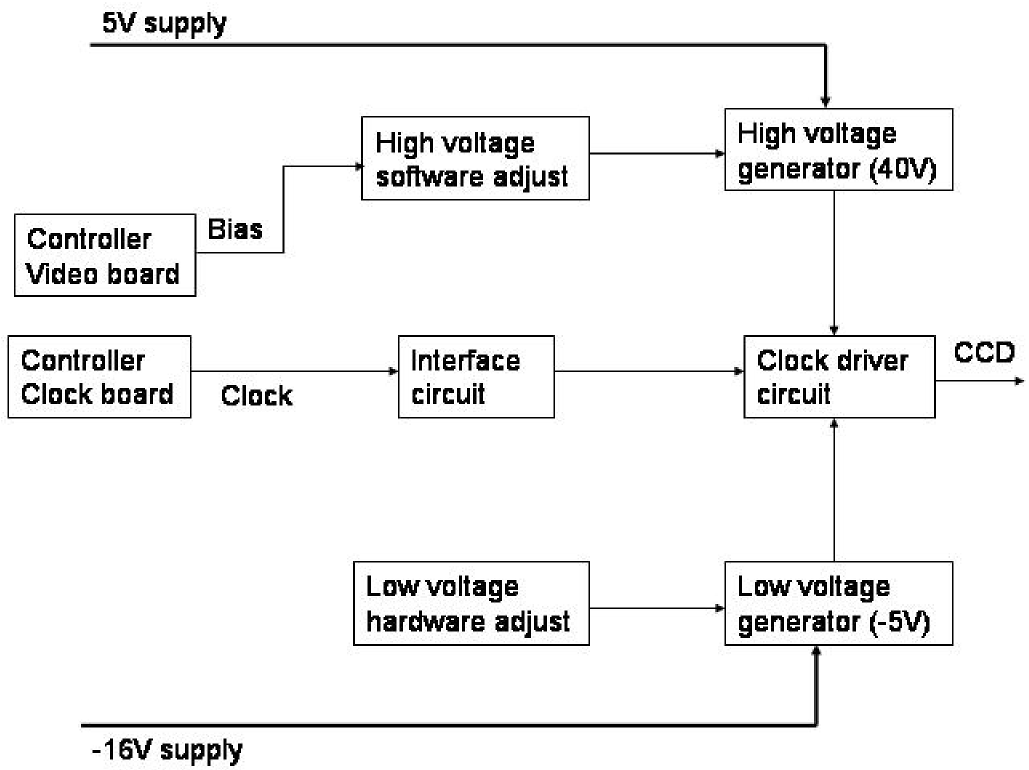

Figure 2 : Block diagram of high voltage clock board design

This bias level is fed into a high voltage op-amp circuit with a gain of 8 to give the maximum 40V level clock swing required for an avalanche gain of a few thousand. This user adjustable upper voltage level is then fed as a supply to a simple push-pull circuit that can swing between the upper and lower voltage levels. The gain of the CCD avalanche stage is only determined by the upper clock level so the circuit solution offers full software control of this level. The lower level may affect the charge transfer efficiency of the CCD but once set this need not be changed so there is only allowance for a hardware change to this level using an adjustable potentiometer. The high voltage itself is generated from a circuit that takes the controller 5V digital supply voltage and boosts it all the way up to 60V. The DCP02 device from Texas Instruments, which is a miniature DC/DC converter providing an isolated unregulated voltage output, is used. Two such devices are used to provide the 60V supply. This voltage is then regulated down to 43V in two linear regulator stages to reduce the power dissipation across a single device to acceptable levels. The final 43V is then fed to the positive supply of the high voltage op-amp which can swing to within a few volts of this supply. The high voltage clock board configured for operation in the ASTROCAM controller is shown in Figure 3. We typically can adjust the avalanche gain by a minimum factor of approximately two from no gain up to a gain of greater than one thousand at a detector operating temperature of 160K.

Figure 3 : EMCCD high voltage clock PCB developed for the ASTROCAM controller

Two 9 way D type connectors have also been added to the front of the board. One of these connectors allows for the possibility of by-passing the onboard 60V supply and using an external 60V supply instead to power the clock driver circuitry. This option has been added to allow testing and comparison of the noise performance of the on board switching dc:dc converters and regulators against an external low noise linear supply. In fact it has been shown that there is no difference in the noise achieved and any future upgrades would discard this option. The second 9 way D-type connector is used to take the required input clock and bias signals from the controller clock and video boards. The final circuit in the PCB form shown and in the controller configuration described, is able to run at approximately 4 MHz rate with rise and fall times of 25 ns, under no load condition.

4. CAMERA OPERATION

We typically operate our CCD in ULTRASPEC at 160K which gives measured dark current rates of approximately 1 e/pixel/hour and exceedingly low Clock Induced Charge rates (CIC), more of which will be discussed later in this paper. We use slightly faster vertical clock rates than specified in the data sheet (7µs/row) with lower clock swings (10V) to minimize the CIC effects. Typical performance parameters taken from our last science run are given in Table 1.
The frame read time is actually greater in avalanche read out mode than normal mode because of the extra clocking required through the avalanche gain register per row of the CCD. There is no shutter fitted to the camera system to allow maximum windowed clocking speeds. The device is a frame transfer device and all “shuttering” and clearing functions are carried out using this feature of the CCD. The following user options are available to the astronomer :-

- Binning in both rows and columns
- Multiple windows
- Multiple pixel read out speeds
- Output selection (normal or avalanche)
- Avalanche gain selection (from 0 to >1000)
- Integration time (1ms – >1000 s)
- Clear or no clear between frames

Table 1 : Performance parameters for ULTRASPEC EMCCD camera

Output	**Pixel Time (µs)**	**Frame rate (s)**	**Read noise (e- rms)**	**Window Rate (Hz) (800 x50 pixels)**
Normal	11.5	13.1	2.3	
	3.4	3.9	4.1	
	1.95	2.25	6.7	
Avalanche (no gain)	12.7	14.63	5.3	
	4.7	5.42	12.3	
	2.1	2.5	22.3	12

The user can easily and quickly switch between the normal CCD output as used on the latest generation of astronomical CCDs and the avalanche gain register through the use of a simple GUI interface. Both CCD outputs are biased and fed to appropriate video and digitisation channels in the controller. The user can also choose up to ten avalanche gain settings from the same GUI. This allows the astronomer to quickly match the detector performance to the science. It also means that a detailed comparison can be made between a standard astronomical CCD and EMCCD, all on the same device, on the same instrument and under similar operating conditions. Such a test has been carried out in an astronomical context and the results are reported later in this paper. We still use correlated double sampling to remove the reset noise and minimise the output stage read noise. This is important because the maximum gain required in photon counting to optimise observing efficiency and minimise coincidence losses can then be kept to a minimum which is important because of the ageing effects associated with high avalanche gain. Lowering the multiplication gain and signal level significantly reduces the ageing. Long term ageing means that higher and higher avalanche clock voltages would be required to give the same avalanche gain[6].

5. EMCCD PERFORMANCE

Much has been reported elsewhere on modelled performance of these detector types[3,4]. For high speed astronomical spectrometry in the photon counting regime, the clock induced charge can be a major issue since it can reduce the signal to noise performance of an EMCCD compared to an ideal shot noise limited detector as shown in the following equation.

$$S/N = \frac{S}{\sqrt{S + \left(R/g\right)^2 + C}}$$

Where S is the signal level, R is the read out noise, g is the avalanche gain and C is the clock induced charge measured in electrons/pixel/frame.

Usually there is a factor of two times the signal in the denominator which is due to the probability distribution of the avalanche gain which leads to an effective quantum efficiency loss of two. However this loss can be recovered by photon counting and setting the count threshold appropriately. The avalanche gain term reduces the read out noise to zero thus leaving the term due to clock induced charge. This induced charge takes the form of electrons randomly distributed throughout the CCD which are typically generated by the CCD clocks during the readout process. Similar to dark generated events they are indistinguishable from true signal events and so constitute a faint background with associated noise. This equation highlights the importance of minimising the CIC in optimising the signal to noise ratio and maximising observing efficiency. A simple way to emphasise the importance of reducing the CIC rate is to plot the exposure time required for an EMCCD to give the same performance as an ideal detector limited only by the photon shot noise on the received signal. Daigle[3] and Marsh[9] have produced similar plots in slightly different formats in their published papers. Our variation of this plot is shown in Figure 4 for a case where the avalanche gain is set to 1000, the readout noise is 10 e- rms and the CIC rate is 0.02 electron/pixel/frame. There are three regions in this plot. The "normal" region is where the CCD is used in normal operation without avalanche gain and the main sources of noise are the photon shot noise for high signal levels and the read out noise for lower signal levels. For high signal rates the CCD is almost ideal but begins to drop off when the signal level becomes less than 100 electron/pixel/exposure. The next region is the "linear" mode of operation, where the avalanche gain is used to minimise the read out noise, but the CIC is also included together with the effective loss in quantum efficiency due to the probability distribution of the avalanche gain process. In this case we see that the linear mode is at most 50% efficient compared to an ideal detector. However the linear mode still wins over the normal mode for signal rates of less than 40 electron/pixel/exposure as shown in this example. The final mode is the "photon" mode where a "thresholding" algorithm is used to implement photon counting. Obviously this mode can only be used for signal rates of much less than 1 electron/pixel/exposure as significant coincidence losses will kick in well below this mean count rate. Typically the threshold is set to five times the read out noise[3] and the avalanche gain set to ten times this to ensure that the read noise does not generate false counts and that at least 90% of the signal is recovered from the gain probability distribution. This mode is dominated by the CIC and from our modelling it can be shown that for typical real world read noise and signal levels, a CIC rate of less than 0.01 electron/pixel/frame is required for maximum observation efficiency.

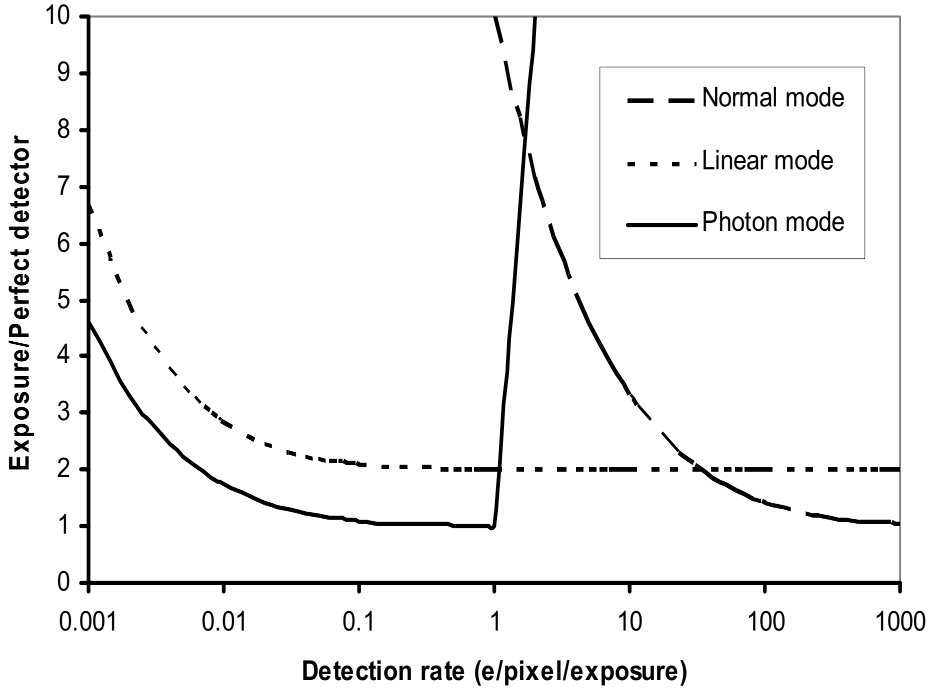

Figure 4 : Efficiency of EMCCD versus an ideal detector for different read out modes (avalanche gain=1000, read out noise = 10 e and CIC=0.02 e/pixel/frame)

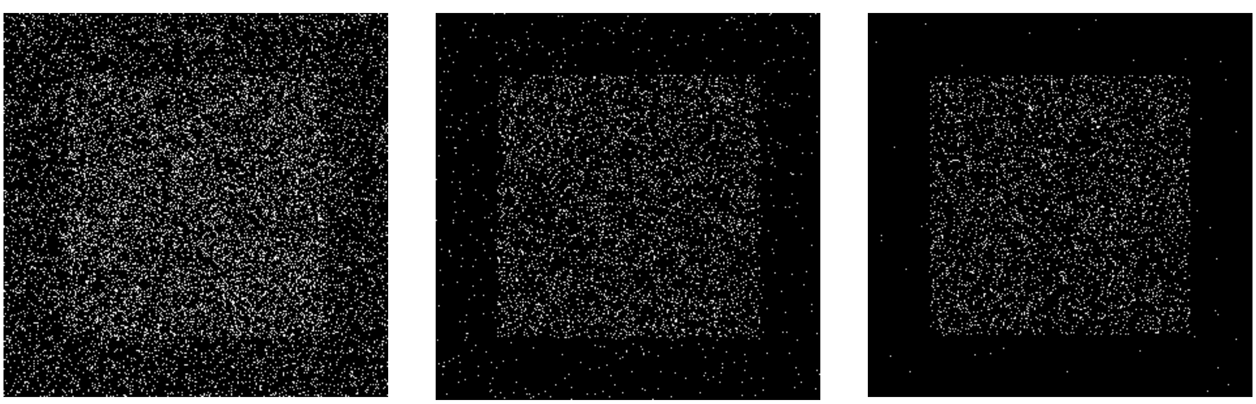

Figure 5 : Images showing modelled effects of different rates of CIC in photon counting mode for a signal level of 0.1 electron/pixel/frame, a read noise of 23 e and a avalanche gain of 1100 (left :CIC is 0.1 e/pixel/frame, middle is 0.01 e/pixel/frame, right : 0.001 e/pixel/frame)

Modelled images of the effects of the CIC on a signal detection rate of 0.01 e/pixel/frame are shown in Figure 5 in a configuration with 23e- rms read out noise and an avalanche gain of 1100. The image on the left shows the effects of a CIC rate of 0.1 electron/pixel/frame which gives a signal to noise reduction of 76% compared to an ideal detector. The image in the middle is for a CIC rate of 0.01 electron/pixel/frame which gives a signal to noise reduction of only 5% compared to an ideal detector. The image on the right is for exactly the same setup but for a CIC rate of 0.001 electron/pixel/frame. This modelling emphasises the need to reduce the CIC and also shows the level the CIC must be reduced to for typical astronomical projects.
It is important to be able to measure in a simple fashion the CIC rate as well as the avalanche gain of the CCD. Others[5] have reported a simple method which uses the CIC events themselves to measure the avalanche gain. This method simply relies on the fact that we assume that the avalanche gain probability distribution for a single electron entering the avalanche register has the form of an exponential curve given in the following equation and that the CIC events are single electron events. A comparison of modelled data versus real CCD images shows this to be a good approximation and in fact other more complicated distributions[8] reduce to this for single electron events.

$$P(x) = \frac{e^{-x/g}}{g}$$

Where *P(x)* is the probability of a certain gain and *g* is the avalanche gain.

If this probability distribution is plotted in a natural log format then this takes the form of a straight line plot. The inverse slope of the line in this natural log plot will give a measure of the actual avalanche gain term *g*. Since CIC events are typically single electron events then we can plot them as described and use the plot to measure the avalanche gain. An example plot from real data taken from the ULTRASPEC CCD is given in Figure 6. The peak to the left of this plot is the bias level with pixels with no CIC events. These bias pixels have been subtracted off in this example to give a bias of zero. The spread of this peak is a measure of the readout noise of the system. The curved section of the plot as indicated by the arrow are CIC events produced in the serial register of the CCD. These events "see" different avalanche gains because they can occur anywhere in the avalanche register. However these events could also be produced by poor serial charge transfer efficiency. There is thus a spread in the gain seen by these events on top of that due to the gain distribution itself.

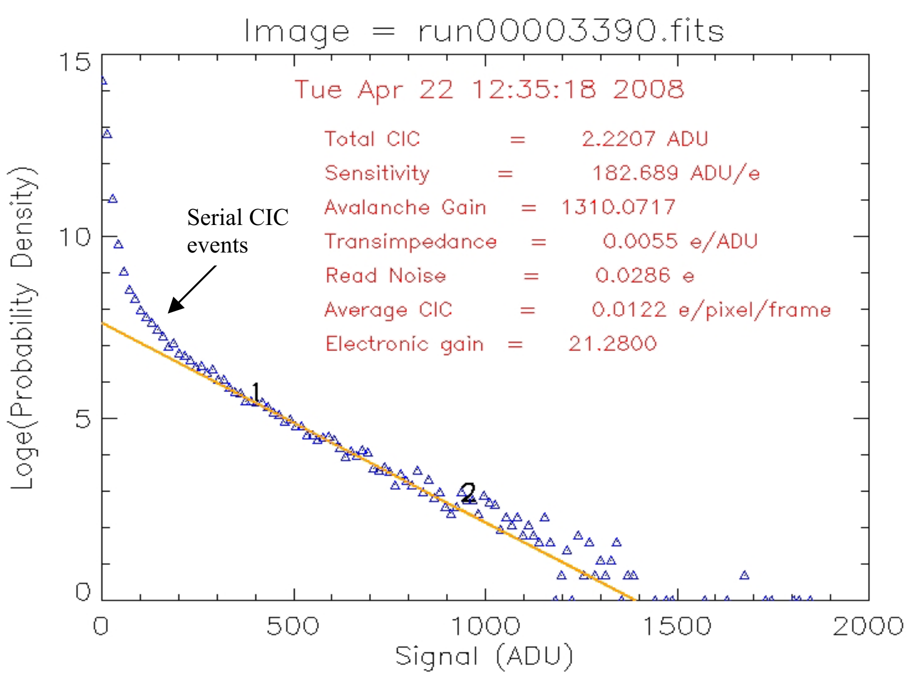

Figure 6 : CIC probability distribution showing calculation of avalanche gain from the slope

The remainder of the events are produced in the image and storage areas of the CCD as clock induced events and can be used to calculate the gain since they lie on a straight line, the inverse slope of which is the gain. As a check the measured avalanche gain using this method has been confirmed within a few percent against another method using a standard light source.
In our system there are 10 gain settings from zero up to a maximum of 1500. The maximum gain has been limited to reduce ageing effects in the CCD where an increased avalanche voltage is required to give the same gain. To keep the gain to a minimum implies keeping the read noise to a minimum also and therefore as already stated it is still important to use correlated double sampling techniques during pixel read out to minimize the reset noise etc.
Typical in our system we measure best case CIC rates of approximately 0.009 electron/pixel/frame. However the CIC rate does depend on many factors. For example, as would be expected, the CIC rate increases dramatically after the CCD has been powered up and in our experience, devices typically require a few hours of settling time to achieve their best CIC rates. We have measured the CIC rate to be >0.16 e/pixel/frame just after power on, which then only drops to the lowest level after approximately 6 hours of settling time. We also find that the CIC rate is determined by the CCD frame rate. For example, for the slowest pixel rate of 12.7 µs/pixel then the CIC rate is typically 0.02 electron/pixel/frame. However if the camera is run at the fastest pixel rate of 2.1 µs/pixel then the CIC rate is more typically 0.01 electron/pixel/frame, all else being equal including the vertical clocking times. We surmise that the CIC rate must be a function of the time between the vertical clocking which is the time to readout the serial and avalanche registers. This must mean that CIC is a function of the time that the charge spends in each row. We conclude from this that the reason for the reduction in the CIC is due to the fact that the vertical clocks do not spend so much time in inversion. This result is more fully described in an E2V technical note[6]. It means also that if you are running in inverted mode, CIC will reduce as the parallel clocking rate is increased. CIC is related to the time the clocks are held inverted which is the time between each vertical clock triplet action, so going faster in serial register transfers should help.
To summarise, to keep CIC to a minimum then clock voltages need to be carefully controlled and because there is a lifetime component involved in CIC generation, then faster clocking of the CCD as a whole seems to result in lower CIC. Even at these low CIC rates of < 0.01 electron/pixel/frame, the CIC dominates for signal detection rates of <0.01 e/pixel/exposure. To operate in these regimes means trying to push the CIC rate down still further by an order of magnitude to < 0.001 e/pixel/frame, if possible.

6. ASTRONOMICAL RESULTS

White dwarfs are the remnants of stars like the Sun, packing almost a solar mass into a volume no larger than the Earth's. ES Cet[7] is one of only three known members of a class of star known as the "ultra-compact binaries". These are believed to consist of two white dwarfs, separated by just a few earth radii and orbiting each other in about 10 minutes or less. Ultra-compact binaries are believed to be relatively common in our galaxy, but their faintness makes them very difficult to find and study. They are of great astrophysical interest as they are the shortest period binary stars known, and due to this, they are the only systems currently known that will be detectable by proposed gravitational wave observatories such as LISA. Figure 7 shows ULTRASPEC spectra, in its raw data form, of ES Cet, a binary of magnitude V ~ 17 for both standard and avalanche outputs.

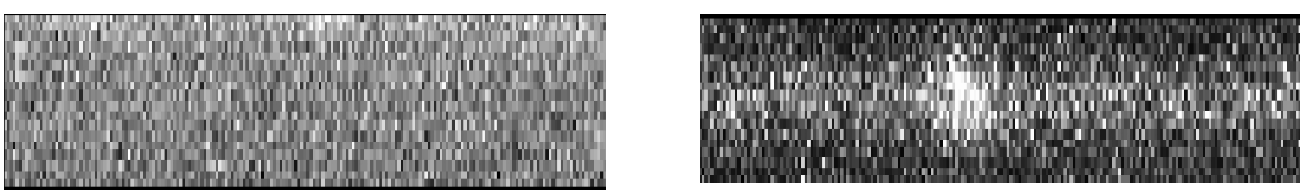

Figure 7 : Left image is a raw 10 s exposure of ES Cet using standard CCD output, right image is 74 accumulated exposures each of 0.13s using the avalanche output, giving a 10 s exposure for comparison. The spectrum is clearly seen in the right image.

One of the white dwarfs is filling its Roche lobe and transferring material to its companion, producing the strong HeII emission at 4686 Angstroms visible in its spectrum. The top plot of Figure 8 is a simple line plot of 10 second spectrum using the avalanche output of ULTRASPEC as shown above. The bottom plot is a similar line plot of the 10 second spectrum taken using the normal output of ULTRASPEC. The latter is identical to what would be obtained using a conventional CCD. The spectral line is clearly seen in the top line plot taken from the avalanche gain output of the CCD. The gain in signal to noise is approximately a factor of three. Given that these are detector read out noise limited observations, this shows that using an EMCCD on the ESO 3.6 metre is therefore equivalent to using a conventional CCD on a 6.3 metre telescope! The gain is even greater if the negligible dead time of the frame transfer EMCCD (~ 10 milliseconds) compared to a conventional CCD (~ 10 seconds) is also taken into account.

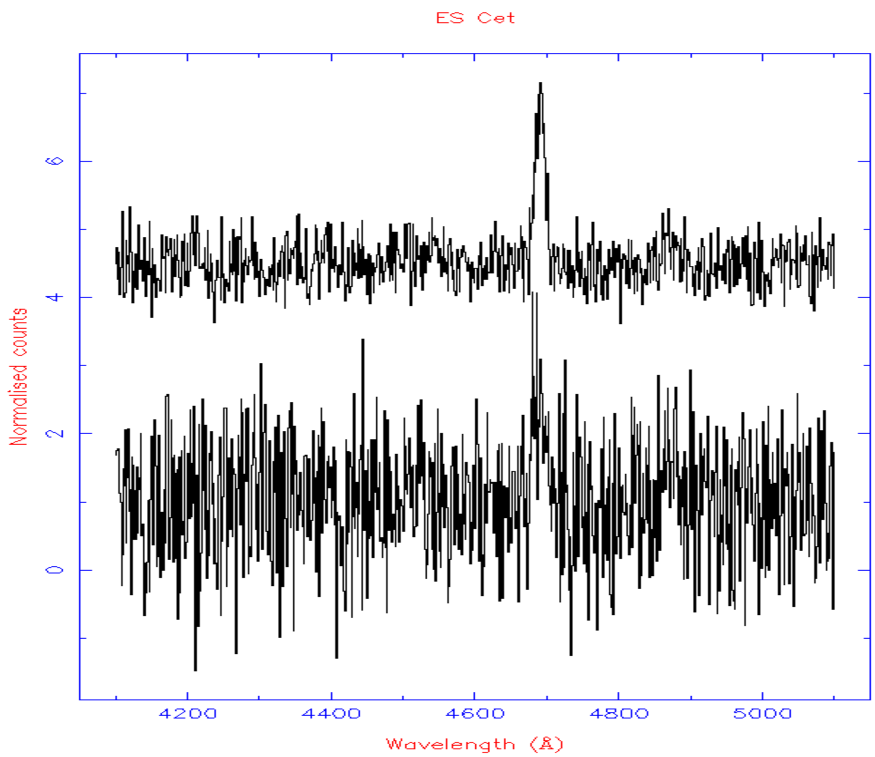

Figure 8: ULTRASPEC spectra of the star ES Cet. Top: A 10-second spectrum using the avalanche output of ULTRASPEC. Bottom: A 10-second spectrum taken using the normal output of ULTRASPEC. The latter is identical to what would be obtained using a conventional CCD. The gain in signal-to-noise is approximately a factor of 3, turning the ESO 3.6m into an equivalent 6.3m telescope.

7. PROPOSAL FOR A NEW ELECTRON MULTIPLICATION CCD FORMAT

A new detector type is proposed which will cover the full spatial and spectral ranges of most astronomical spectrographs in use on today's generation of telescopes. This new CCD will take the following form as shown in Figure 9.
This device will have 4096 x 1024 imaging pixels and a similar number of storage pixels in a frame transfer format. It will have eight avalanche gain outputs each of which will be optimised for 3 e- rms noise at 100 kHz pixel rates in non avalanche mode. These outputs will also be designed to be able to operate at 5 MHz pixel rates for avalanche read out mode. The goal is to produce a device that can read out a 4096 x 100 window at 100 Hz continuous frame rate. The device would have all the other usual characteristics of standard astronomical CCDs, such as being thinned for high quantum efficiency.
The pixel rate expected from this new detector far surpasses the processing capabilities of the ASTROCAM controller and the new clock board used on the present camera system. This controller is limited by the clock period of its waveform generator circuit and also by the data rate of the fibre link for transmitting the pixel data. However a new controller is specifically being designed by ESO to operate the new E2V EMCCD wave front sensors for ESO telescopes. Our new CCD proposal, together with this new controller development will open up new areas of science in astronomy because the camera system will operate in regimes not previously possible. The CCDs will not only offer improved performance in the low light regime because of their avalanche gain but they can also offer read out efficiency improvements in bright time because they can be read out so much faster than standard equivalent sized CCDs.

A plot of the modelled observational efficiency improvements in high background regimes for a 4096 x 256 pixel window region using a single high speed avalanche output device compared to a similar sized CCD window with normal output is given in Figure 10, for different signal to noise regimes and assuming different values for read out noise dependent if running in avalanche mode or normal mode. The plot shows that the fast pixel times of the avalanche output even with the effective reduction in quantum efficiency due to the avalanche gain distribution can still win in certain bright operating regimes. The main point of this modelling exercise is to emphasis that users of EMCCDs should take all their requirements into careful consideration to ensure maximum observational efficiency because the devices can be used not only for high speed faint objects but can also be used for bright sources as well where their high speed readout can be used to increase the observing efficiency.

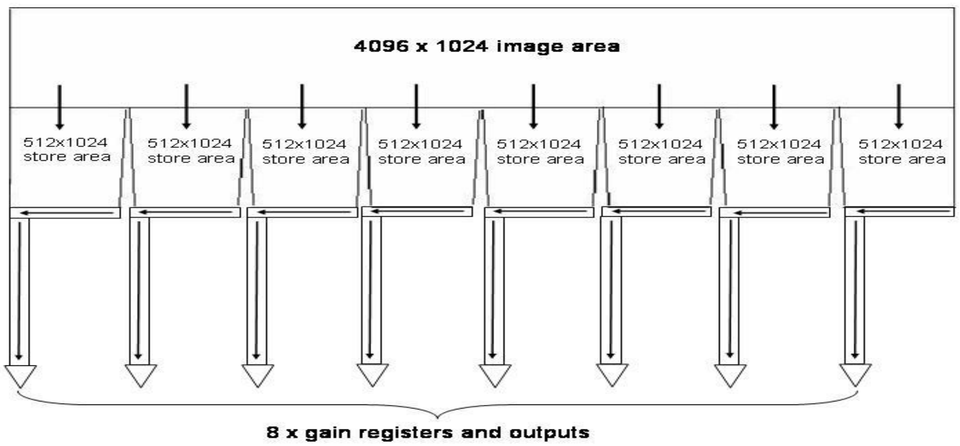

Figure 9: Proposed architecture for new EMCCD

The proposed new device is even more efficient because it will have 8 outputs as well as the frame transfer architecture. This ensures that there is no dead time at all between consecutive exposures. The storage area can be used as an image pipeline to maximize the frame rate. This pipeline process has been used very successfully in the ULTRACAM instrument.

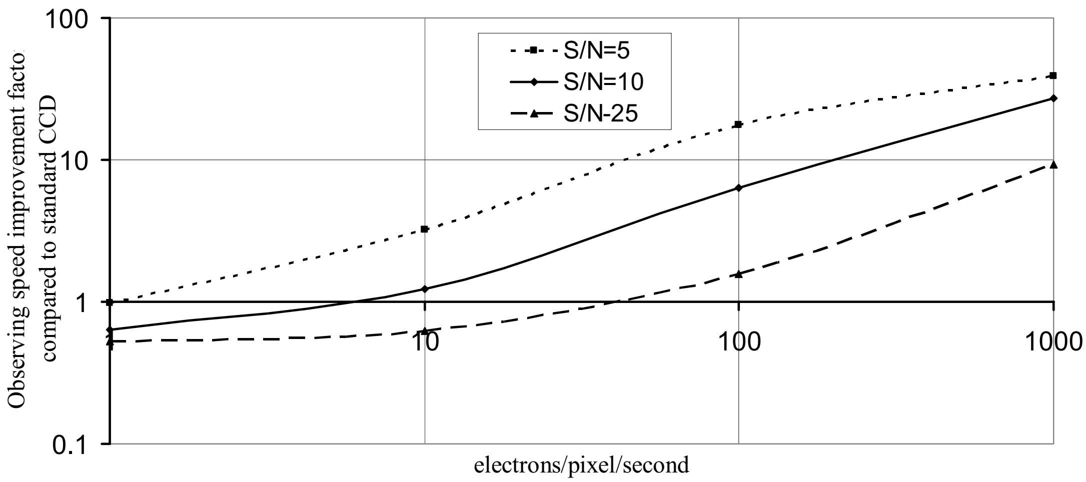

Figure 10 : Modelled efficiency gains for EMCCD in high background regime (20 e- rms read noise, gain of 100, 1 µs/pixel) compared to standard CCD (4 e- rms, 12 µs/pixel) for different signal to noise regimes. The y axis shows the factor of improvement in observational efficiency compared to a standard CCD.

8. CONCLUSIONS

ULTRASPEC has shown that there are still new and exciting possibilities for astronomy and that telescopes can still be made more efficient with the continued development of the detectors used. A signal to noise gain of three is possible if the astronomy community can move from standard CCD technology to new Electron Multiplication CCDs. However the present generation of EMCCDs do not cover the available field of view of a typical spectrograph. Therefore development of a new larger EMCCD is required to sample a typical field and still give the signal to noise improvements described. Such a device will probably cost >1M Euro to develop. ULTRASPEC has proved itself to such an extent that it has already won 17 nights of real science time on an ESO telescope. It is hoped that greater awareness in the astronomical community of the benefits of electron multiplication might lead to financial support for the development of the larger detectors. Astronomers with readout noise limited observations will gain very considerably by using EMCCDs. In fact, no one loses, implying that EMCCDs should become the detector of choice for spectroscopy at the world's major observatories, providing that larger formats become available.

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