

Electron Multiplying Charge Coupled Devices

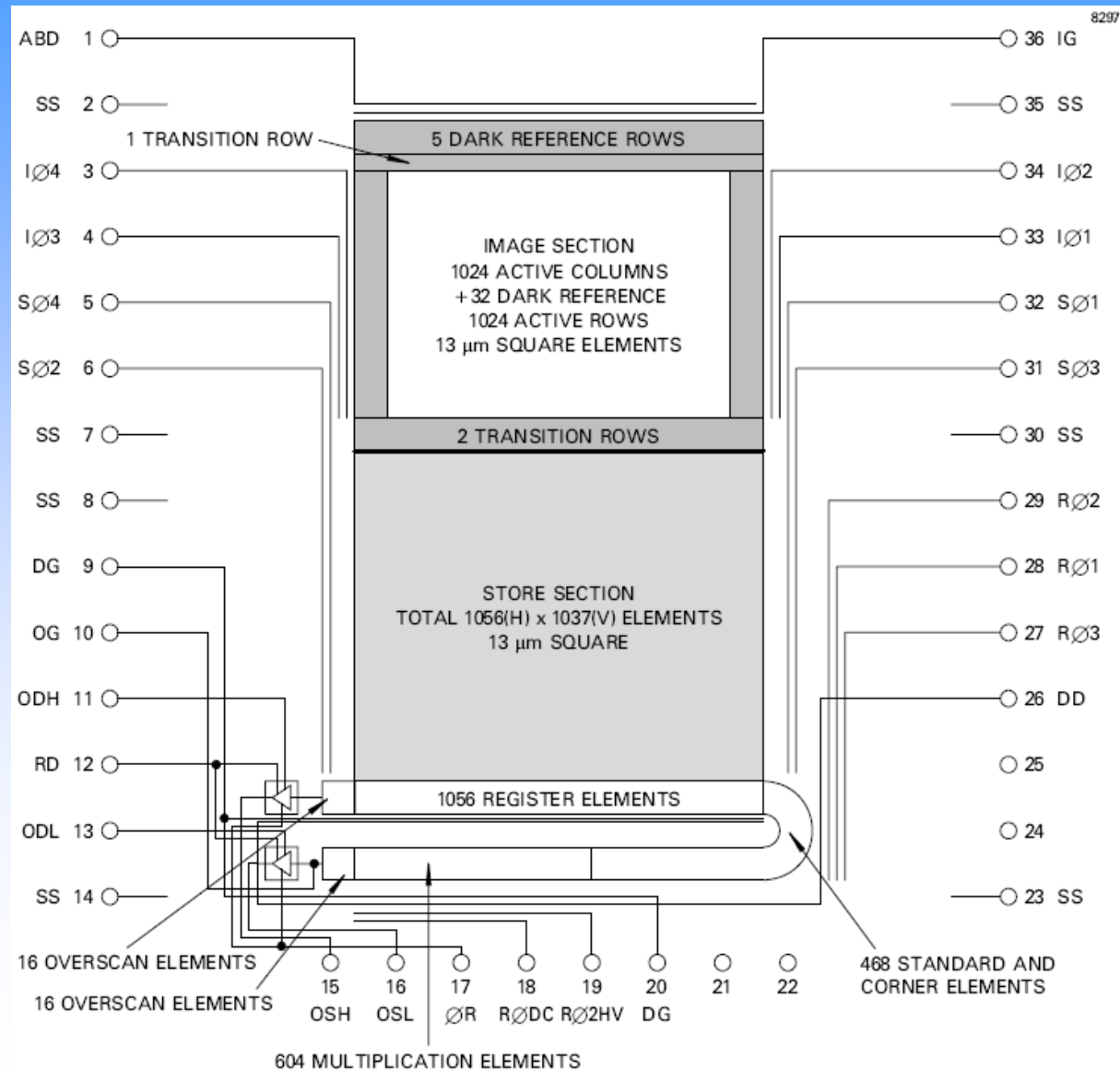
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Outline

- Introduction to EMCCDs: General Characteristics
- Applications of EMCCDs: Current and Potential Applications
- When are EMCCDs the best choice?
- General Availability of EMCCDs:
- The Care and Feeding of EMCCDs: Gain Characteristics, Drive Requirements, Cooling, Ageing
- Photon Counting Strategies with EMCCDs
- Clock Induced Charge: What Is It and how to Minimise It.
- Conclusions

Introduction to EMCCDs: General Characteristics

- EMCCDs are standard CCDs plus an electron multiplication stage.
- One serial electrode runs at high voltage (~45 volts).
- An electron has a low probability (~1%) of a 1 electron avalanche.
- Gives $604^{1.01}$ or 1.02 ~few x100 gain.



Introduction to EMCCDs: General Characteristics

- EMCCDs may be read out at high pixel rates (up to 30 MHz for E2V EMCCDs, probably up to 60 MHz for TI EMCCDs).
- The gain mechanism increases the variance in the output signal so that the signal-to-noise ratio goes as $\sqrt{(2N)}$ rather than $\sqrt{(N)}$.
- Equivalent to halving the detective quantum efficiency.
- Photon counting can substantially restore this effective loss in quantum efficiency.
- Clock induced charge (CIC) affects all CCDs, but you will only really notice it with high gain EMCCDs.

Applications of EMCCDs In Astronomy.

- High time resolution astrophysics (HTRA) covered by Andy Shearer in his talk.

Science from Crete 2010 HTRA workshop

- – magnetars, pulsars and neutron stars
- – black hole binary systems
- – white dwarf binary systems
- – gamma ray bursts and supernovae
- – normal stars - stellar oscillations
- – solar system objects through transits and occultations

Planets and satellites

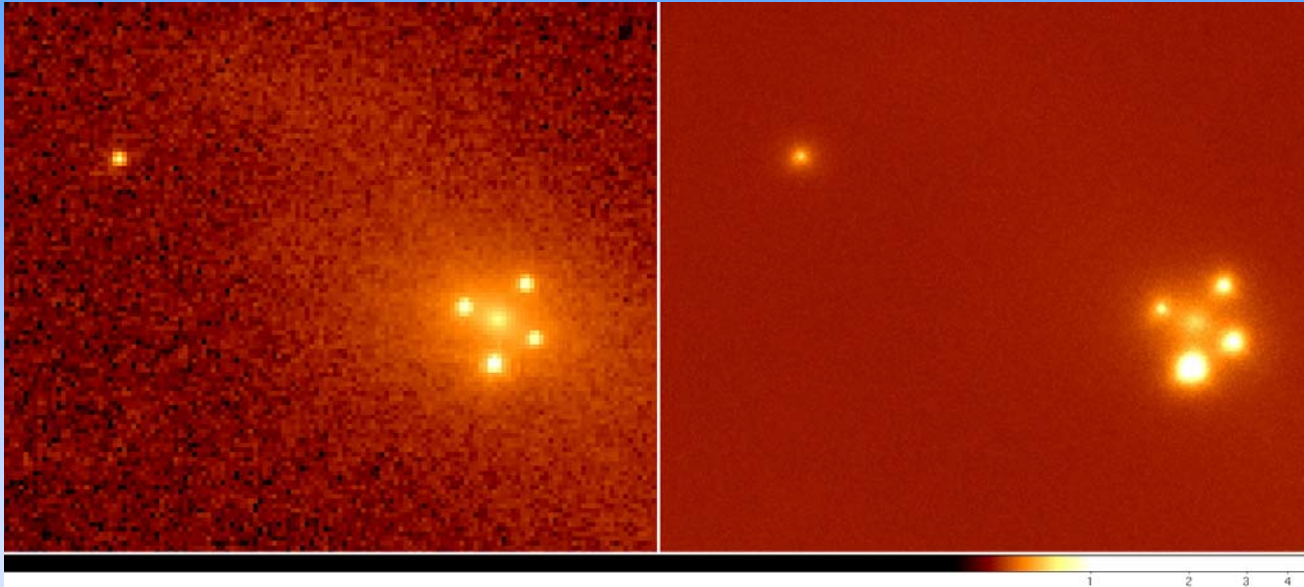
Kuiper belt objects

Applications of EMCCDs In Astronomy.

- Conventional CCDs are noisy when read out fast ($>100 e^-$).
- Large area CCDs used by astronomers can take many minutes to read out for best noise performance ($\sim 3 e^-$). Wastes valuable telescope time.
- With genuine photon counting detectors, very faint periodic signals may be accumulated using large numbers of repeated cycles.
- Techniques for overcoming atmospheric fluctuations require fast, very low noise, high sensitivity detectors.
- Examples are wavefront sensors such as Shack-Hartmann and curvature sensors. They need to operate with frame rates in the 50-2000 Hz range.

Applications of EMCCDs In Astronomy.

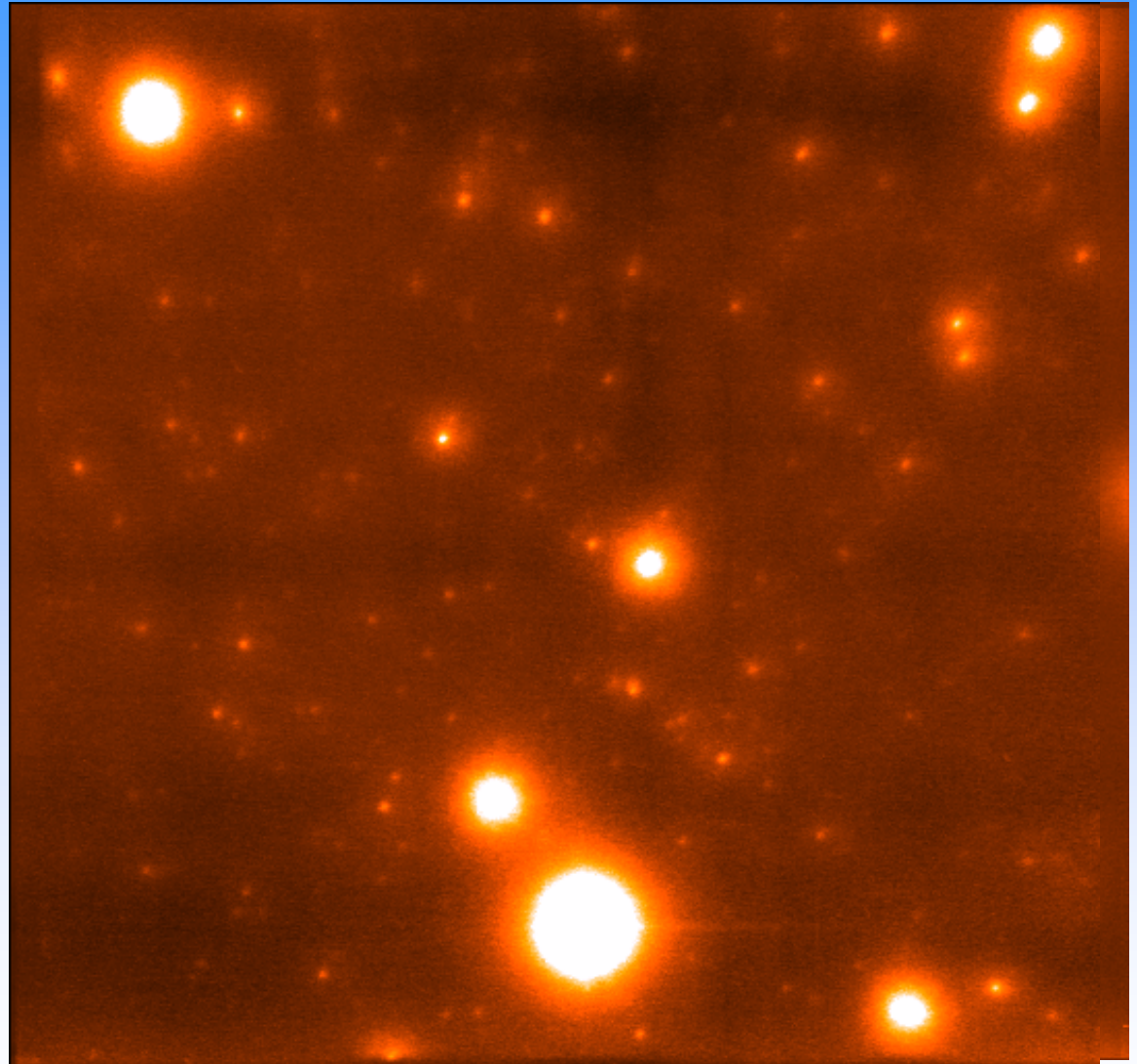
- In Lucky Imaging, fast frame rates (~ 25 Hz) are used to give Hubble resolution on Hubble size telescopes from the ground.



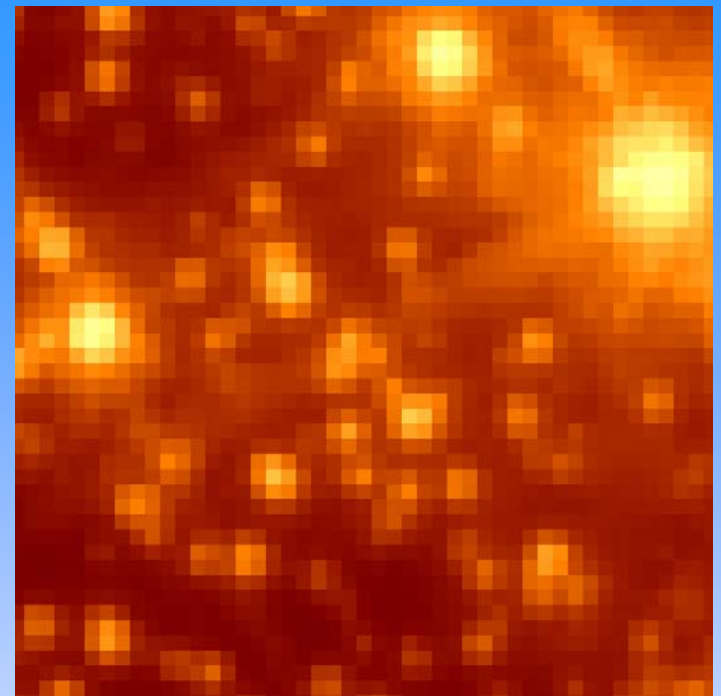
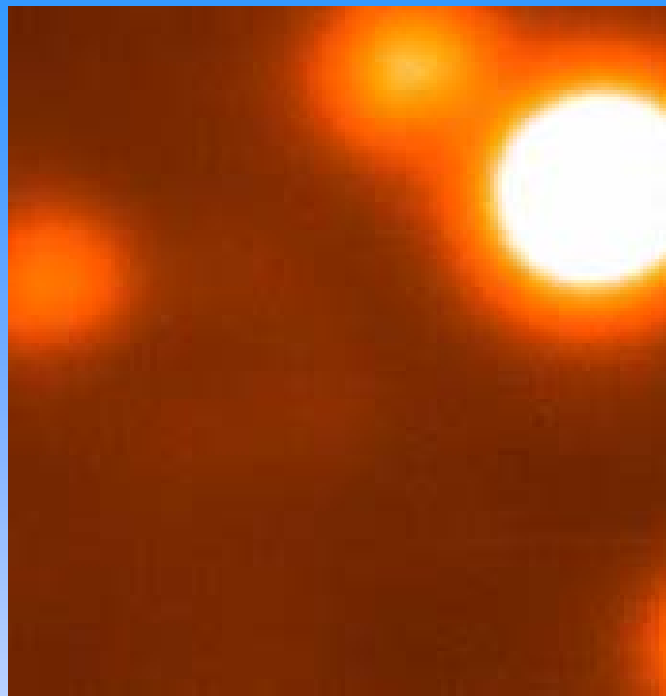
- The image on the left is from the Hubble Space Telescope Advanced Camera for Surveys (ACS) while the image on the right is the lucky image taken on the NOT in July 2009 through significant amounts of dust.
- The central slightly fuzzy object is the core of the Zwicky galaxy, ZW 2237+030 that gives four gravitationally lensed images of a distant quasar at redshift of 1.7

Applications of EMCCDs In Astronomy.

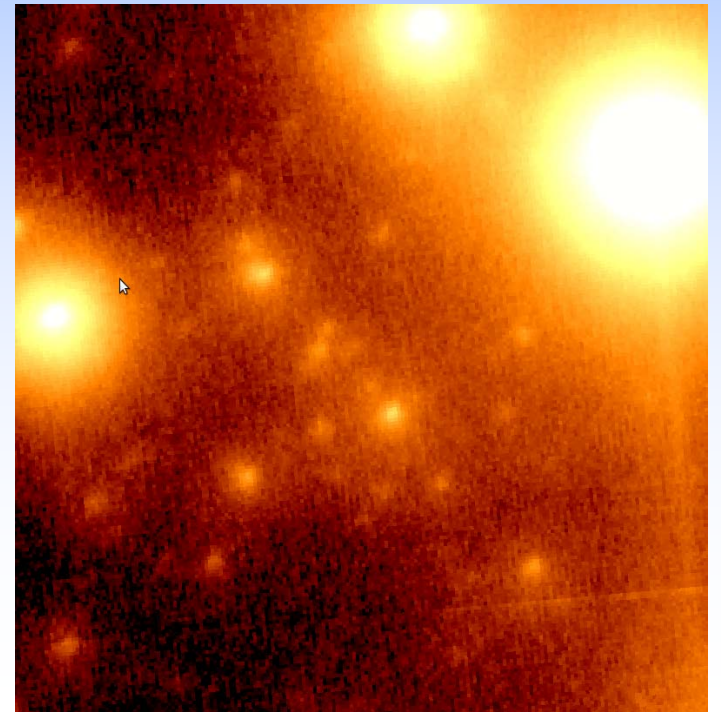
- Globular cluster M13 on the Palomar 5m.
- Natural seeing ~ 650 mas.
- Imaged via the PALMAO system and our EMCCD Lucky Camera.
- Achieved 17% Strehl ratio in I-band, giving ~ 40 mas resolution.
- This is the highest resolution image ever taken in the visible.
- Field shown here is about 7×7 arcsec.



Lucky Imaging on Palomar 5m.



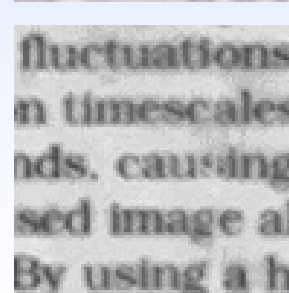
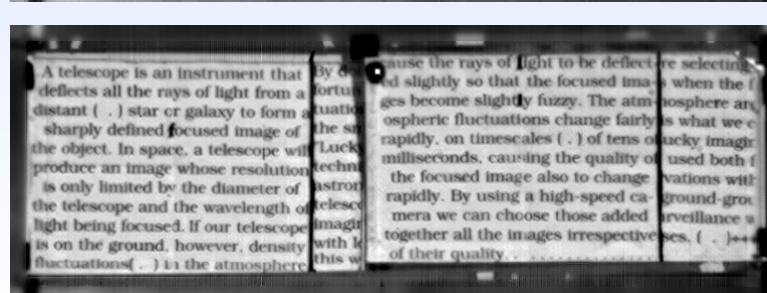
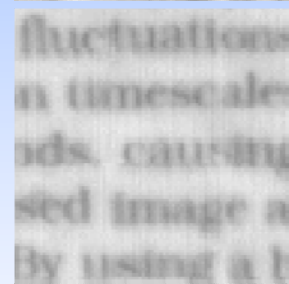
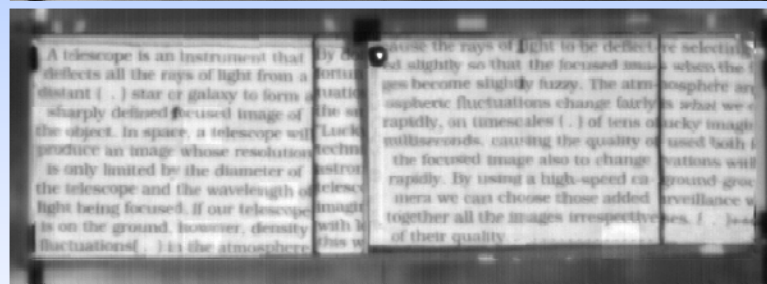
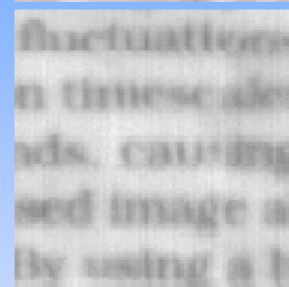
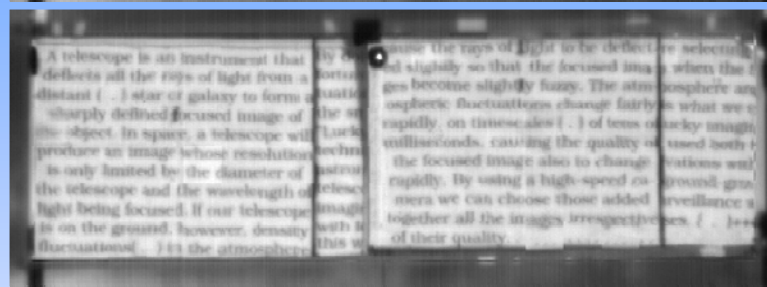
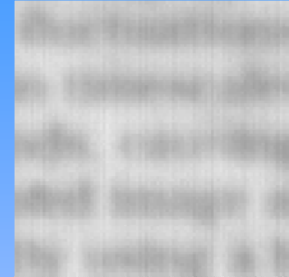
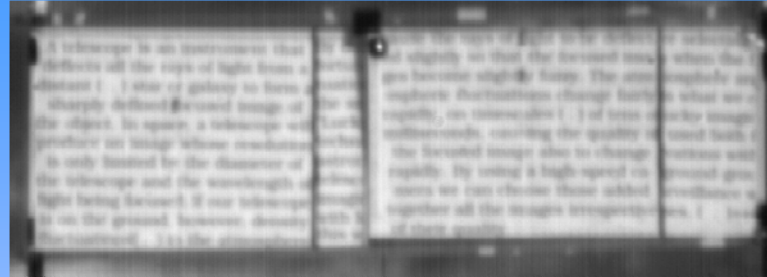
- The comparison of our system with Hubble Advanced Camera (ACS) is quite dramatic.
- Lucky/AO image resolution ~ 40 milliarcseconds or ~ 3 times Hubble.



Other Applications of EMCCDs.

Surveillance: high-speed allows freezing of atmospheric turbulence.

- The top image is the sequence average (what you would get with a long exposure image).
- Others show selections of 10%, 1% and 1% post-processing.
- The resolution improvement is dramatic.
- We typically are able to reduce the effective distance of a target by a factor of 8-12.



Other Applications of EMCCDs.

- Surveillance for crime prevention and detection.
- Neuronal Imaging: need for high-speed very low light level imaging of fluorescently labelled neurons.
- Confocal microscopy: achieving the highest resolution in optical microscopy.
- Live cell (dynamic) imaging. Tracking microorganisms and cells in order to understand their metabolism etc.

When Should You Use EMCCDs?

- Any time that you are really limited by readout noise.
- This is more likely to be the case when running with high pixel rates. Conventional CCDs give excellent read noise but only at low read-out rates.
- Recent developments in sCMOS technology are changing this by offering low read-out noise ($\sim 1-2$ electrons) and 100 Hz frame rates, though best in rolling shutter mode.
- However, do not forget the equivalent loss in detector quantum efficiency using an EMCCD in analog mode.
- At the lowest signal levels, photon counting gives close to the theoretical full DQE at high frame rates.

EMCCD Availability.

- E2V Technologies Ltd (Chelmsford, UK) were the first to produce EMCCDs (they use the term L3CCDs).
- Texas Instruments also produced devices that they have since ceased manufacturing them.
- In certain applications they had clear advantages so this is a disappointment for camera designers.
- In particular, their internal amplifiers were much higher sensitivity ($14 \mu\text{V}/\text{e}$ vs. $1.4 \mu\text{V}/\text{e}$ for E2V) and much lower clock voltages to deliver high gain (20V vs 45V for E2V) largely eliminating ageing effects.
- Other aspects of the TI design were less desirable.

EMCCD Availability.

- CCD 60:128 x 128 pixels of 24 x 24 μ
- CCD 65:288 x 576 pixels for TV use
- CCD 97: 512 x 512 pixels of 16 x 16 μ ., FT device.
- CCD 201:1024 x 1024 pixels of 13 x 13 μ ., FT device
- CCD 207:1632 x 1608 pixels of 16 x 16 μ , full frame device (not a stock item)
- CCD 220:240 x 240 pixels of 24 x 24 μ , FT device with 8 parallel outputs giving 1 KHz frame rate.
- CCD 251:1024 x 1024 pixels of 8 x 8 μ , FT device 37 MHz output amplifier. Same physical size as CCD97

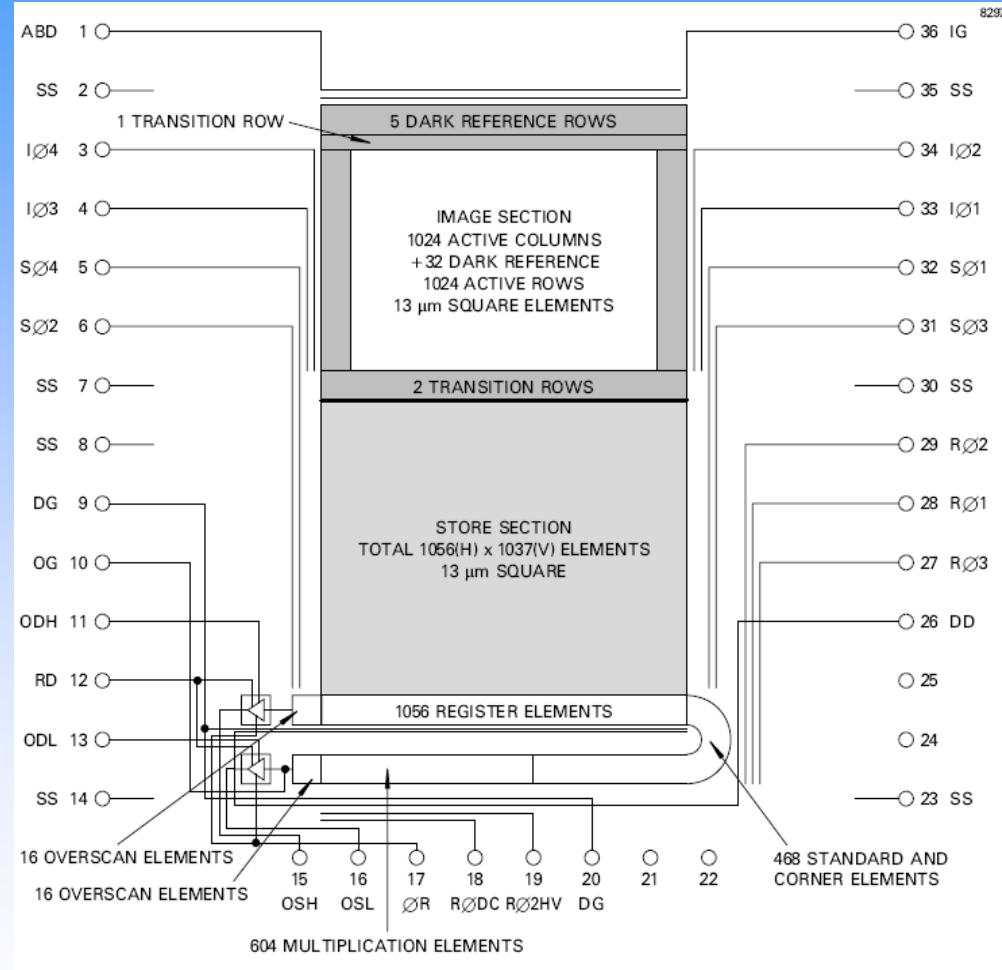
- In development:
- (unnamed): 4096 x 4096 pixels of 12 μ .² split frame device with 8 parallel outputs giving 4 Hz frame rate

EMCCD Availability: Other Devices

- CCD 242, pinhole device with biased concentric ring electrodes that allows the signal collection area to be changed. This is used for confocal microscopy.
- Lidar CCD 223, developed for the European Space Agency (ESA): single pixel device that runs at very high frequency with EMCCD multiplication register so effectively solid-state photomultiplier, 650 nsec/sample max.
- Back illuminated (thinned devices) are available in different thicknesses and with different antireflection coatings including a new one soon to be released for maximum 400-900 nm flat response.

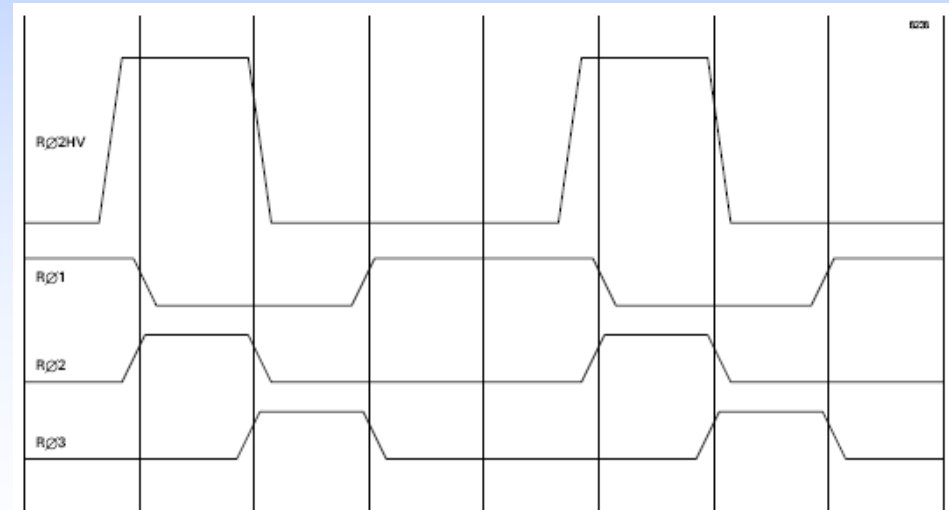
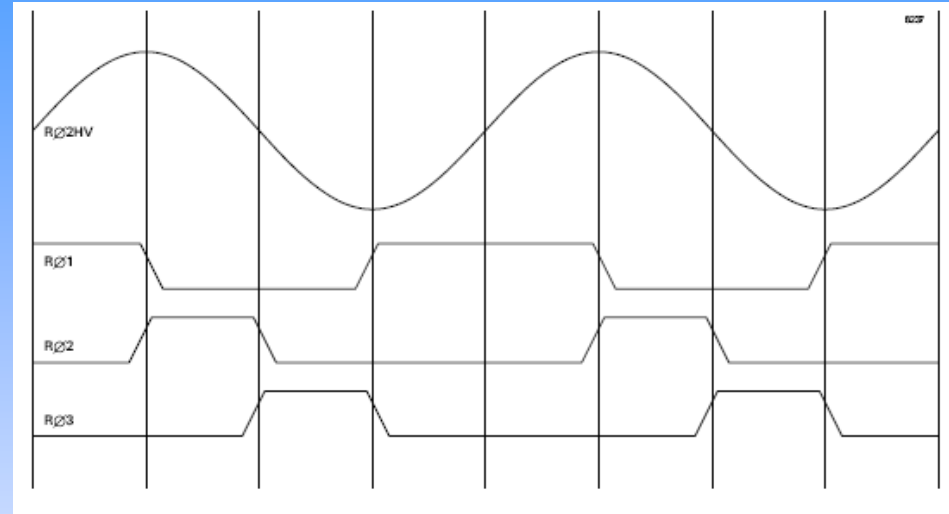
Operation and Evaluation of EMCCDs.

- Operation is exactly as for standard CCDs except for the multiplication register
- Here only the high-voltage clock is a significant difference.
- The gain is adjusted by changing the high-voltage peak clock level.



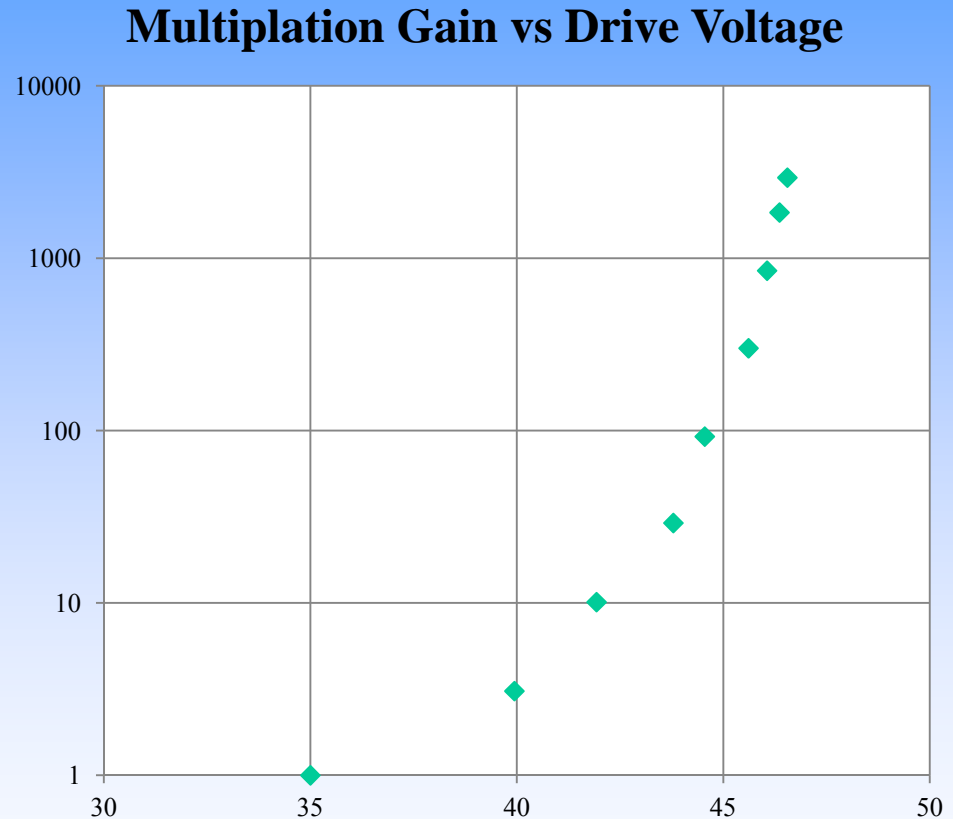
Operation and Evaluation of EMCCDs.

- The clocking scheme needed for EMCCDs is shown here.
- The high-voltage clock may be switched or a sine wave.
- For high-speed readout sine wave drivers are much easier to make and use much less power.



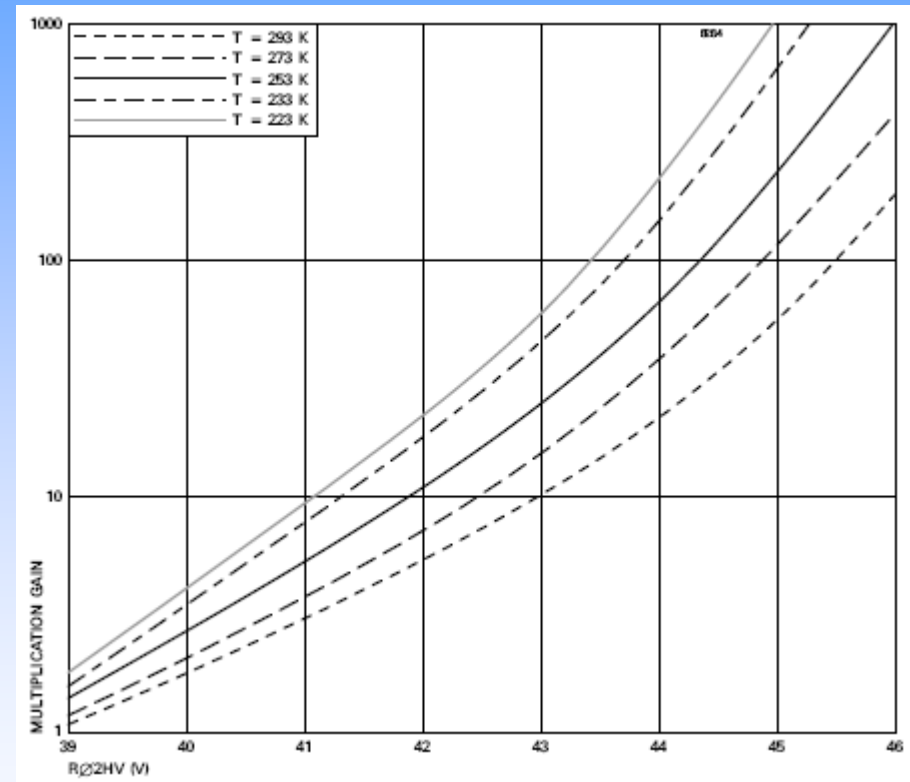
Operation and Evaluation of EMCCDs.

- The gain/HV curve is very steep at high gains. It doubles from 1000 to 2000 in about 0.25 V.
- High-voltage stability key if operating in analog mode.
- High gains only important in photon counting mode where the constraints are much more relaxed (see later).



Operation and Evaluation of EMCCDs.

- At a fixed multiplication voltage the gain changes markedly with temperature.
- The voltage needed to give a gain of 1000x is 1.6 V lower at -120°C than that needed at -60°C .



EMCCD Ageing

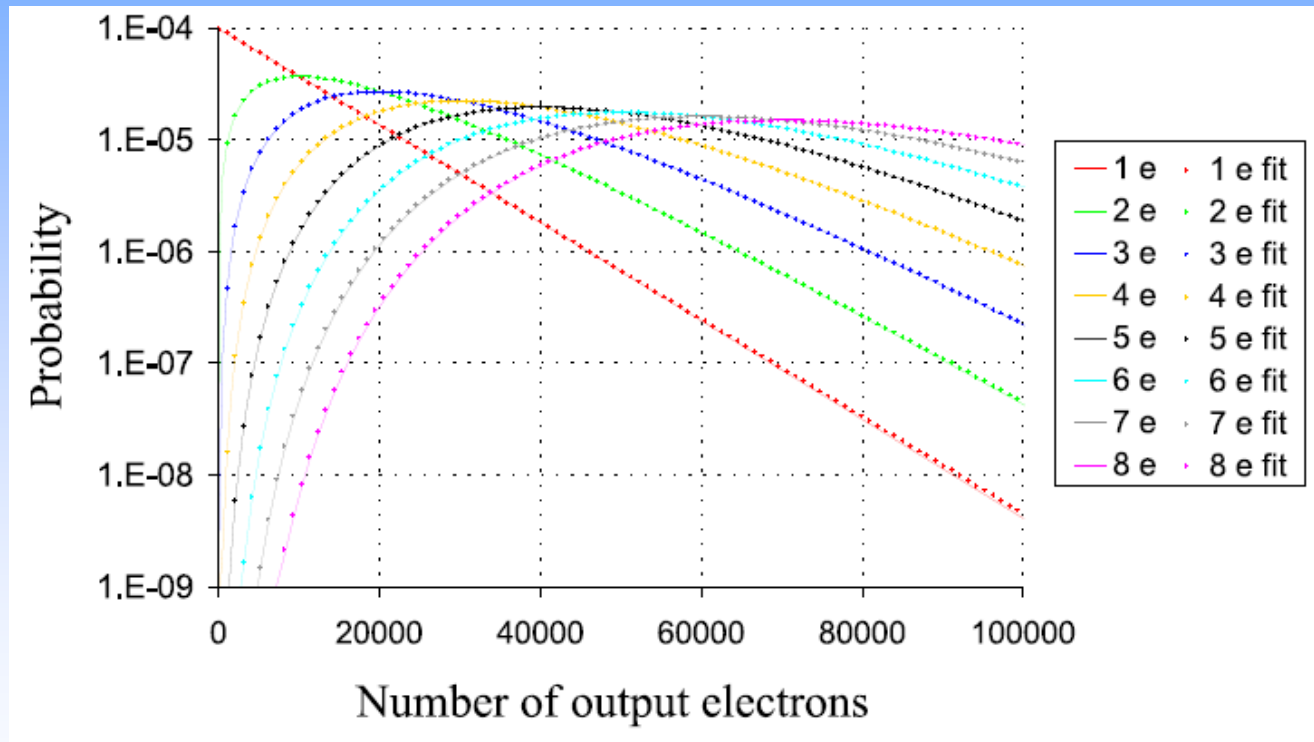
- Illuminating the image area to saturation and running the device at a gain of 1000x will cause the device to fail within a few hours.
- In practice these devices will be used at much lower illumination levels.
- With reasonable care in system design, many years of operation will be obtained.
- The ageing effect is seen as an increase in the high-voltage (multiplication) clock level needed to achieve a specific gain.

EMCCD Ageing

- At low gains (gains of a few) no ageing is seen.
- Increasing the gain from 100x to 1000x roughly doubles the short-term ageing rate with little effect on the long-term ageing.
- The ageing is principally caused by excessive signal levels in the multiplication register.
- An increase of 5 V over the life of the device is about the limit before failure occurs.

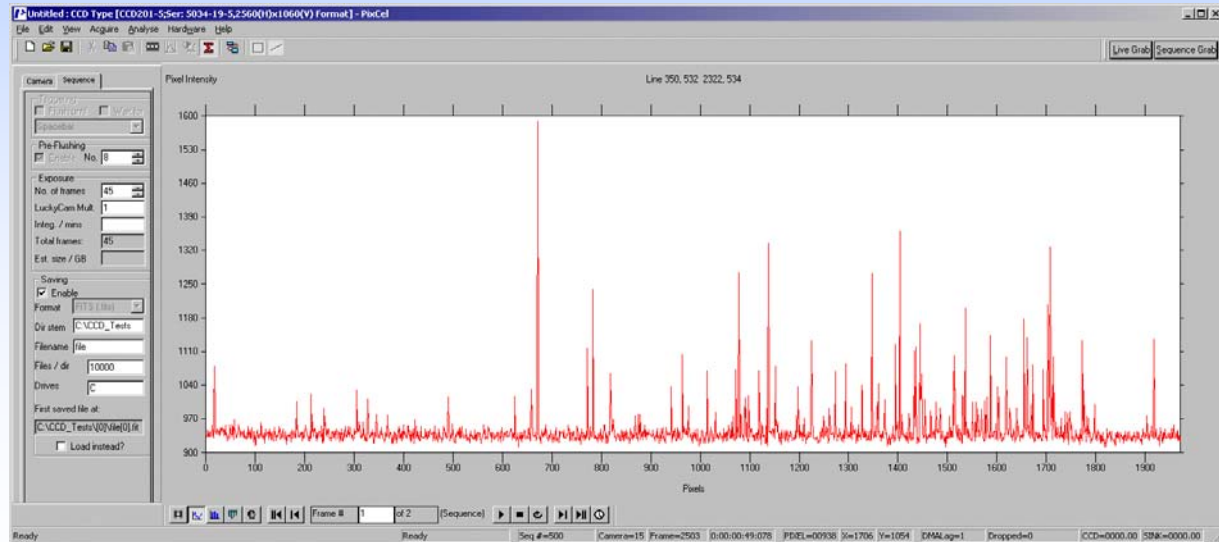
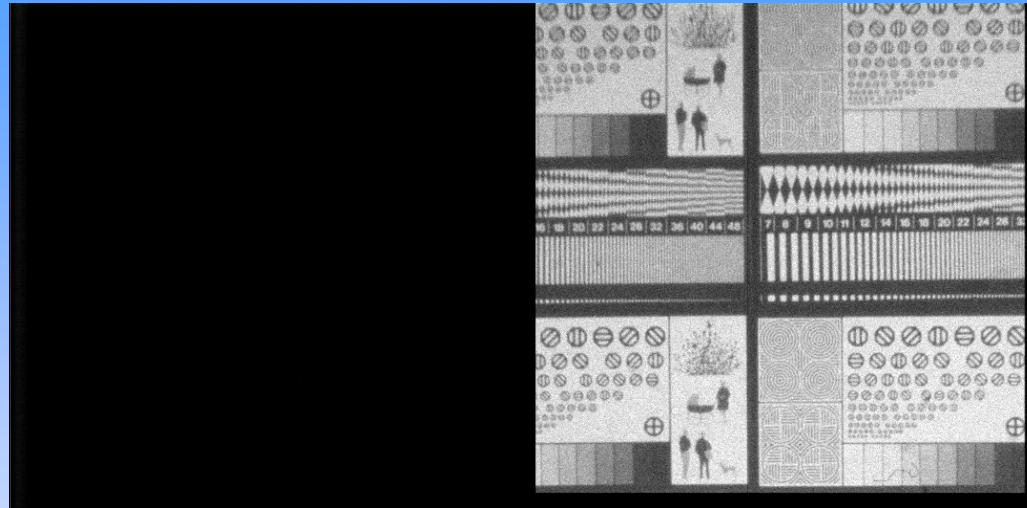
Photon Counting with EMCCDs

- The most likely gain for an EMCCD is unity.



Photon Counting with EMCCDs

- All these tests are with our own camera design (available from www.pixcellent.com).
- A substantial overscan allows effects in the parallel register to be separated from those in the serial register.
- A cut across an EMCCD image at very low signal level and high gain shows a wide range of events sizes.

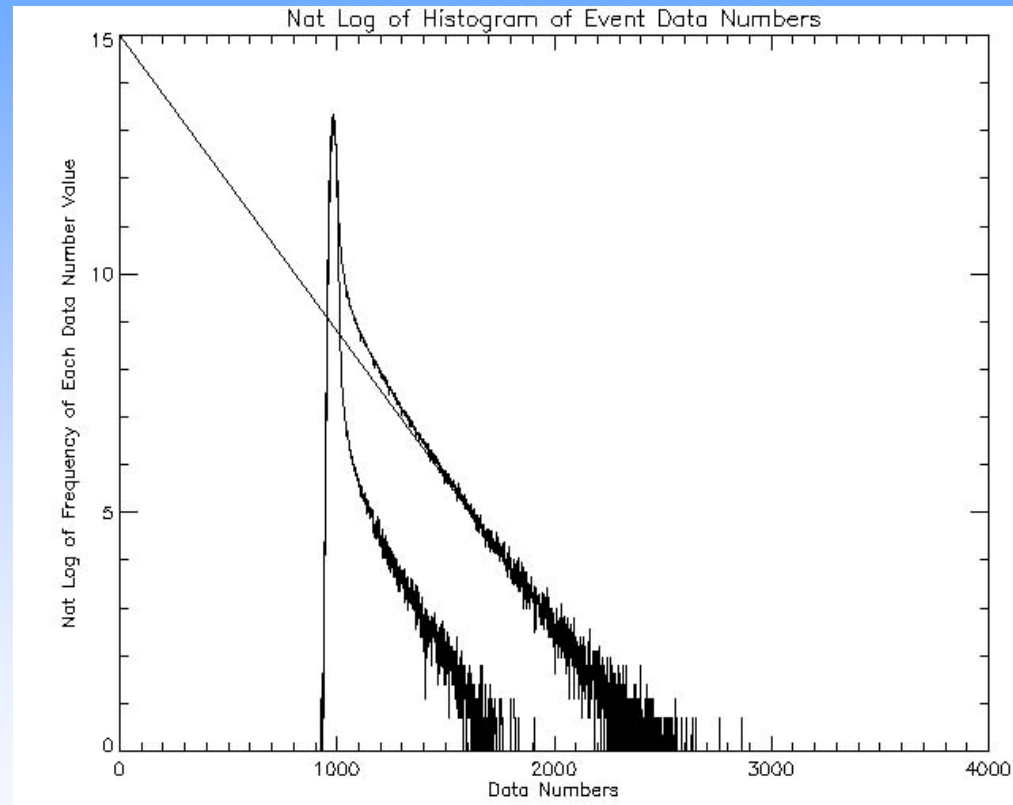


Photon Counting with EMCCDs

- The additional variance introduced by the multiplication stage increases the amount of noise.
- We normally expect the $\text{SNR} = \sqrt{N}$.
- With the EMCCD the $\text{SNR} = \sqrt{2N}$.
- This is equivalent to halving the detective quantum efficiency of the device.
- However, if we threshold the image and replace each event by a single value equal to the median gain then the variance is eliminated and the detective quantum efficiency restored.
- In photon counting mode, long-term absolute gain stability is much less important. An event is an event is an event.

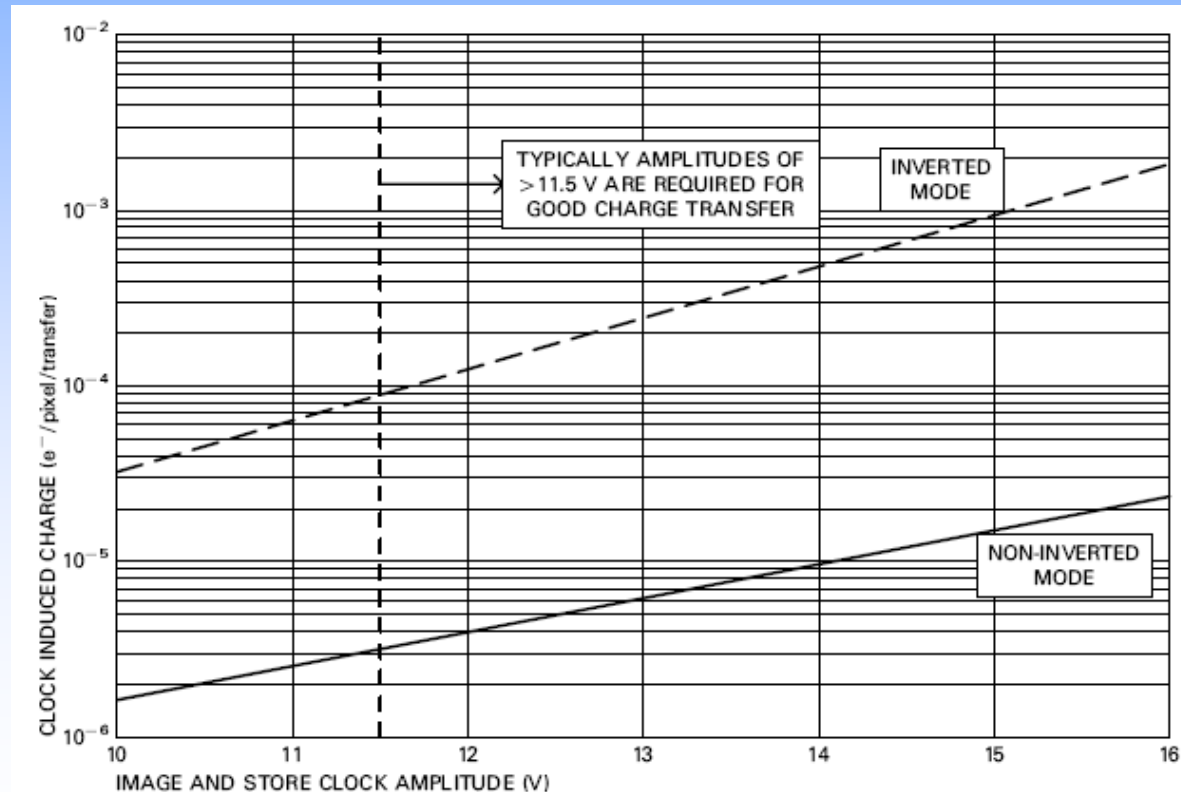
Photon Counting with EMCCDs

- We can also tolerate some loss in performance when we run at pixel rates well above those recommended.
- With the CCD201, E2V give a max. speed of 13-20 MHz,
- All our results here use 30 MHz pixel rate.
- The gain may be determined by looking at the statistics of the photon events sizes detected.



Clock Induced Charge (CIC)

- Two components of the dark signal: thermal dark signal, reduced x10 for every ~ 20 °C temperature reduction.
- Clock induced charge (CIC), essentially constant per readout.
- CIC is present in all CCDs.
- With EMCCDs working at high gain it is more noticeable and can seriously limit sensitivity.
- CIC depends exponentially on clock high to substrate bias.



Clock Induced Charge (CIC)

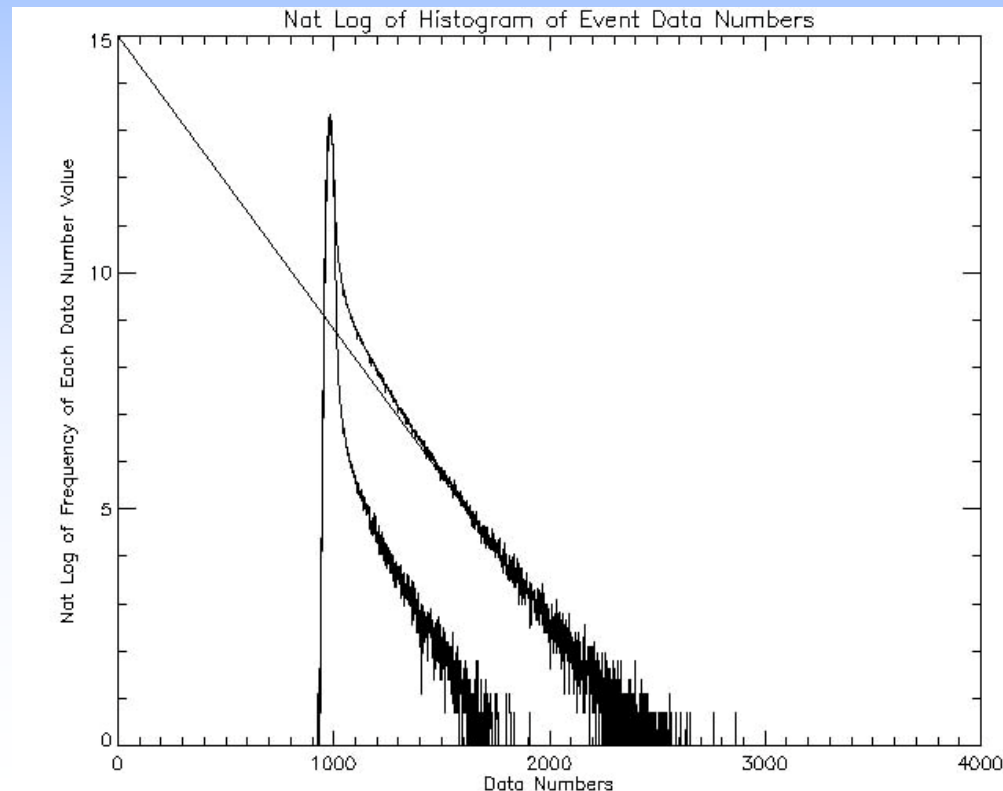
- CIC is much worse with low parallel transfer frequencies.
- CIC is worse with sharp clock transitions.
- Clock waveforms must be properly formed and drivers matched.
- CIC appears to be relatively unaffected by temperature.
- In photon counting operation the gain is high (typically x1000-x2000) so the image/store peak signal requirement is extremely small (<100 electrons).
- Allows smaller parallel clock swings to transfer charge efficiently.
- We typically run with 9.5-9.7 V, bringing the surface completely out of inversion giving $\sim 1-1.5 \times 10^{-7}$ events per transfer, so less than 0.1% CIC.

Setting up and Using EMCCD Cameras

- By over-scanning the detector we can separate out what is happening in parallel and serial parts of the detector.
- With camera design targeted at photon counting the performance can be extremely good and CIC reduced to a negligible level.
- Commercial cameras that must work with unity gain and high full well are forced to use larger clock amplitudes inevitably worsening substantially CIC.
- With our camera design we find parallel CIC to be almost unmeasurable.

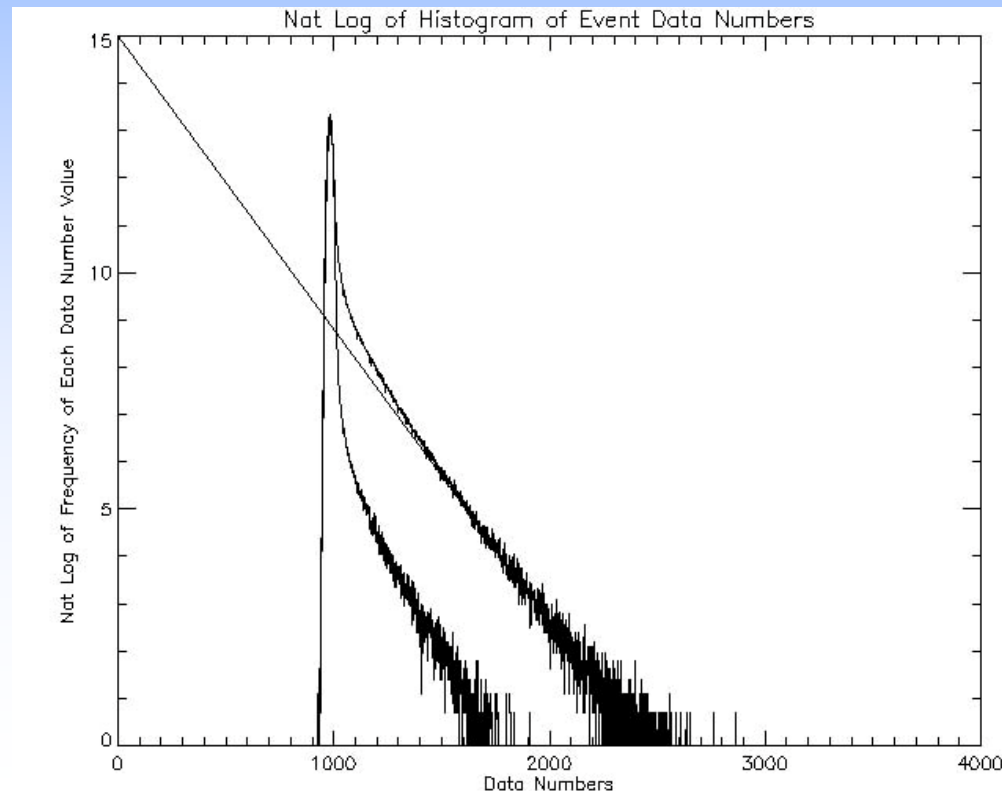
Setting up and Using EMCCD Cameras

- Serial CIC is harder to reduce since high gain implies getting close to serial full well so clock amplitudes cannot be reduced too much.
- However serial CIC generates carriers on average halfway along the multiplication register so they experience on average a gain that is the square root of the full register gain.
- Event histograms from both halves of the readout image are here:



Setting up and Using EMCCD Cameras

- These histograms tell you how to threshold optimally depending on signal level, readout noise and multiplication gain.
- Setting the threshold too high causes many genuine photon events to be excluded.
- Setting the threshold too low allows spurious events (the tail of the readout noise distribution, serial CIC events) to contaminate the signal.



Conclusions

- EMCCDs offer the potential of very high performance at the lowest signal levels ever with two-dimensional imaging systems.
- With careful design, CIC may be reduced to negligible levels.
- In photon counting mode we achieve maximum DQE.
- Even in analog mode the excellent read noise achievable can allow operation at extremely low signal levels indeed.
- These cameras can offer astronomers and scientists in other areas the opportunity to carry out entirely new kinds of research at the very faintest signal levels.

Thanks to E2V (Paul Jordan) for latest info on E2V future products

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