Active Pixel Sensors for Direct Detection of Soft X-rays

Andrew Blue*[a], R. Bates[a], A. Clark[c] , S. Dhesi[b], D. Maneuski[a], J. Marchal[b], P. Steadman[b], G. Stewart[a] N. Tartoni[b], R. Turchetta[c]

a: University *of* Glasgow, School of Physics and Astronomy, Kelvin Building, University Avenue, Glasgow, G12 8QQ

b: Diamond Light Source Ltd, Diamond House, Harwell Science and Innovation Campus, Didcot, Oxfordshire, OX11 0DE

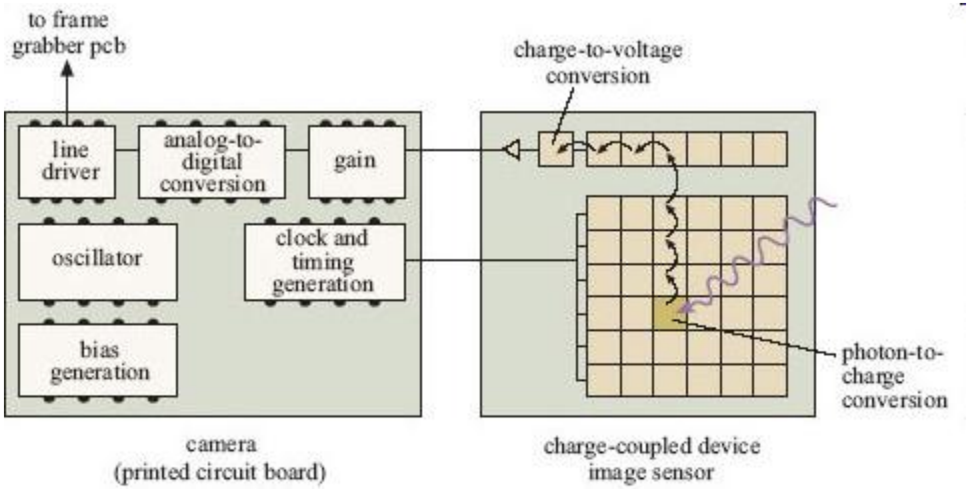
c: STFC Rutherford Appleton Laboratory, Harwell Oxford, Didcot, OX11 0QX

Introduction

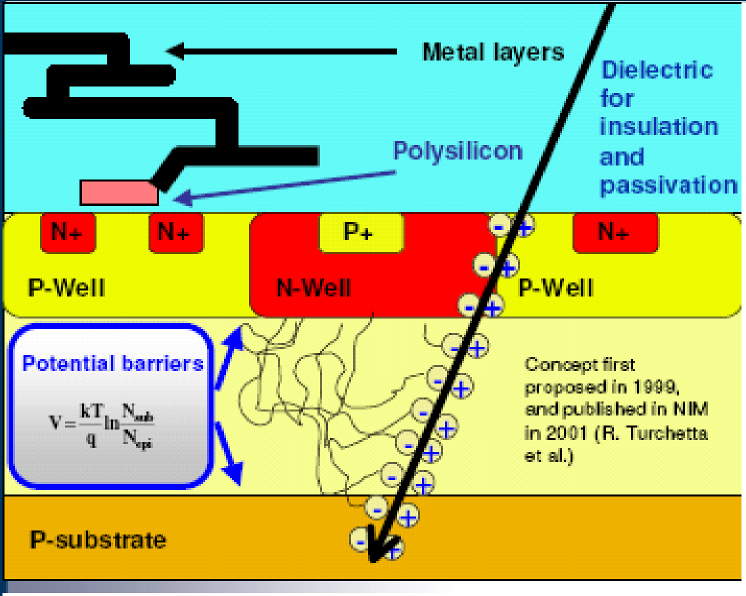
- Motivation for CMOS APS
- Lab Tests
  - Photon Transfer Curve
  - QE
- Diffraction Experiment At Diamond Light Source
  - Noise Sources
  - Signal-to-Noise Profiles
- Conclusions

Charge Coupled Devices

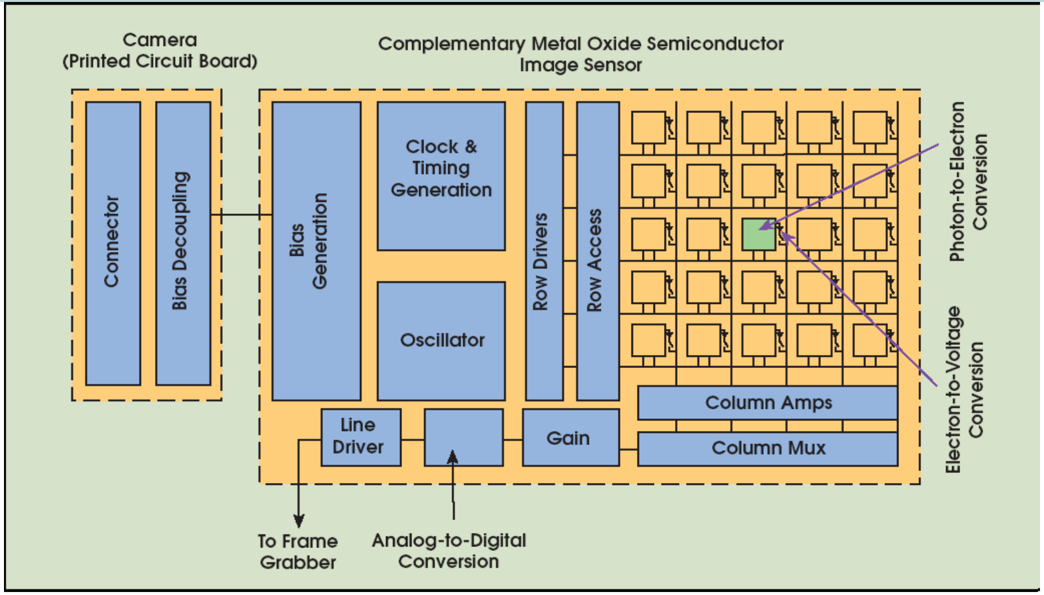
- CCDs collect charge within their pixel architecture, each pixel acting as a capacitor.
- Once the integration time is complete, each capacitor passes charge sequentially down a column.
- If a pixel saturates, charge can spread to neighbouring pixels (an effect known as blooming).
- Most popular imaging device, due to their low noise and high sensitivity.
- CCDs often have thick, fully depleted substrates and epi-layers.

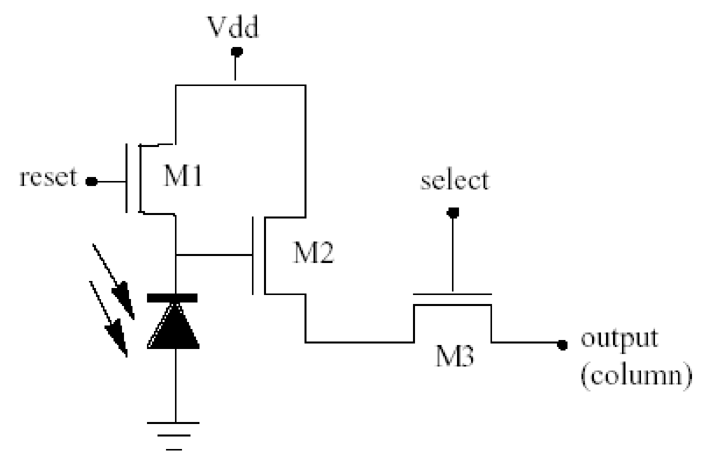


Active Pixel Sensors



Concept first proposed in 1999, and published in NIM in 2001 (R. Turchetta et al.)



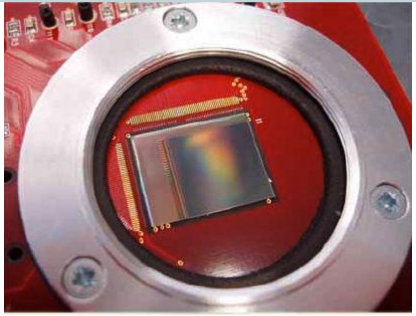


- Photon to Voltage conversion done within pixel

- Integrated electronics in circuit to suit applications (eg discriminator, flags)
- Low mass, low power cameras.
- Faster frame rates achievable.
- Charge sensed inside pixel . . .
  No charge transfer.
  Greater radiation tolerance.

•Design reduces streaking that can be prevalent in CCDs

Motivation for CMOS APS



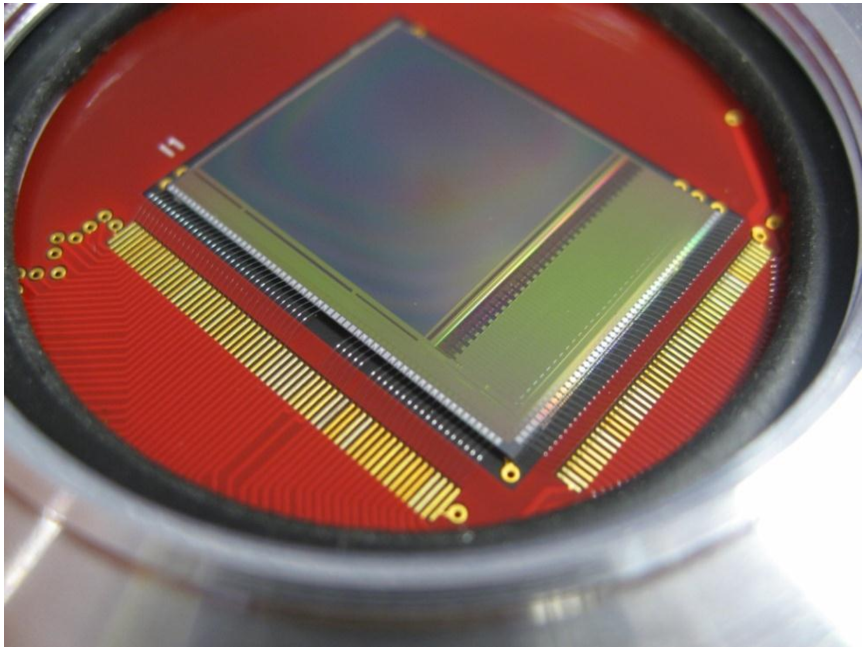
- The CMOS APS have fast frame rates.
  - Fastest CCD operation 0.1Hz
  - Fastest full frame CMOS APS operation 20Hz
- On-chip processing can combine the image sensor and image processing functions, increasing speed and reducing physical size.
- CMOS APS can read out a Region of Interest (RoI) for even faster frame rates
- CMOS APS are cheaper to fabricate
- CMOS APS do not have to be operated at low temperatures for reasonable signal to noise performance.
- They can be backthinned for improved detection of UV photons

How does APS compare to CCD's for direct detection of soft X-rays?

University of Glasgow

Vanilla APS

- Made as part of the M-I^3 RC-UK Basic Technology grant
- 520x520 25μm pixels (1.3cm x 1.3cm)
- A readout rate of 20Hz – 0.1 Hz (full frame mode)
- Region of Interest (ROI) readout
  - Readout rate of 24kHz for 6x6 region
- The sensor designed to allow back thinning
- Designed full well capacity of ~100k e$^-$
- The pad layout allows for the butting of sensors on two sides.
- **NOT designed specifically for synchrotron applications**



Characterisation

- Before any demonstrator use, sensors must be fully characterised for
  - Noise
    - Shot Noise
    - FPN
    - Read Noise
    - Dark Current
  - Gain
  - Full Well Capacity
  - Linearity
  - Quantum Efficiency
  - Stability
- Similar for both CCD and CMOS devices (mostly)
- Imaging devices => tested with photons (not conventional “particle physics” approach)

Noise

Shot Noise

- The standard deviation for the number of interactions per pixel
- Fundamentally related to the charge generated by a photon's interaction with a semiconductor

$$\boxed{\sigma_{\mathrm{SHOT}}(P_I) = P_I^{1/2}}$$

Fixed Pattern Noise

- In sensors, some pixels collect charge more efficiently than others
- This results in pixel-to-pixel sensitivity differences
- This noise is "Fixed" as it is not random, but is spatially the same pattern from image to image

$$\boxed{\sigma_{\mathrm{FPN}} = P_N S}$$

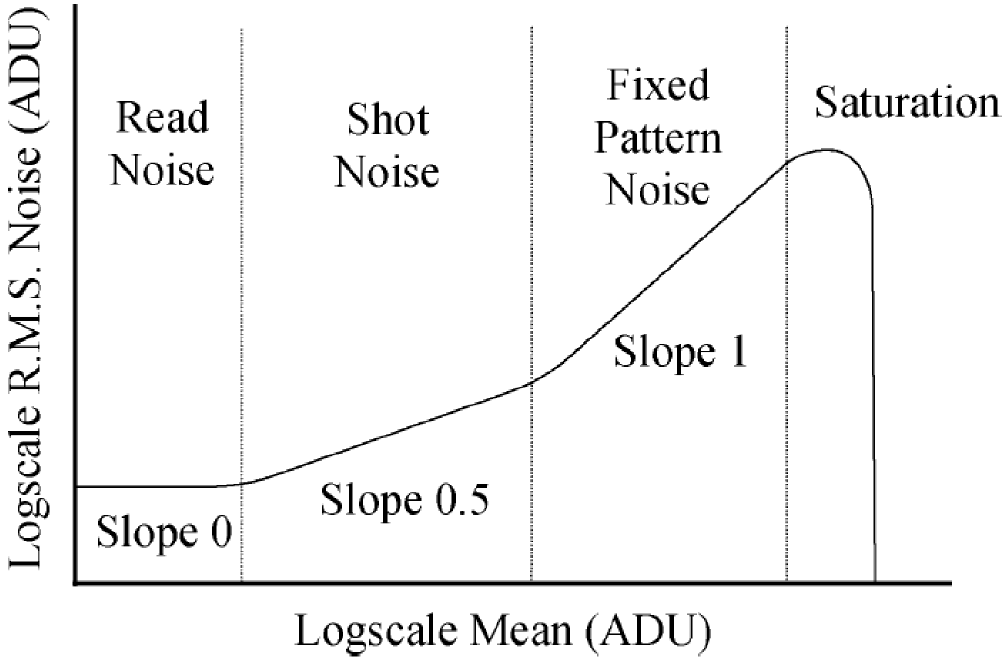
Read Noise

- Defined as any noise source encountered in imagers which is not a function of signal

$$\boxed{\sigma_{\mathrm{READ}}(P_I) = A}$$

Photon Transfer Curve

- The PTC (or Photon Transfer curve) is the most curial and important analytical technique for imaging sensors
- The rms noise is plotted as a function of average signal at different light levels (or exposure times)
- The plot is made in log-log scale



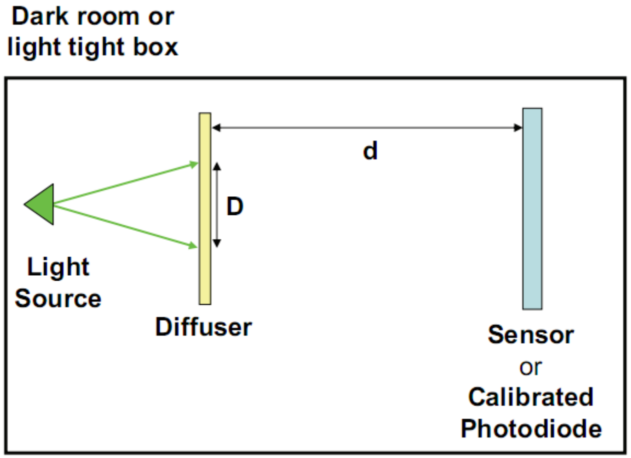
Andrew Blue PSD9 14/9/11

PTC Measurements

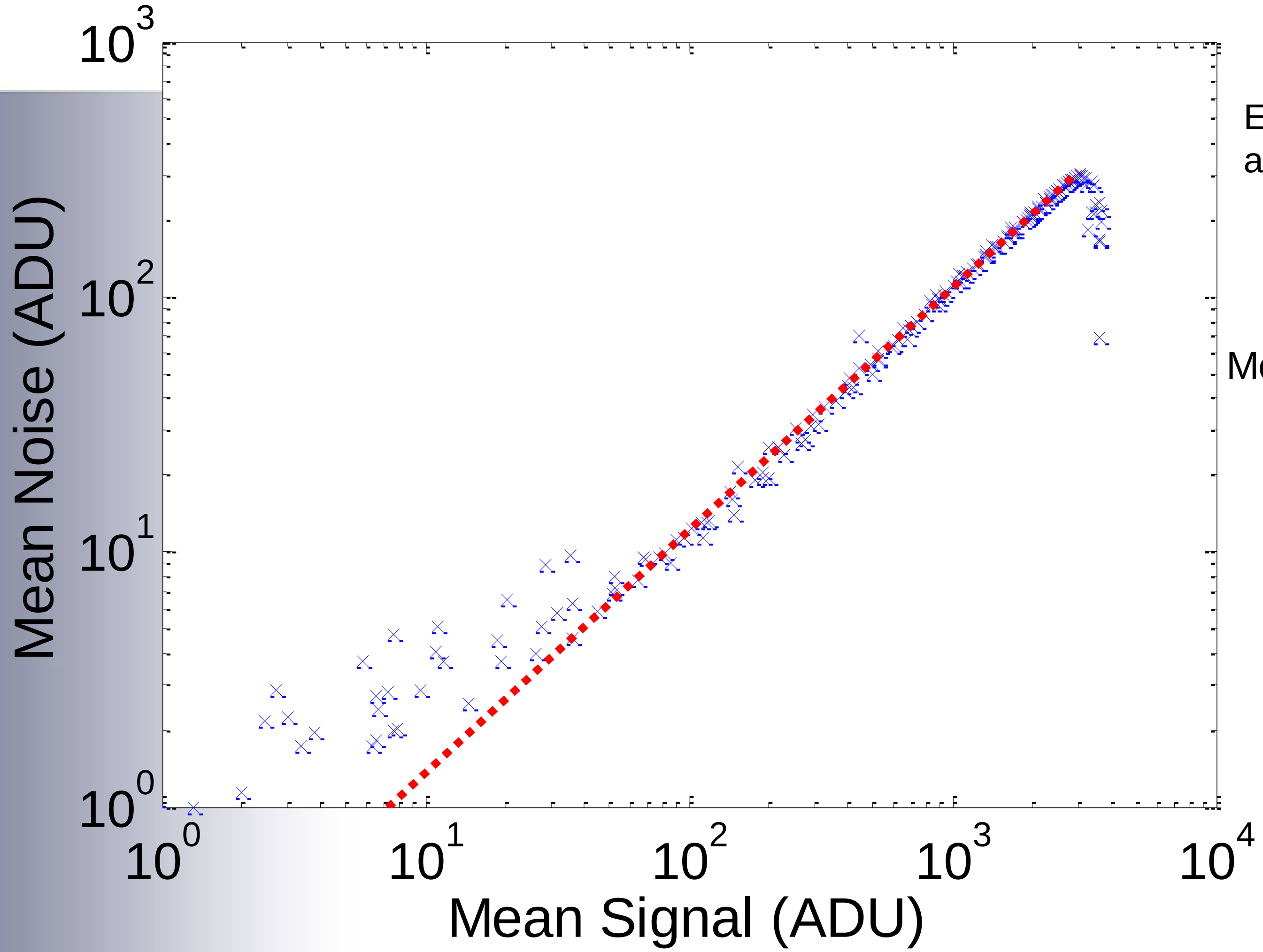
- Illuminations achieved using super-bright, narrow bandwidth LED (520nm) Coupled with diffuser produced uniform illumination (<1% dev.)
- The light intensity was varied by changing the voltage applied to the LED until saturation
- 100 Frames at each illumination stage
- Shot Noise area extrapolated from fit to calculate the Camera Gain Constant

K (e^-/DN)

'Comparison of Methods for Estimating the Conversion Gain of CMOS Active Pixel Sensors'
'SE Bohndiek, A Blue, A Clark et al **IEEE SENS J 8 (2008) pg 1733**



Lab Measurements



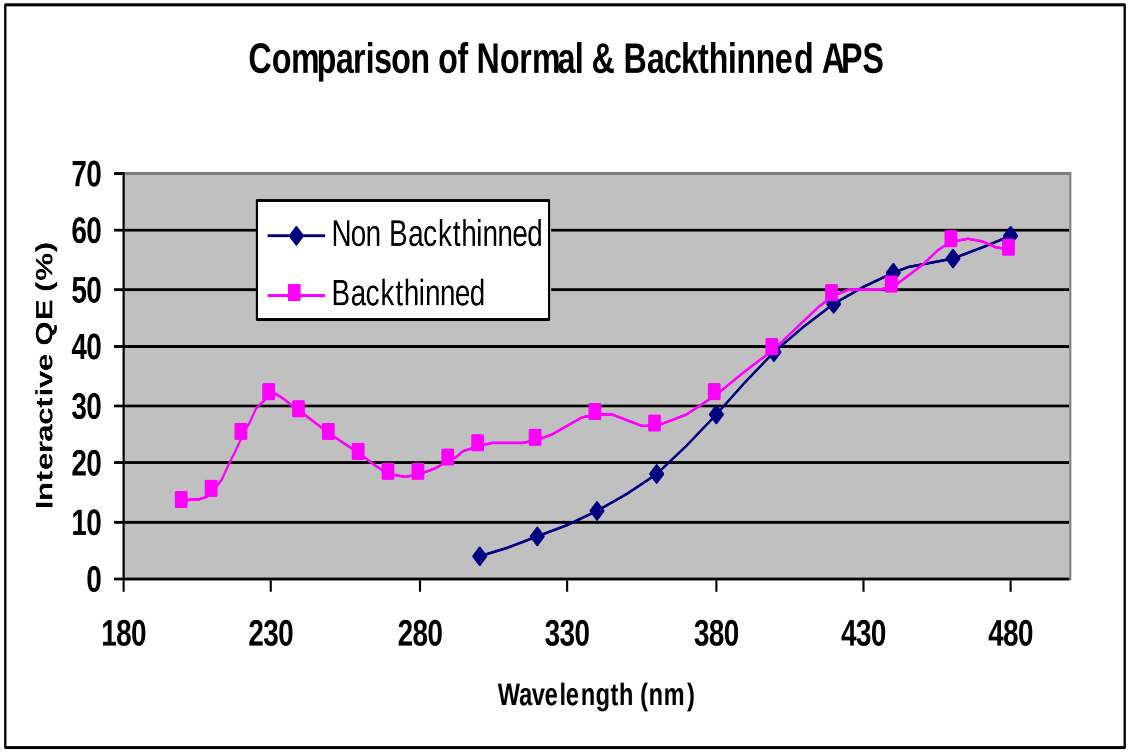
Example PTC with FPN and read noise removed

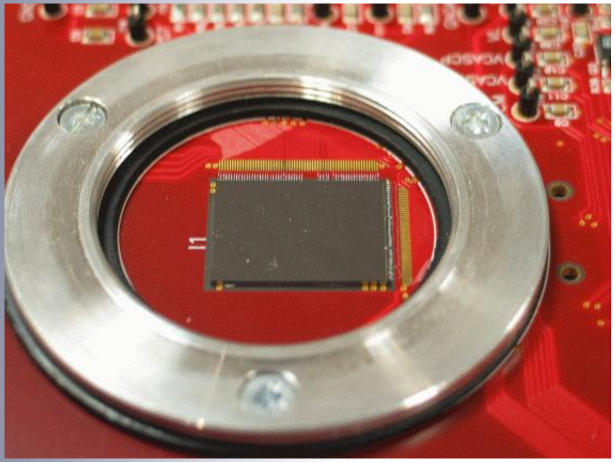
Mean Gain:

K = 7.3 e$^-$/ADU

Backthinned – QE

- Sensor used was backthinned using a mixed process of polishing, wet etch, and plasma etch
- Sensor was then flipped to allow detection from back side





- QE Improved in the low visible and UV
- “bump” at 230nm is actually beginning of absorption of UV in air

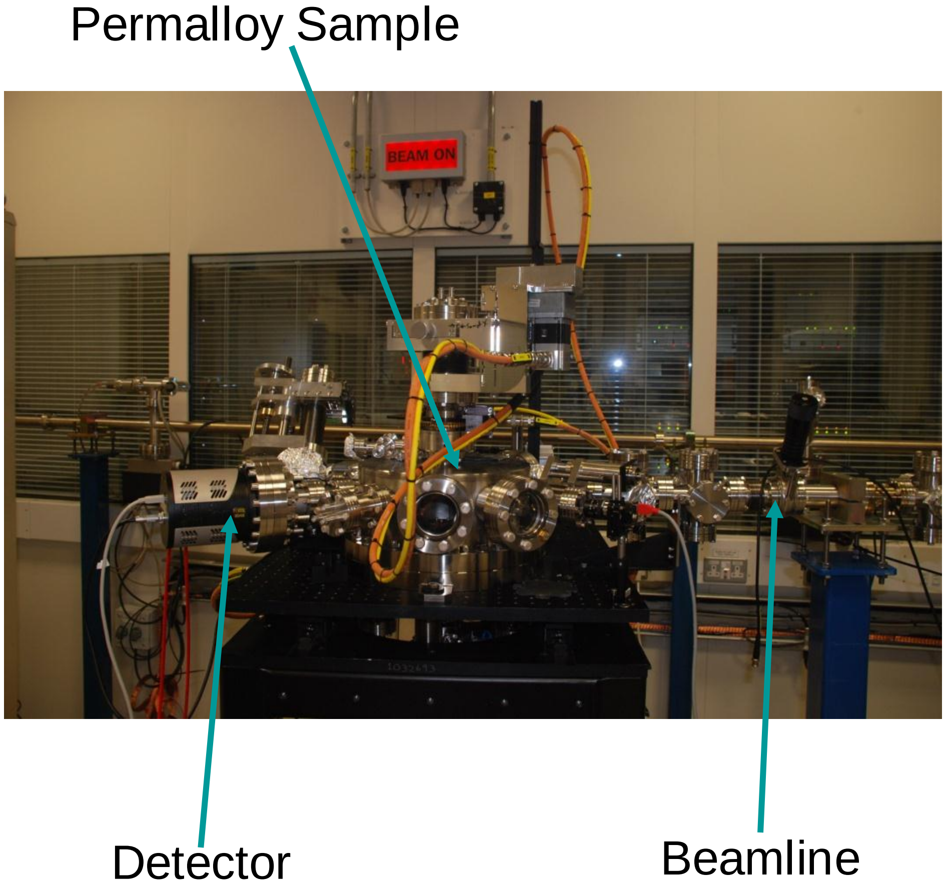
Sensors Under Test

	Princeton PIXIS CCD	Vanilla CMOS
Pixel Size	13.5 µm	25 µm
Number of Pixels	2048 x 2048	520 x 520
Total Dimensions	2.8 x 2.8 cm	1.3 x 1.3 cm
Frame Rate	0.1 – 0.003 Hz	20Hz – 0.1 Hz
Full Well Capacity	100 000 e^-	100 000 e^-
Operating Modes	Low Noise Input High Capacity Output	Analogue Readout Digital Readout

- CCD used: Princeton PIXIS-XO: 2048B
  - High Capacity and Low Noise modes for high or low flux applications.
  - Each mode has 3 different gain modes.
- APS used: Vanilla, developed by a UK funded collaboration (MI^3)
  - Backthinned for enhanced UV detection.
  - Faster frame rates

Diffraction Experiment

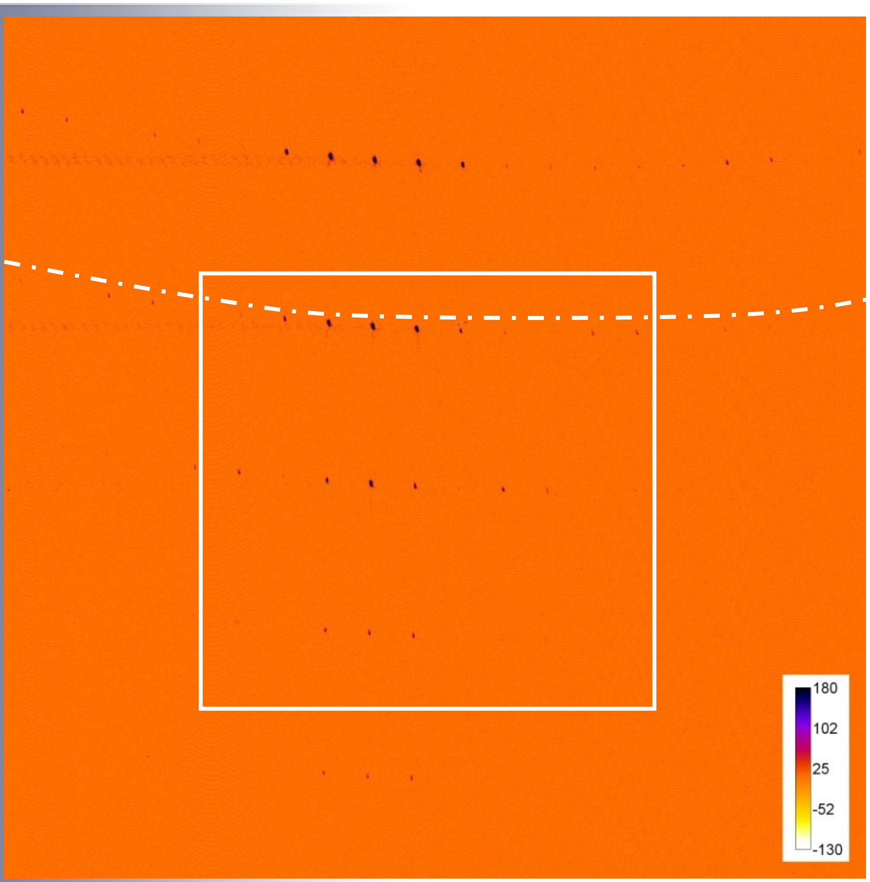
- Experiment performed at Diamond Light Source, Beamline I06.
- A permalloy sample was used to create a diffraction pattern.
  - Permalloy is a Nickel-Iron alloy, used here as a representative test sample.
- Soft X-rays (700 eV) diffracted.
- Sensor was back-illuminated and kept in a vacuum.
- CCD kept at -55°C, Vanilla cooled from 20°C to -20°C.
- Noise, Signal to Noise, Peak to Trough, Dark Current and charge collect were all measured with both sensors.



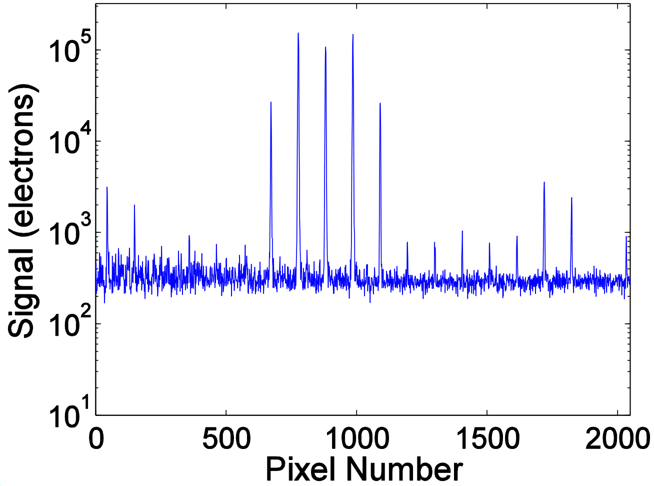
CCD Diffraction Pattern

Low Noise Mode, -55°C

10s Integration Time



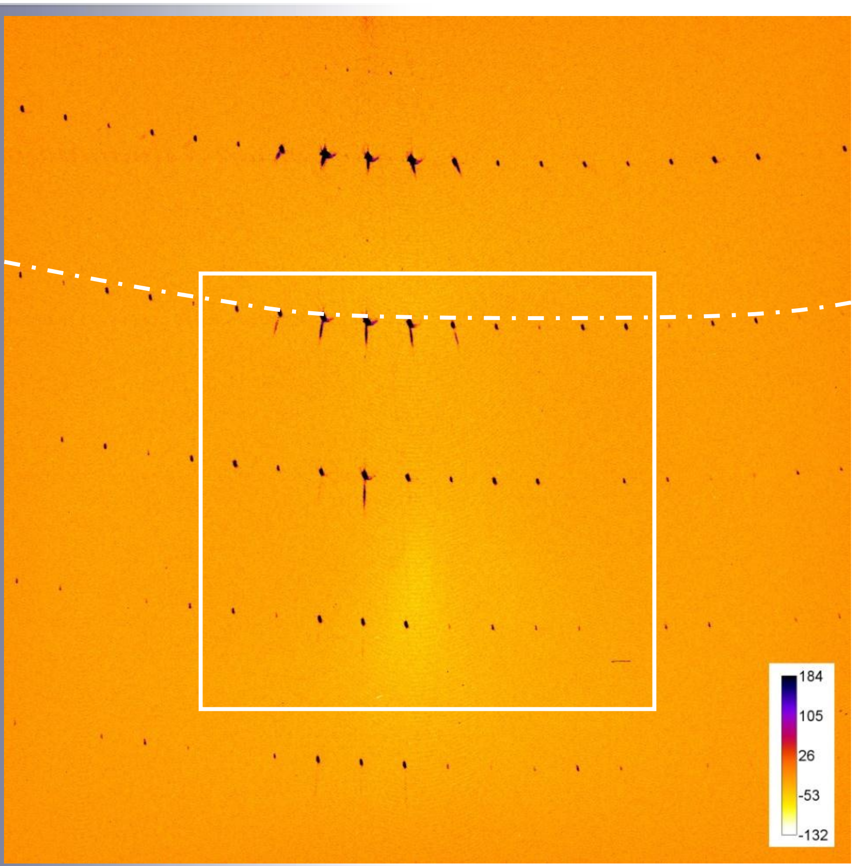
- Dashed line is where the line profile is taken from.
- Solid square indicates the area the vanilla sensor covered.
- 300s integration time shows some blooming in saturated pixels.
- Ratio of peak height to inter-peak average give a Peak-to-Trough value.



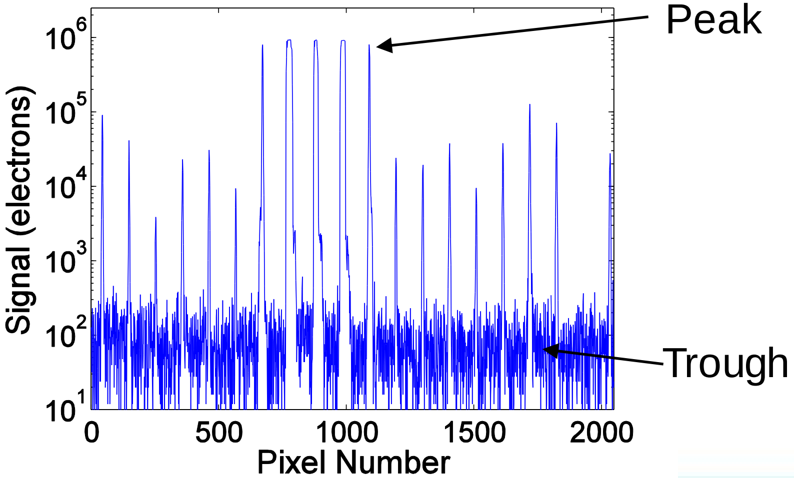
CCD Diffraction Pattern

Low Noise Mode, -55°C

300s Integration Time



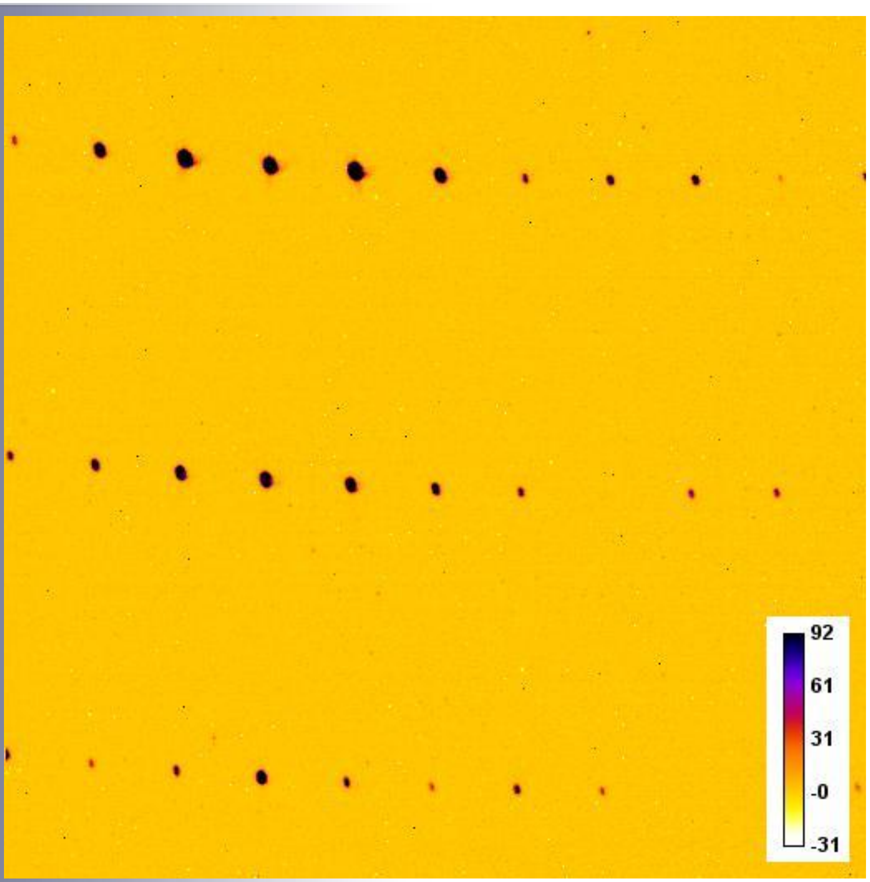
- Dashed line is where the line profile is taken from.
- Solid square indicates the area the vanilla sensor covered.
- 300s integration time shows some blooming in saturated pixels.
- Ratio of peak height to inter-peak average give a Peak-to-Trough value.



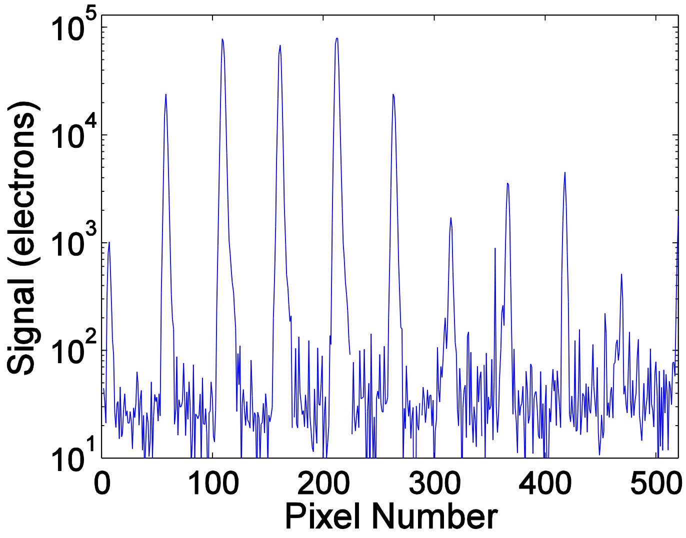
Vanilla CMOS Diffraction

Digital Mode, -10°C

10s Integration Time



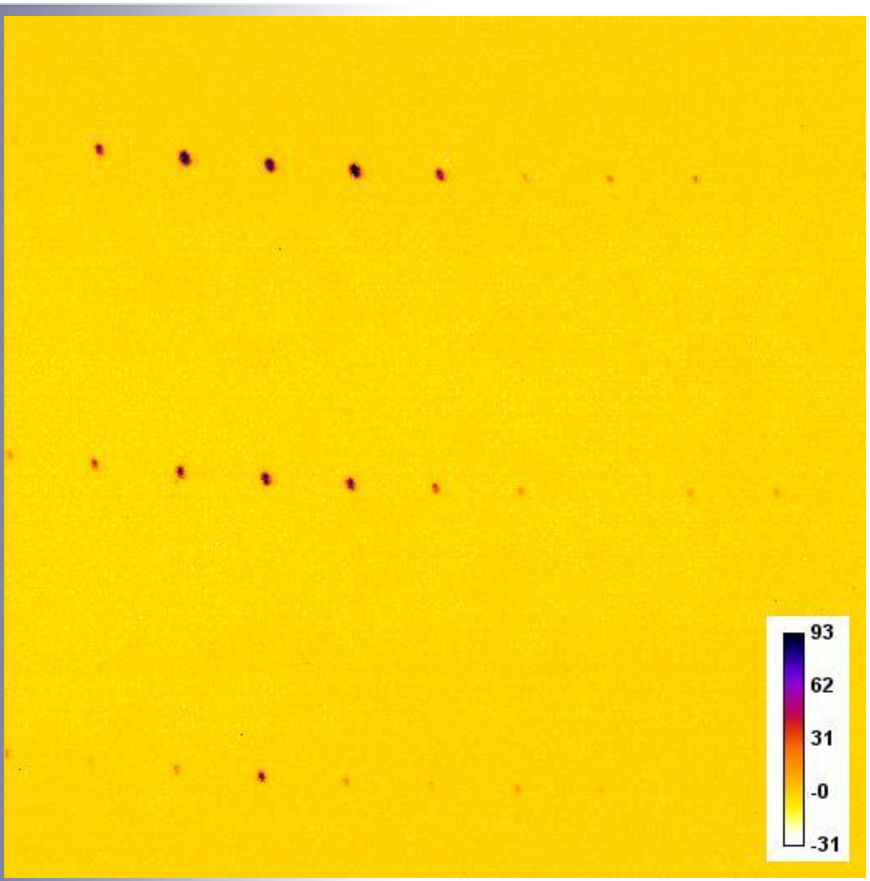
- Longest integration time shows no blooming when saturated.
- Shortest integration time can still identify all peaks.
- Relative peak heights the same regardless of frame rate



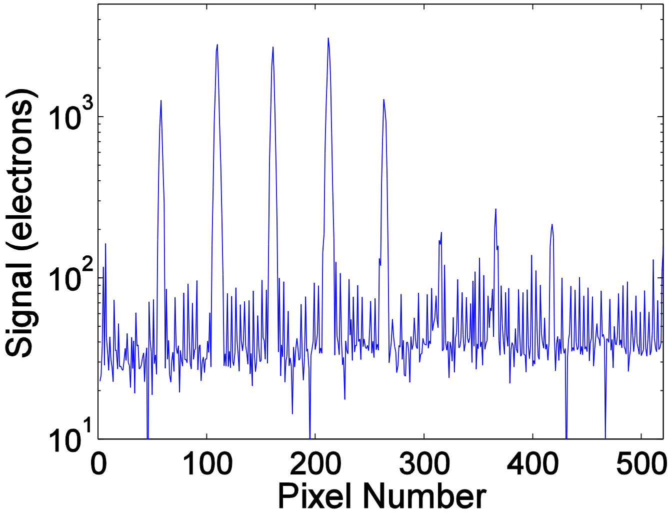
Vanilla CMOS Diffraction

Digital Mode, -10°C

0.05s Integration Time



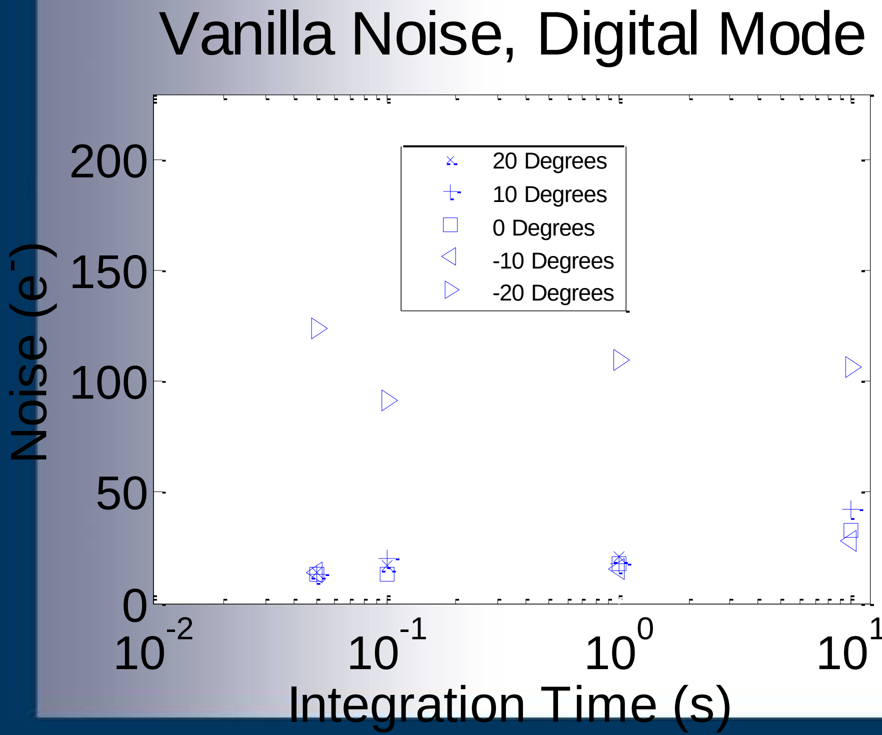
- Longest integration time shows no blooming when saturated.
- Shortest integration time can still identify all peaks.
- Relative peak heights the same regardless of frame rate

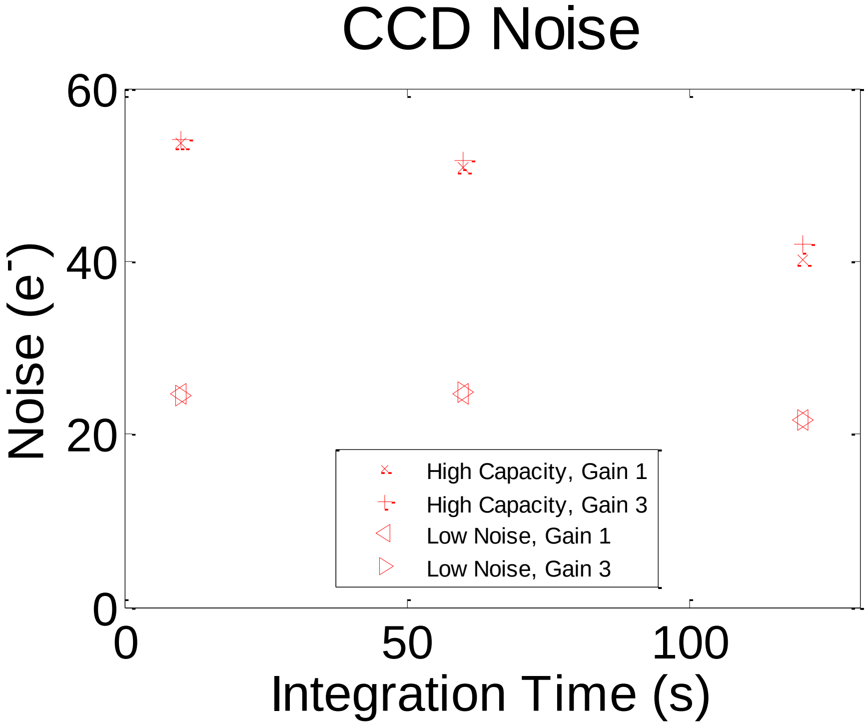


Noise

- Common Mode Noise removed via subtraction of 2 consecutive frames and pedestal subtraction.
- Statistical variation of resultant frame is Read Noise and Shot Noise.

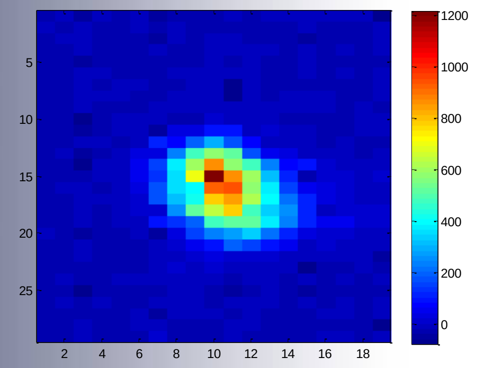
- Vanilla CMOS APS noise increases greatly at -20°C
  - Component(s) not designed for lower temperatures?

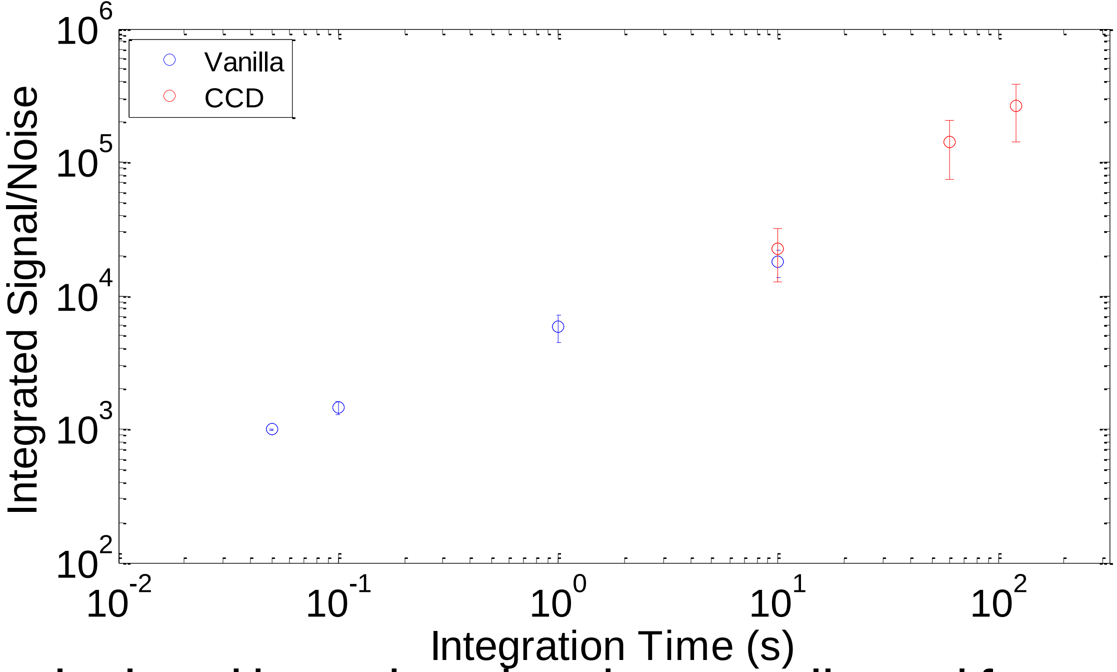




Signal to Noise

- Princeton CCD maintained at a temperature of -55°C. S/N ratios calculated then averaged for different modes.
- Vanilla CMOS APS S/N calculated at -10°C in Digital mode.





- Signal to Noise ratio calculated based on the charge collected from an unsaturated spot.
- Signal to Noise ratio increases linearly with integration time

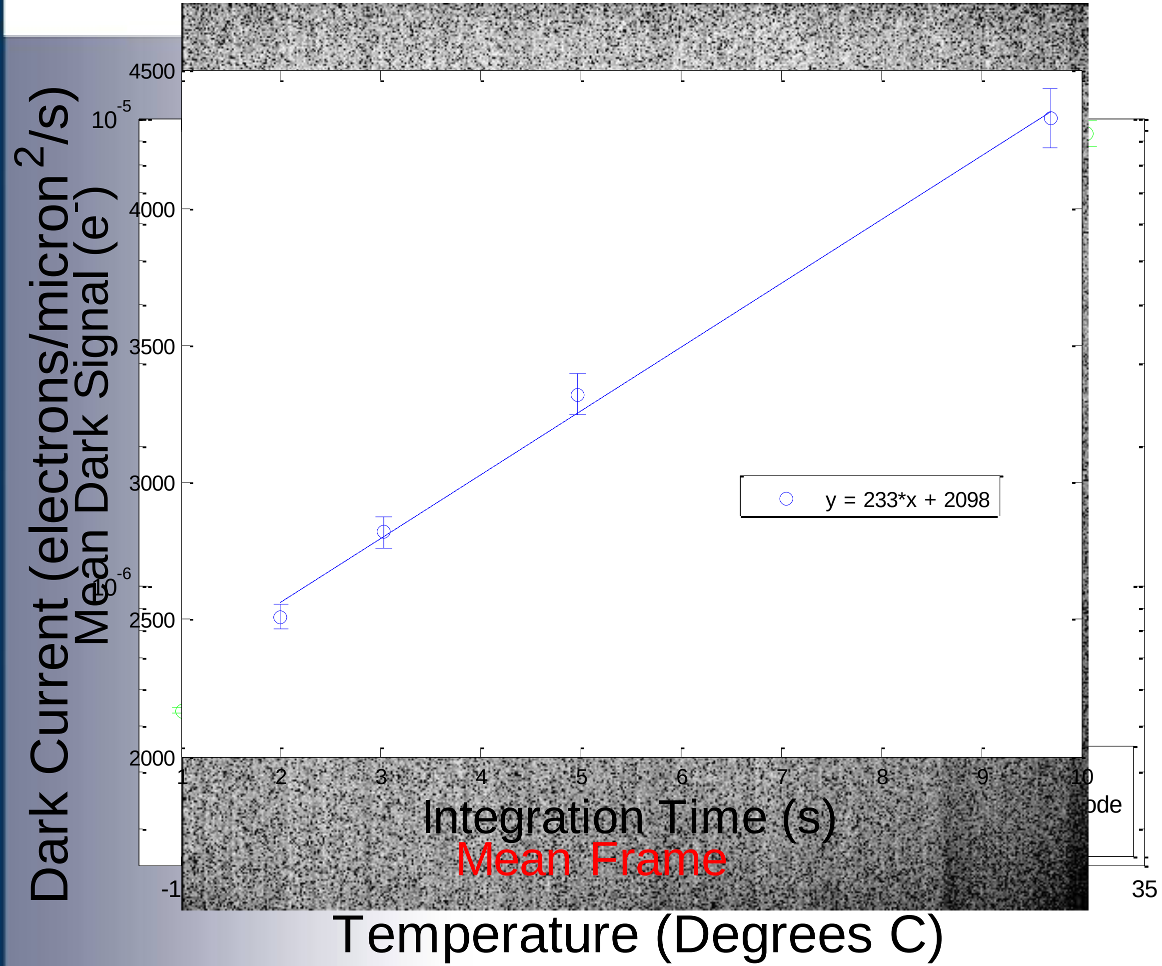
Summary of Results

	Princeton PIXIS CCD	Vanilla CMOS APS
Frame Rate	0.1 Hz – 0.003 Hz	20 Hz – 0.1 Hz (300fps ROI)
Gain	High Capacity mode – ~15e^-/ADU Low Noise mode – ~3e^-/ADU	Digital – 7e^-/ADU
Operating Temperature	-55°C	-10°C
Read Noise	HC mode - 50e^- LN mode - 20e^-	28e^-
Peak to Trough	$10^2 – 10^4$	$10^1 – 10^3$
Signal to Noise	$10^4 – 10^6$	$10^3 – 10^4$

Conclusions

- Vanilla CMOS detector, at -10°C, showed comparable noise performance to the Princeton CCD.
  - Maximum noise of 50e$^-$ for both CCD and 28e$^-$ for Vanilla CMOS APS
- At comparable frame rates (0.1Hz), both detectors showed similar S/N levels
- Charge collected increases linearly with integration time.
- Further research remains to be completed on characterising the Region of Interest and higher frame rates
- Future **specially designed** CMOS APS could have kHz frame rates with a comparable S/N.

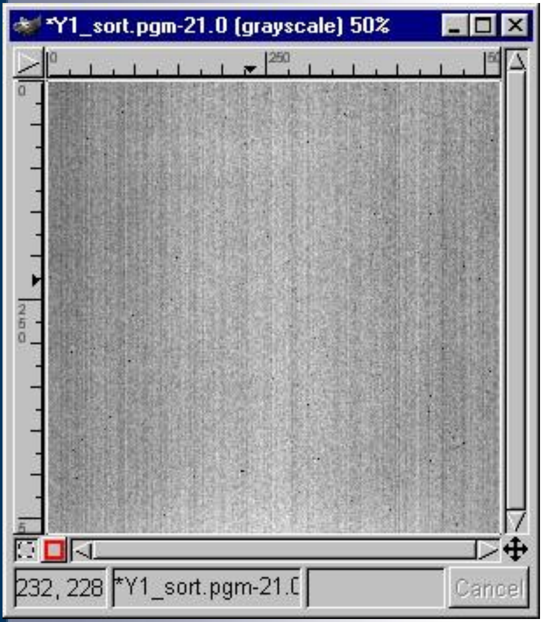
Dark Current



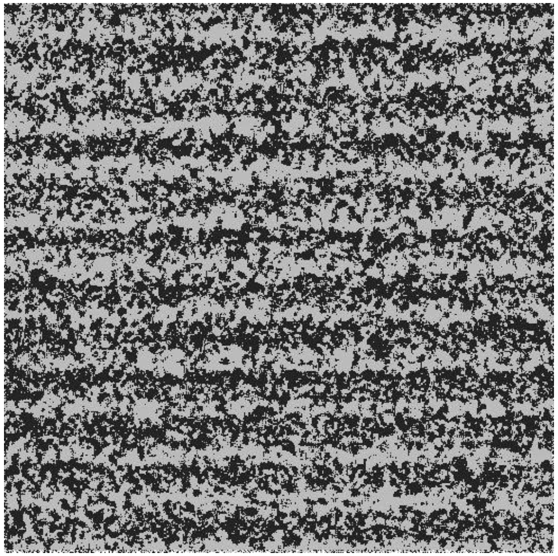
- Dark images taken at a series of frame rates, for each readout mode and temperature.
- Gradient of mean dark signal against integration time gives dark current.
- Dark current should be linear on a log-scale.
- Digital mode’s on-chip electronics affected by cooling.

Imager Noise

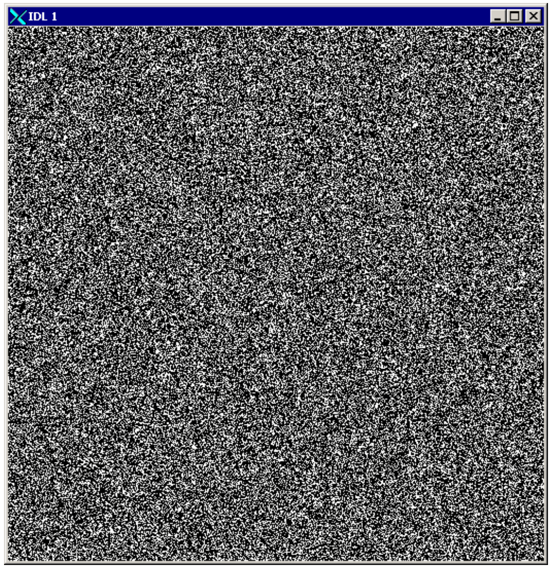
$$\sigma_{\mathrm{TOTAL}} = (\sigma^2_{\mathrm{SHOT}} + \sigma^2_{\mathrm{FPN}} + \sigma^2_{\mathrm{READ}})^{1/2}$$



Total noise image



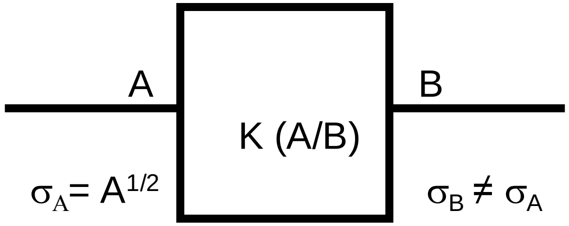
Fixed noise



Statistical noise

Camera Gain Constant

- For a ‘black box’ camera system whose input exhibits shot noise characteristics



- A sensitivity constant *K(A/B)* relates and transfers output signal and noise measurements to the input. In other words

$$A = BK(A/B)$$

and

$$\sigma_A = \sigma_B K(A/B)$$

- Substituting the above 2 equations into $\sigma_A = A^{1/2}$ and we get

$$K(A/B) = B/\sigma^2_B$$

- Input to an imaging sensor is measured in electrons (e^-), and the output is measured in Digital Numbers (DN)

Camera Gain Constant

$$K(A/B) = \frac{B}{\sigma_B^2}$$

- Input to an imaging sensor is measured in electrons (e^-), and the output is measured in Digital Numbers (DN)

$$\boxed{K(e/DN) = \frac{DN}{\sigma_{DN}^2}}$$