SCOTT automation + robotics

UNIVERSITY OF SASKATCHEWAN

MONASH University

Detectors:
Things you should know

Rob Lewis

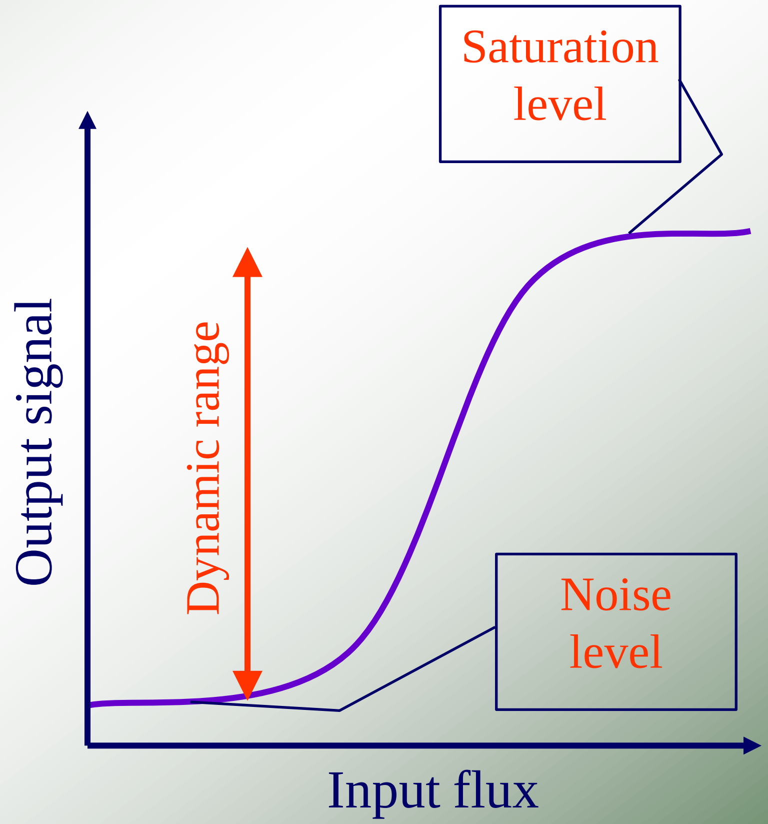
Scott Automation and Robotics

Medical Imaging and Radiation Sciences, Monash University

Medical Imaging, University of Saskatchewan

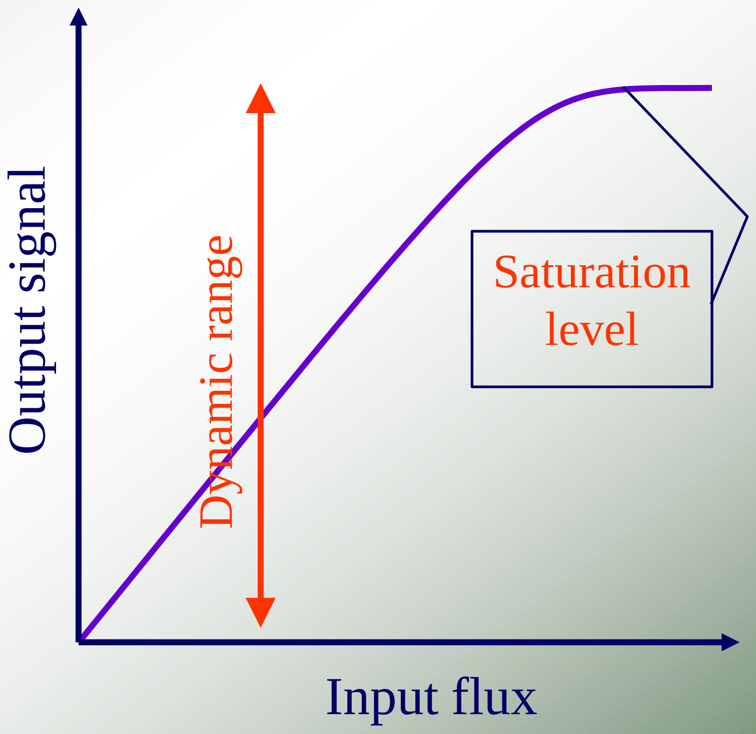
Integrating Detectors

- Mode
  - Measures deposited energy at end of integration period
- Characteristics
  - High input flux capability
  - Read noise dominates at low signal ("fog level")
  - Dead time between frames
  - 2×20 keV phts = 1×40 keV photon i.e. Cannot perform simultaneous spectroscopy and positioning
  - Examples: Image plates, CCDs



Counting Detectors

- Mode
  - Detects every particle as it arrives. Only active pixels read
- Characteristics
  - Quantum limited, Detector noise often negligible
  - No dead time between frames
  - Can measure position and energy simultaneously
  - Limited input flux capability
  - Examples: Geiger counters, Pilatus, Scintillators



Big CMOS


Gpixel INC.
GMAX3005
150 Megapixels Full-Frame CMOS Image Sensor - GMAX3005

Specifications

Gpixel INC.

GMAX3005

SENSOR SPECIFICATIONS

Photon-sensitive area	165mm(H) x 27.5mm(V)	SNR Max	43dB
Pixel size	5.5µm×5.5µm	Dark noise	3.94e-
Resolution	150MP - 30,000×5,000	Dark current	<10e-/s/pix (32° C)
Shutter type	electronic rolling shutter	Dynamic range	67dB (Intra-scene)
ADC	16bit	Dynamic range	75.4dB
Main clock rate	20MHz ~30MHz	Sensitivity (PGA=5.6x)	255DN/nJ/cm^2
Frame rate	10fps @ full frame	Full well charge	23000 e-
Data rate	24Gbit/s @10fps	Output interface	120 LVDS pairs
Supply voltage	3.3V / 1.8V	Operating temperature	-55° C ~ $+85^{\circ}$ C
Max Power	2.5W	Package	395 pins PGA

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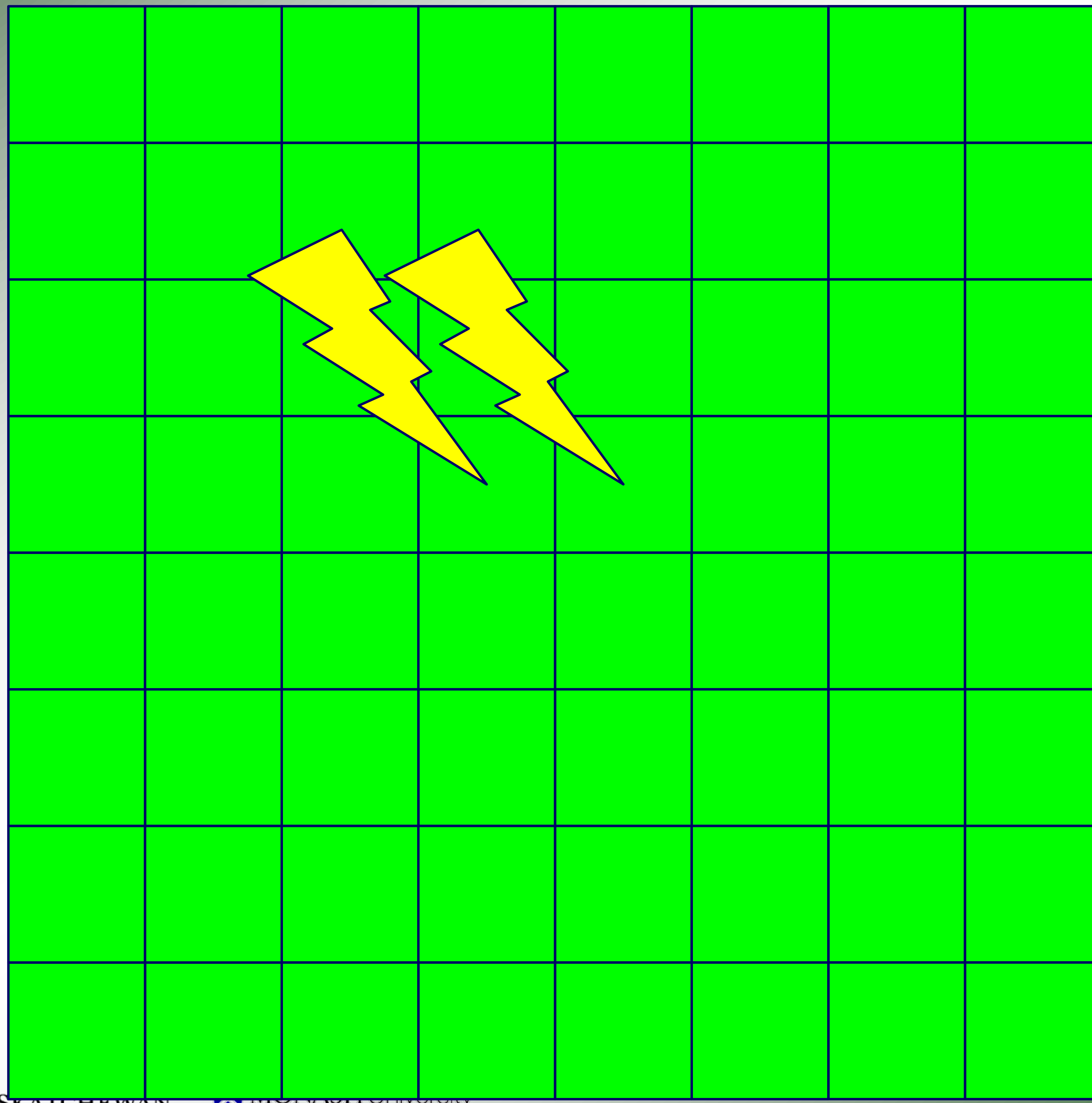

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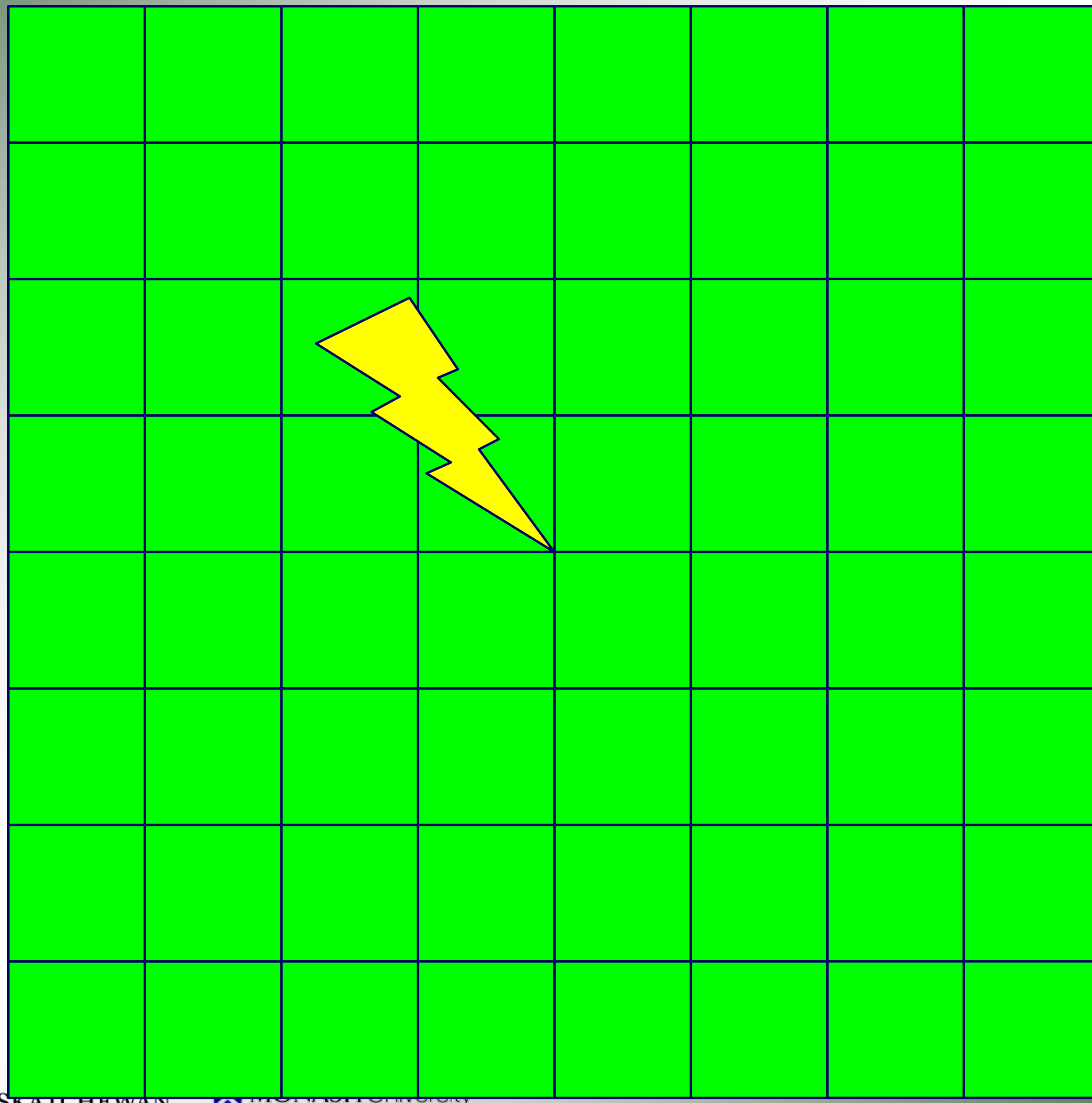
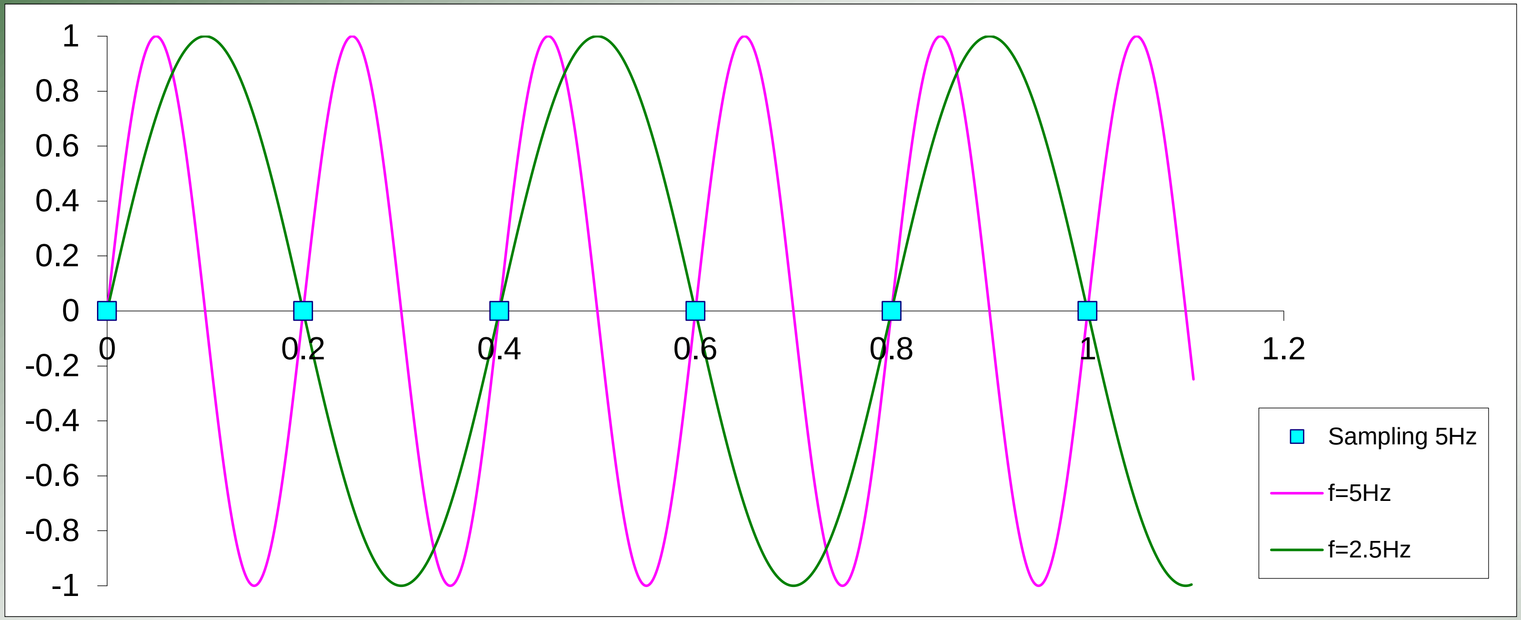
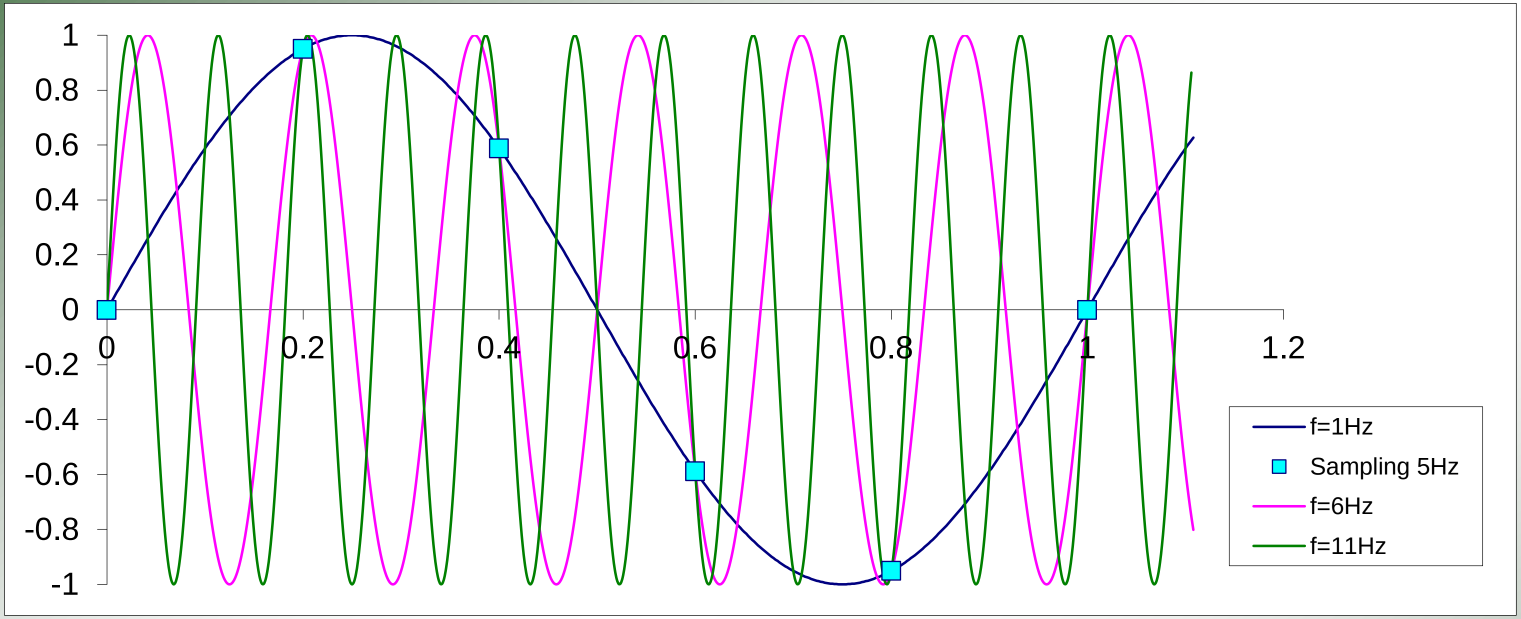


Sampling



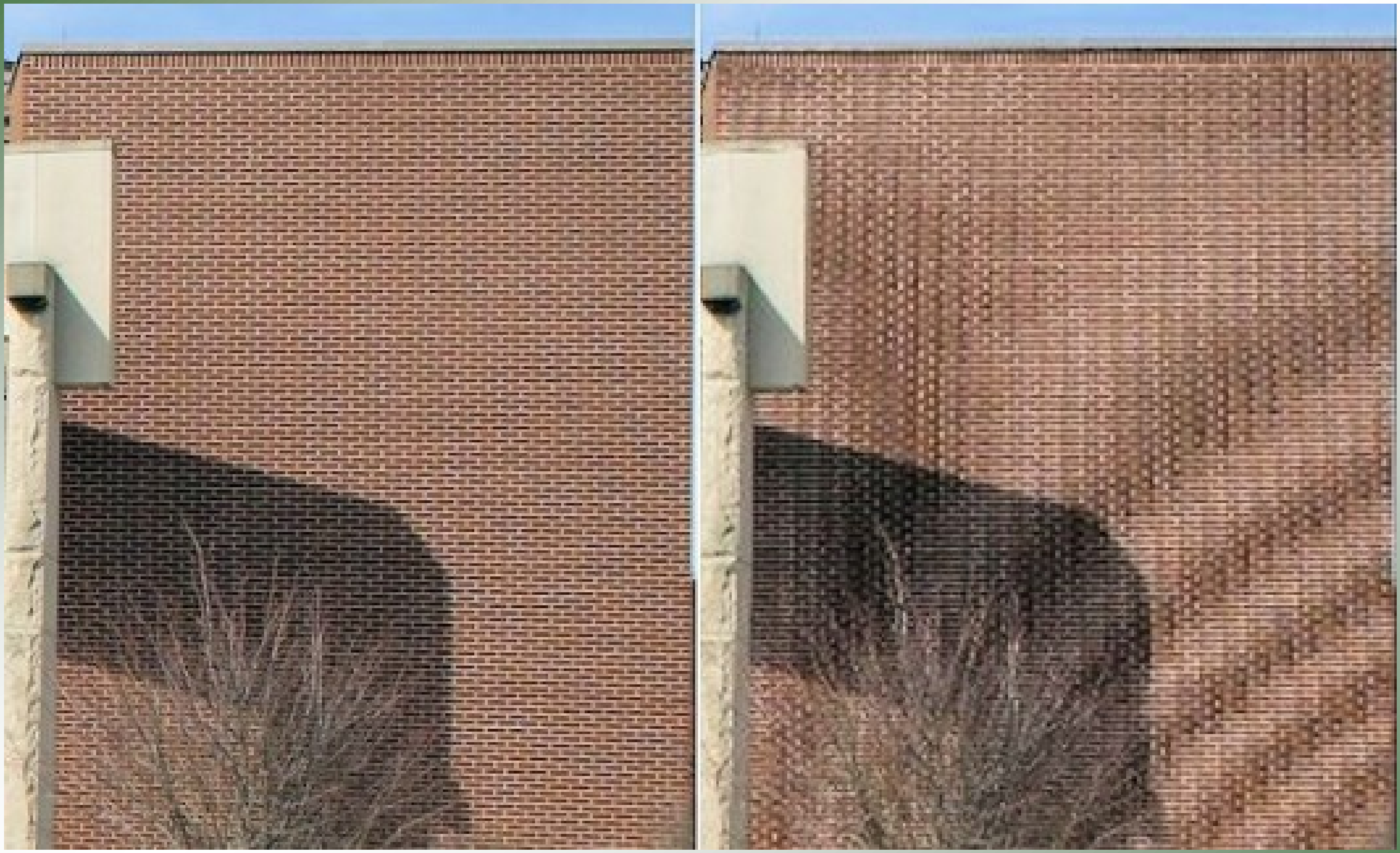
- Shannon's Theorem and Nyquist Criterion
  - The highest frequency that can be 'measured' is HALF the sampling frequency

Aliasing



- If the input is not band limited to frequencies less than $f_s/2$, then aliasing will occurs at frequencies $f \pm nf_s$
  - where f = signal frequency, fs = sampling frequency, n = integer
- If you have 100µm pixels, the very best spatial resolution that you can expect (in the absence of noise) is 200µm
- In any real system > 200µm
- And that is all assuming NO DISTORTIONS!!

Aliasing



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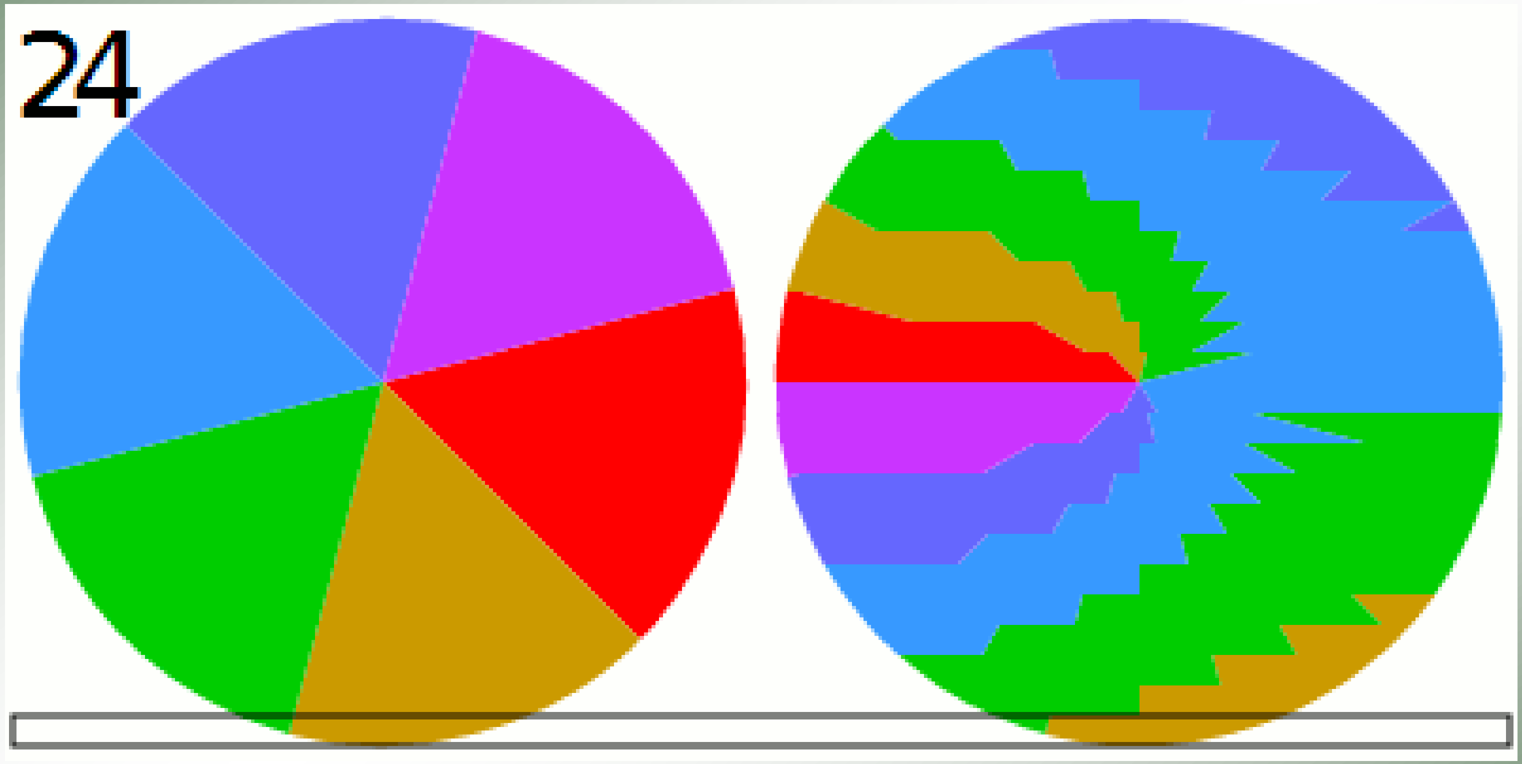
Electronic Rolling Shutter



https://en.wikipedia.org/wiki/Rolling_shutter

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Data Rates

- 120 LVDS pairs at 200Mbps = 24Gbps
  - LVDS = Low Voltage Differential Signalling
- Interfaces
  - USB2: 480 Mbps
  - USB3: 5 Gbps
  - USB3.1: up to 10 Gbps???
  - SATA III: 6 Gbps
  - Thunderbolt 2: 10 Gbps
- Disk write speeds
  - HDD: 200 Mbps
  - SSD: 530 Mbps
- So 45 SSDs in parallel required to store data!!!!

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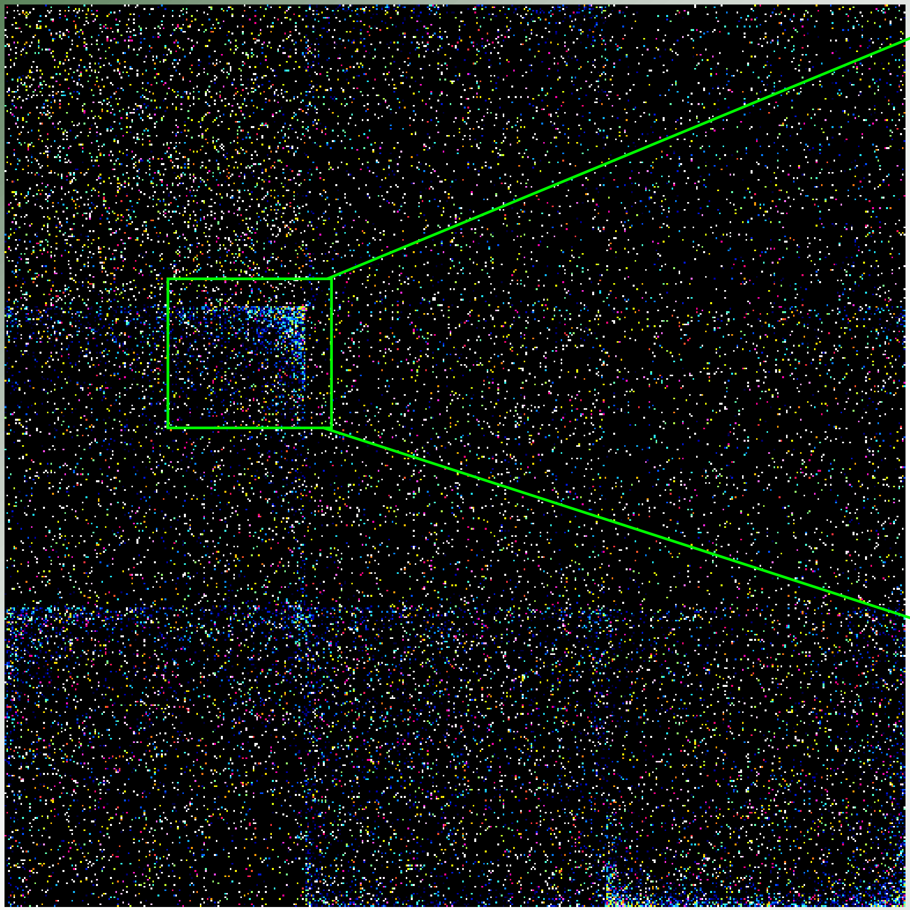
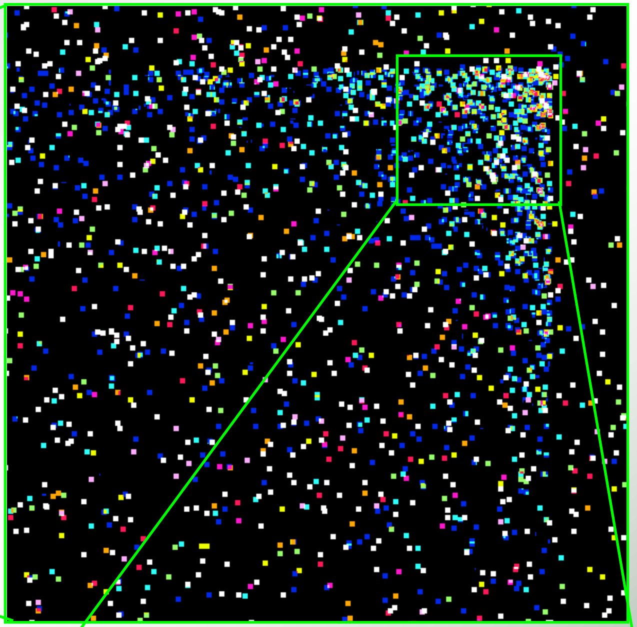
Dark Current

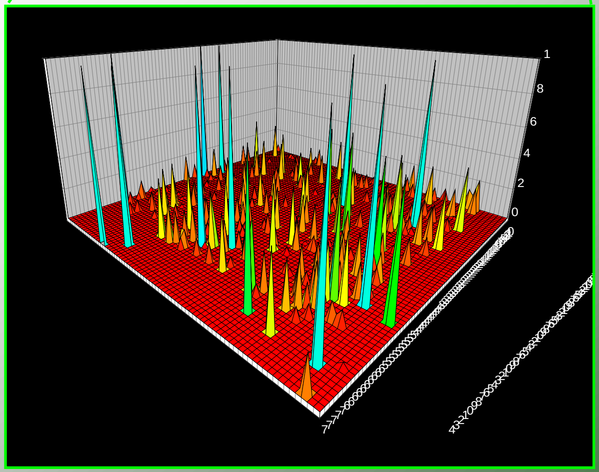
- Dark current is the signal produced under zero illumination
- Dark noise is a measure of the fluctuations in dark current
- Dark noise sets the minimum detectable signal

Dark Current



Pixels above the 0.2 photons pix^{-1} specification





Number failing 2 measurements 5-2000s

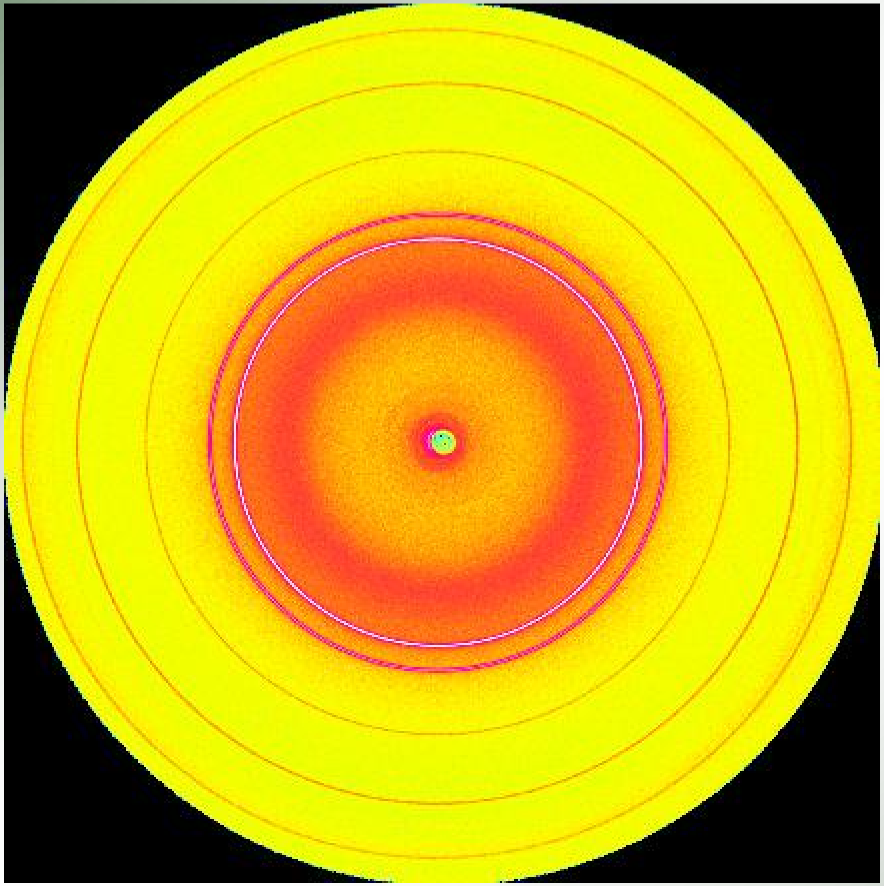
Mean	44764	0.47%
Min	40822	0.43%
Max	48706	0.52%

nb. 14300 pixels not common to both

dpiX Flashscan 30 PaxScan 4030

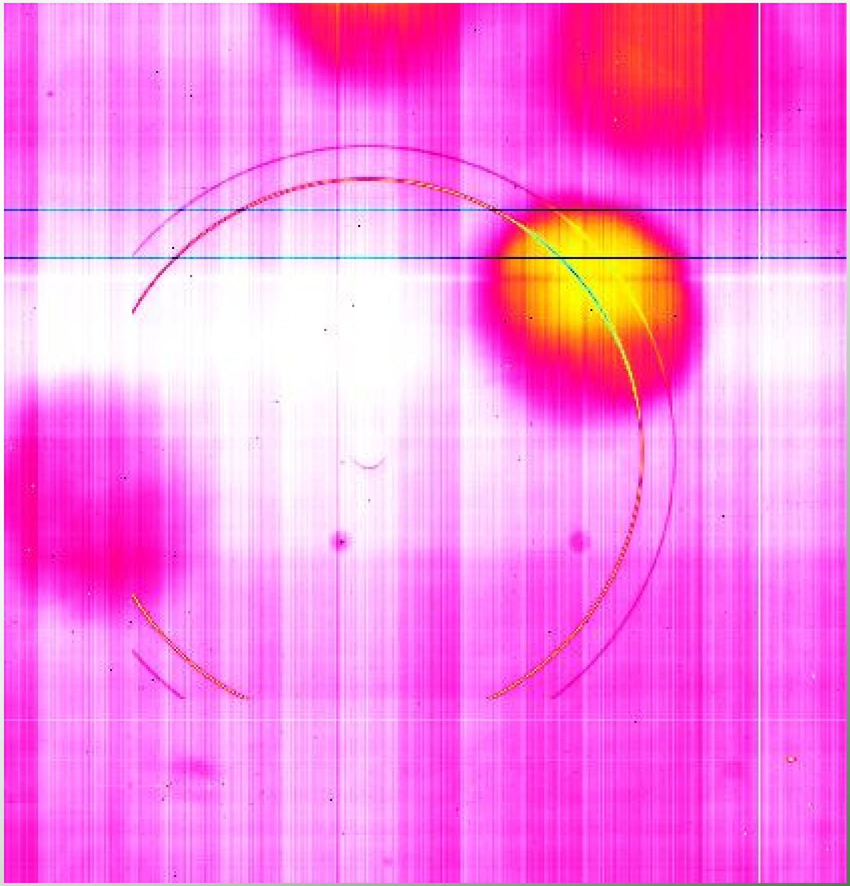
Flashscan 30 - Performance

Mar Image Plate



t_{int}=30s

Flashscan-30



t_{int}=190s

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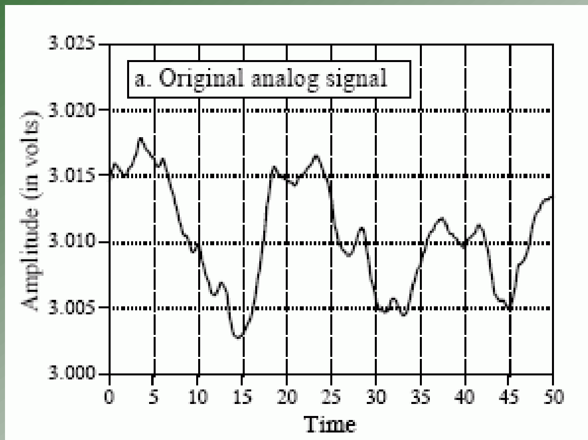
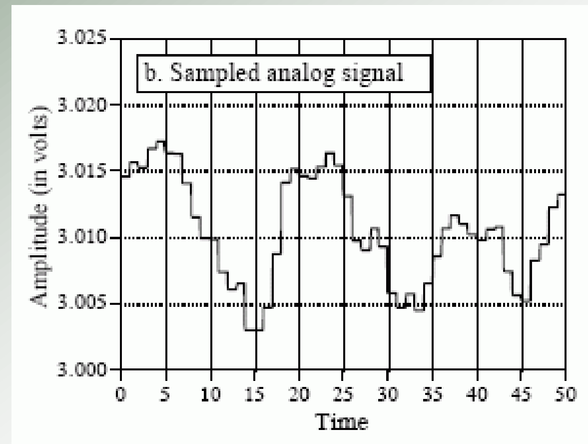
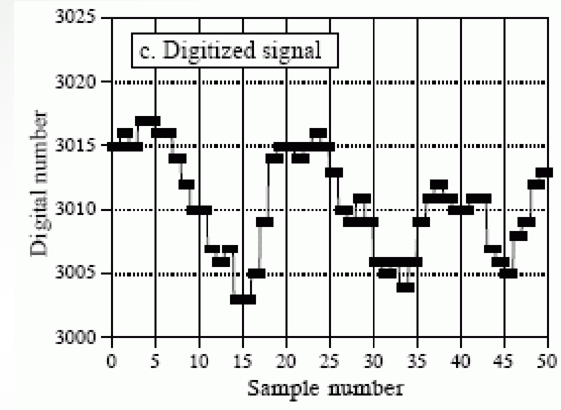
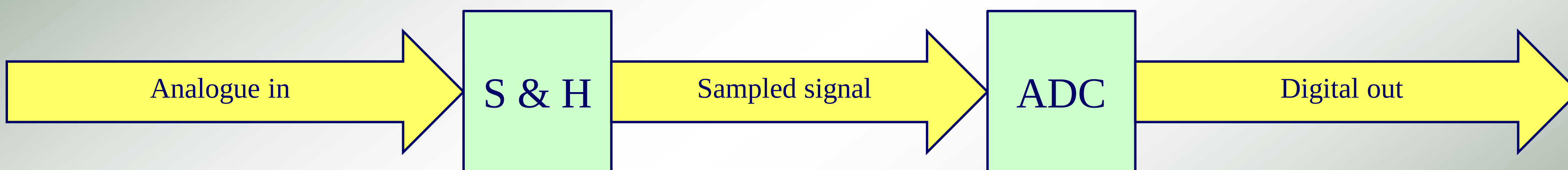
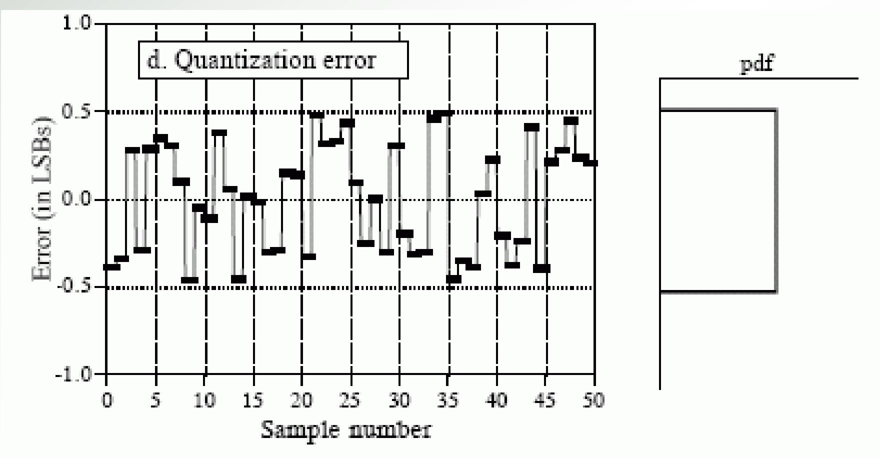
Quantisation Error











- Quantisation errors are ±½ LSB
- Quantisation errors look like random noise and can be treated as such

http://www.dspguide.com/ch3/1.htm

ADC Resolution and Noise

- Max noise is ±½ LSB
- Standard deviation $\sigma = \left({}^{1}/_{\sqrt{12}}\right) LSB$ (Uniform pdf)

nBits	**8**	**10**	**12**	**16**
nLevels	256	1024	4096	65536
Quantisation error (%)	0.113	0.028	0.007	0.0015
Dynamic Range (dB)	48	60	72	96

- More bits usually means slower and more expensive
- Dynamic range is max signal divided by min signal
- Number of bits sets max dynamic range
- Often expressed in dB where dB = 20 $\log_{10}$ (Ratio)

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- All these are interrelated

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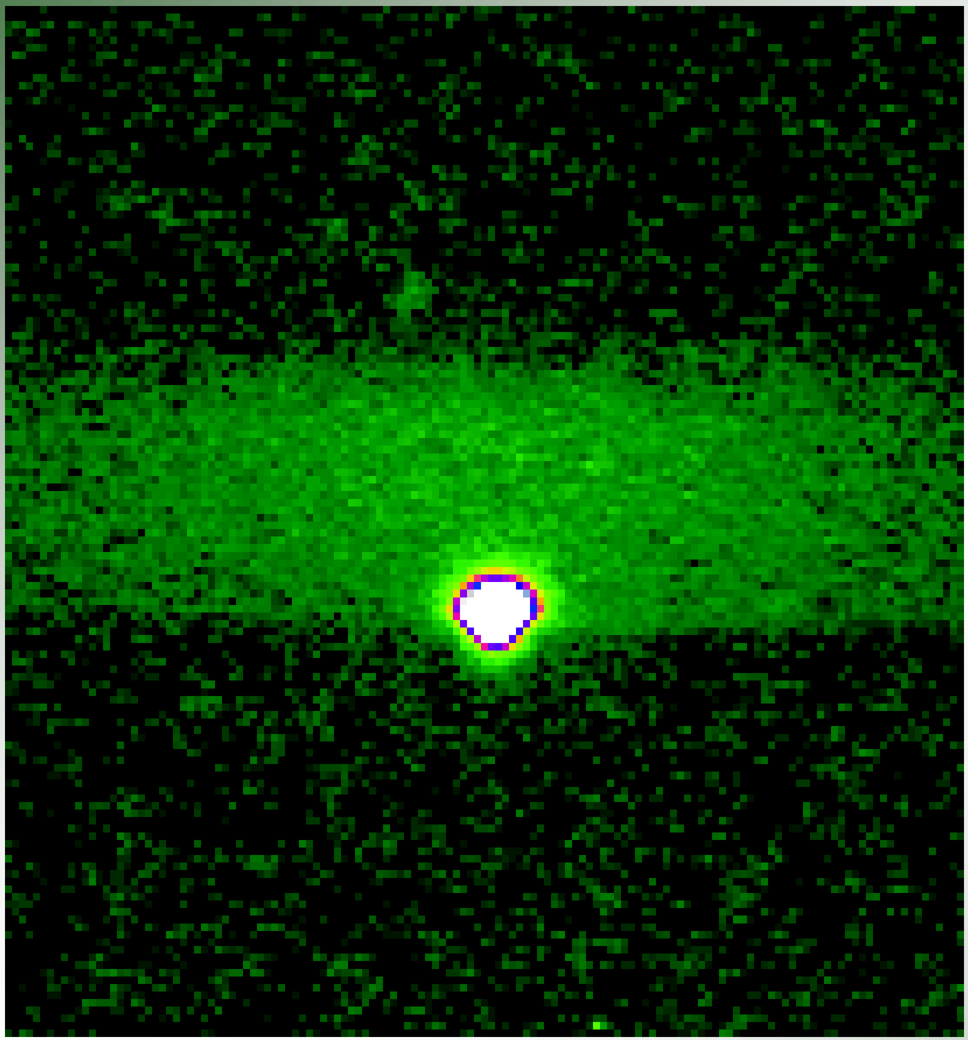
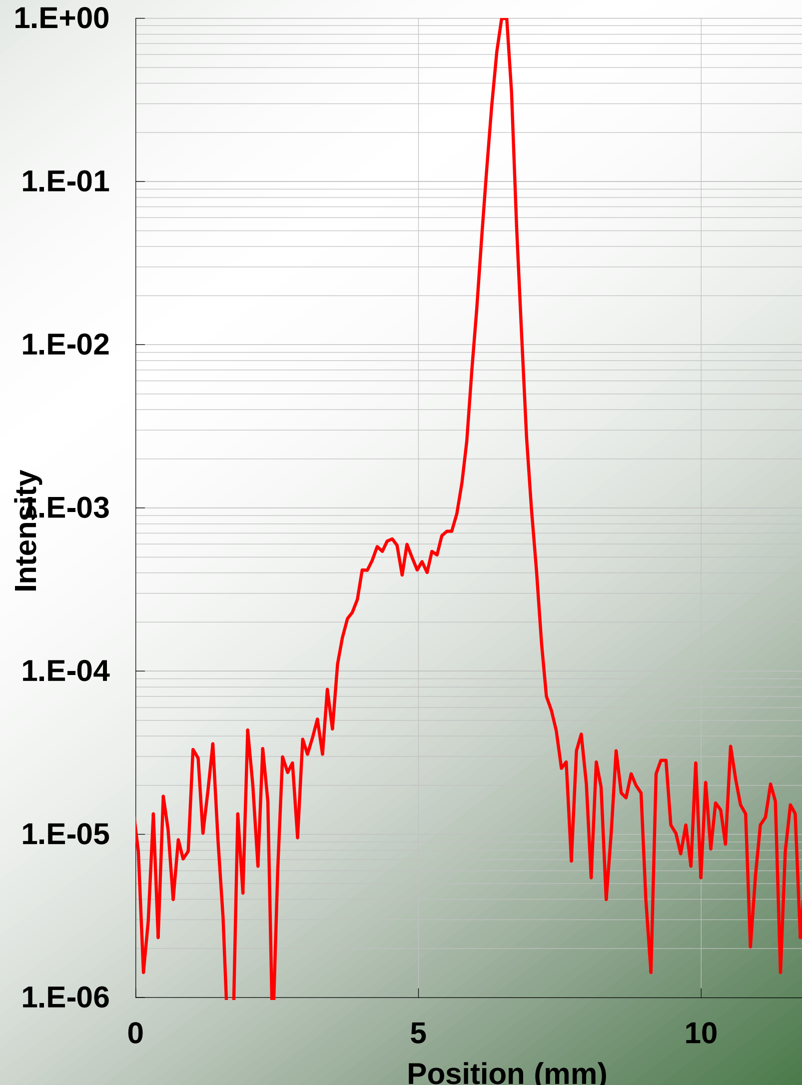
IPlate Single Peak PSF





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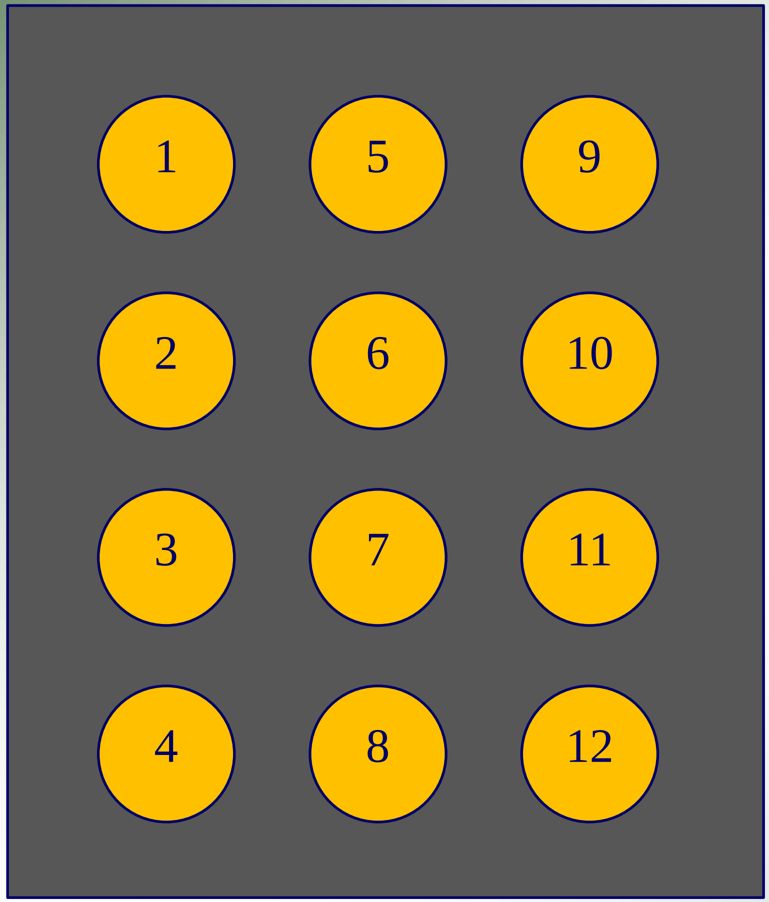
Dynamic Range

- dB = 20 $\log_{10}$ (Ratio)
- So the ratio = $10^{dB/20}$

- Quoted intra scene DR = 67.0dB = 2339
- Quoted inter scene DR = 75.4dB = 5888

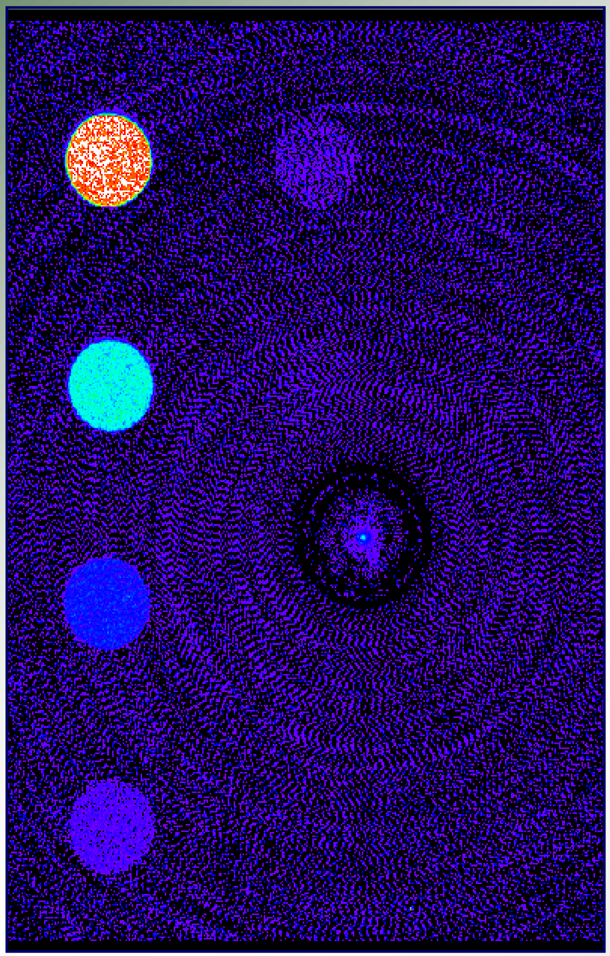
- Why the difference?

Intensity Test

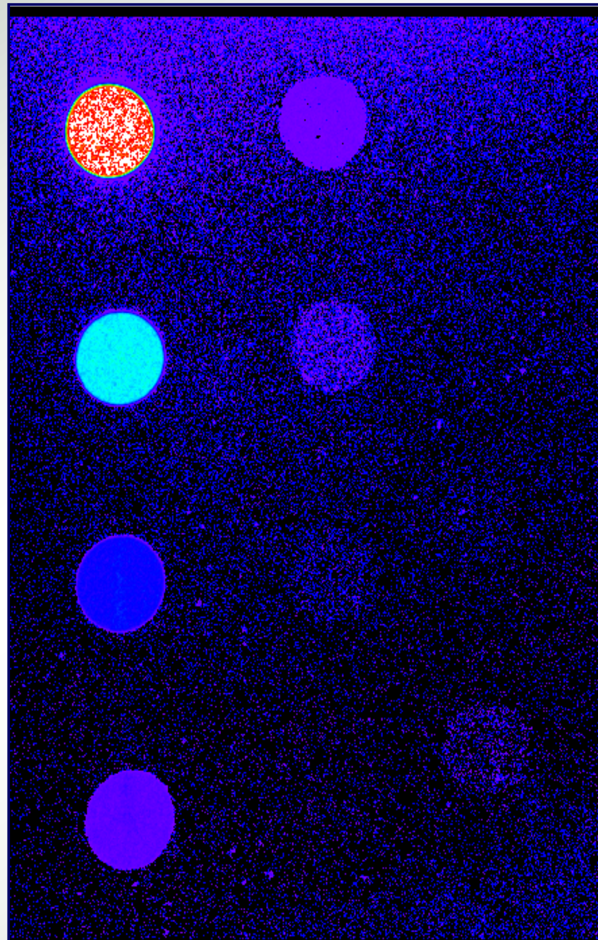


Graded Absorber Comparison

Mar Image Plate



ESRF-Thompson IIT / CCD



Daresbury MWPC

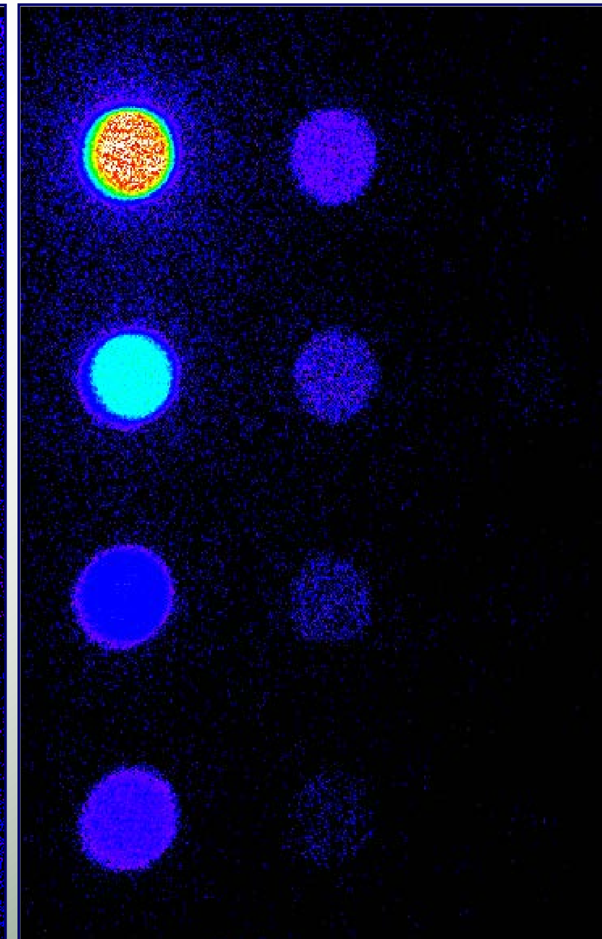
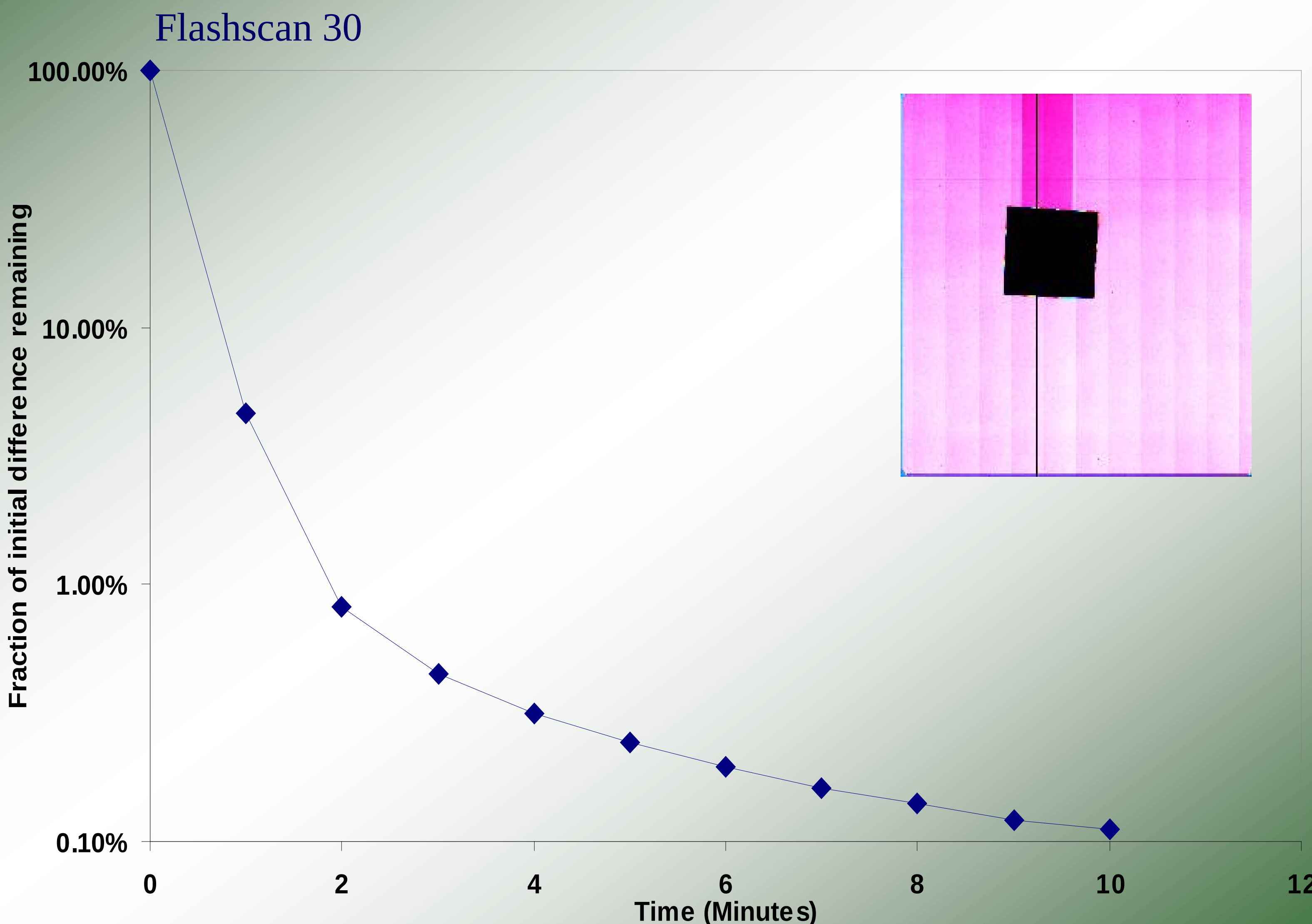


Image Lag



Flashscan 30
Fraction of initial difference remaining
100.00%
10.00%
1.00%
0.10%
0
2
4
6
8
10
12
Time (Minutes)

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Well Depth

- Quoted well depth is 23000e^-
- At 3eV / e^- hole pair a pixel will saturate with 8 x-ray photons of 10keV
- Suddenly dynamic range is 8!
- Indirect detection is crucial to increase dynamic range
- Use a phosphor

Radiation Damage

- Indirect detection is important for another reason……
- Medipix
  - Radiation damage at 40Gy $=1.3\times10^{10}$pht/mm^2 in the readout chip
  - Strong diffraction spots ~ 10^6 phts/mm^2/s
    - Chip destroyed in ~ 8hours
  - Direct beam (10^{10}–10^{13} photons/mm^2/s)
    - Chip destroyed in less than a second

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Sensitivity for Optical Photons

- 550nm photon $E = {}^{hc}/_{\lambda} = 3.6\times10^{-10}$ nJ
- So 1 nJ equates to 3×10^{9} photons
- 1 cm^2 = 3305785 pixels
- So 1 nJ/cm^2 = 908 phts / pixel
- Quoted Sensitivity is 255 $DN/nJ/cm^2$
- 1 Digital Number = 0.3 optical phts / pixel

- But what does this mean for x-rays ?

Sensitivity

- Ideal sensitivity is 1 DN per x-ray photon detected
- Many factors beside chip sensitivity
  - Conversion x-rays to light (1 photon/30eV typical)
  - Ability for light to escape phosphor
  - Transfer light from phosphor to chip, lens, FOT
    - Lenses poor f1.4 = 10% transmission (no reflections)
    - Fibre optic better but distortions

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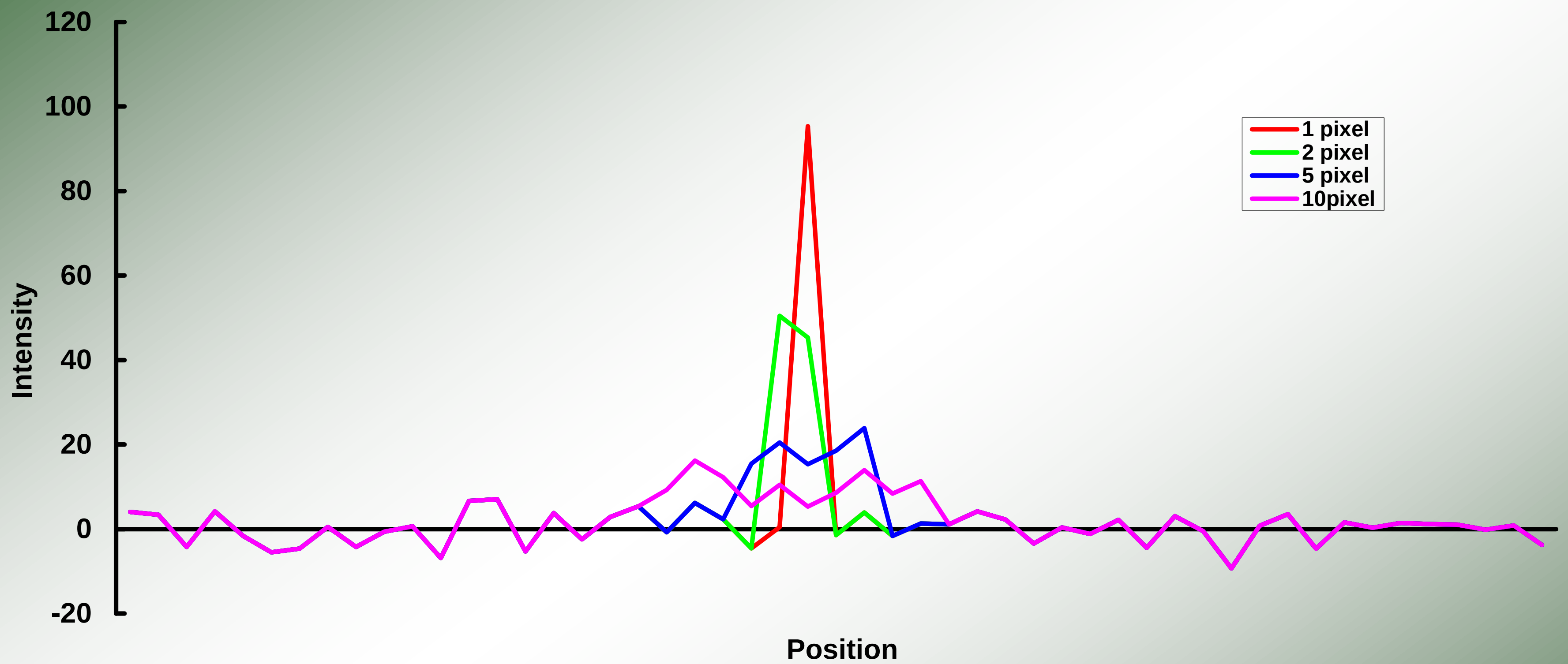
Dynamic Range and SNR

- Datasheet DNR = 75.4dB or 5888

- Datasheet SNR = 43.0dB or 141 !!!!
- Why the difference?
- DNR = Max signal / Detector Noise
  $= 23000e^{-}/3.2e^{-} = 7186 = 77.1dB$
- SNR = Max signal / All noise (inc. photon statistics)
  $= 23000/\sqrt{23000} = 151.6 = 43.6dB$
  - Nb/ Poisson statistics apply to electrons as well as photons

- Difference between my calculation and their values is that they used a full well capacity of 20000

Real SNR

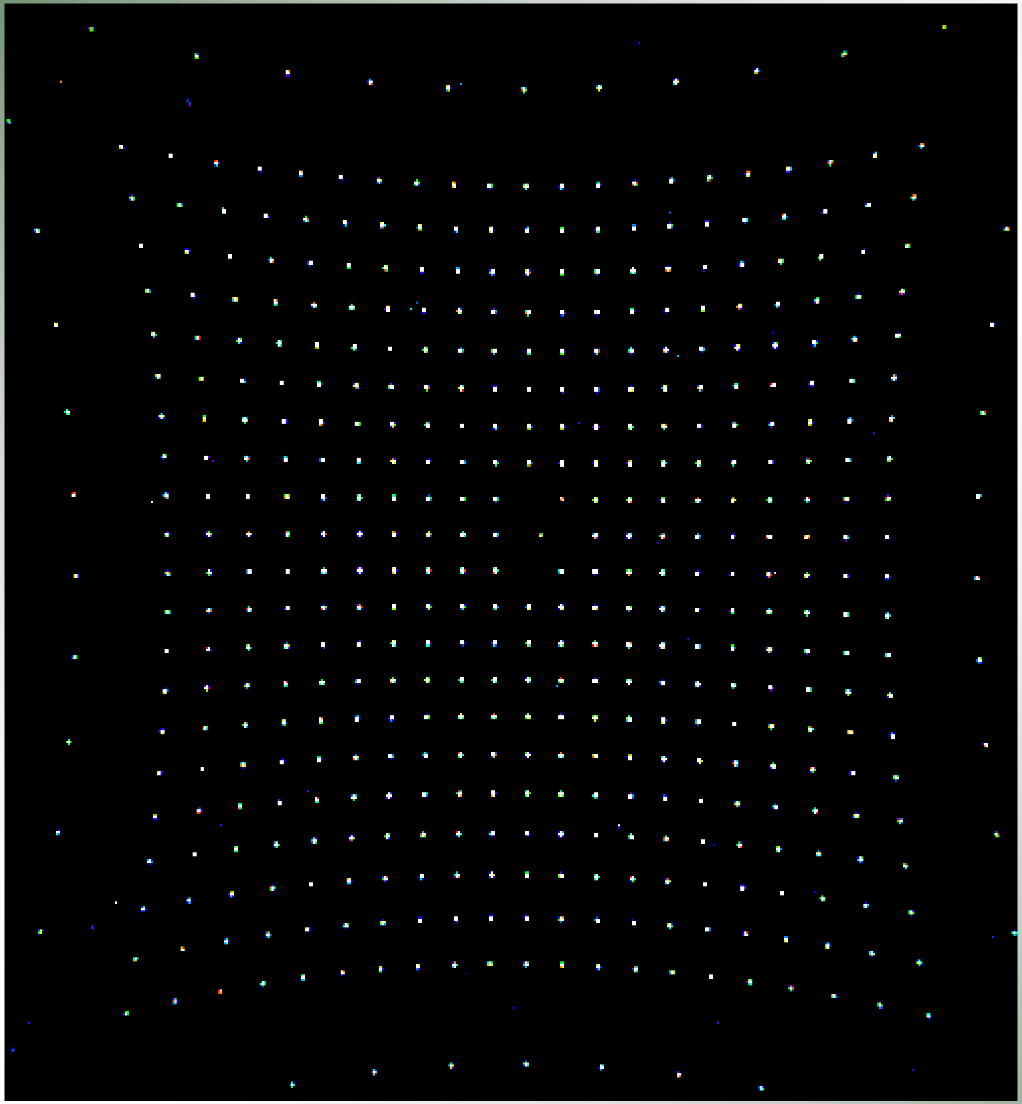


- Usually better to have signal in fewer pixels because each pixel has its own noise

Things not in Specifications

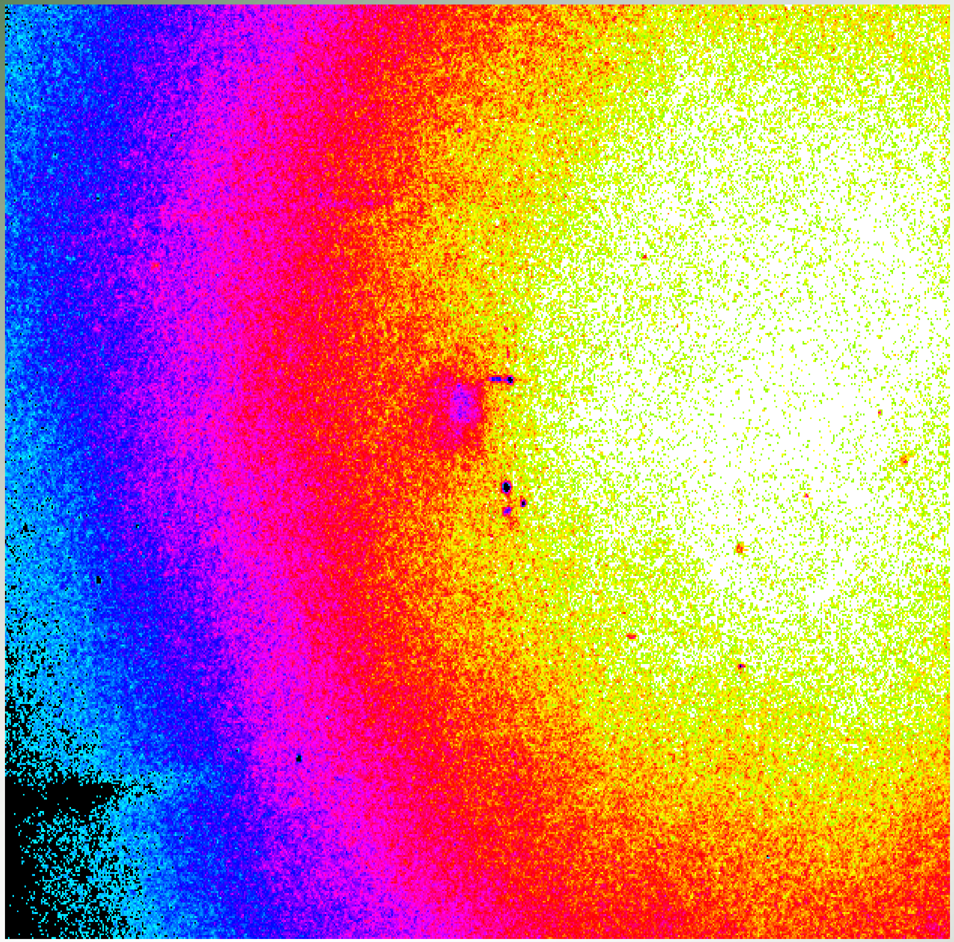
- Spatial distortions
- Sensitivity uniformity

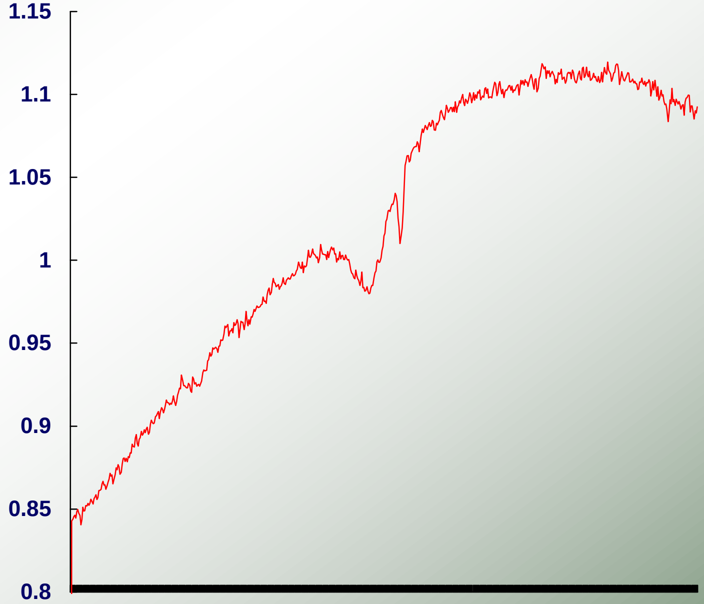
Spatial distortion x = f(y)



ESRF Image intensifier detector

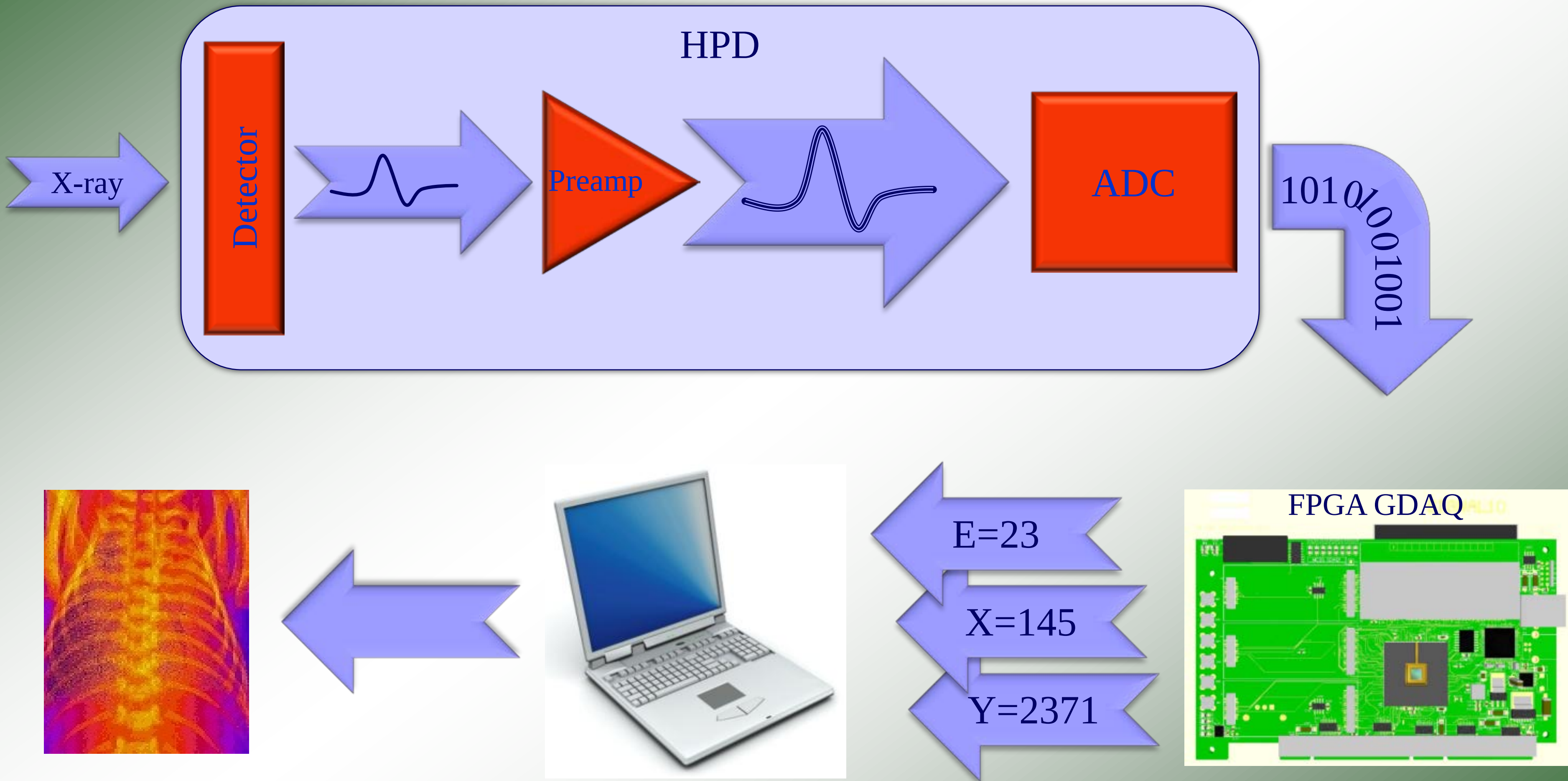
Response to Uniform Illumination





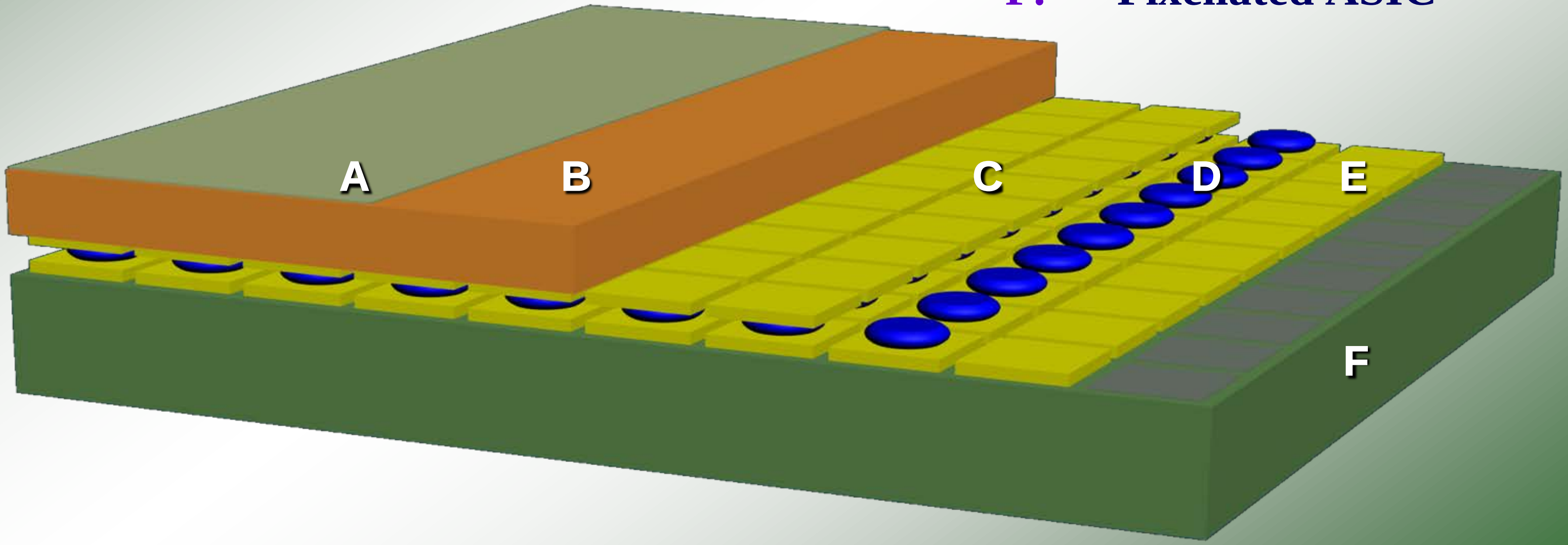
We would like sensitivity to be a constant, neither varying in time or position

Combine Imaging and Spectroscopy

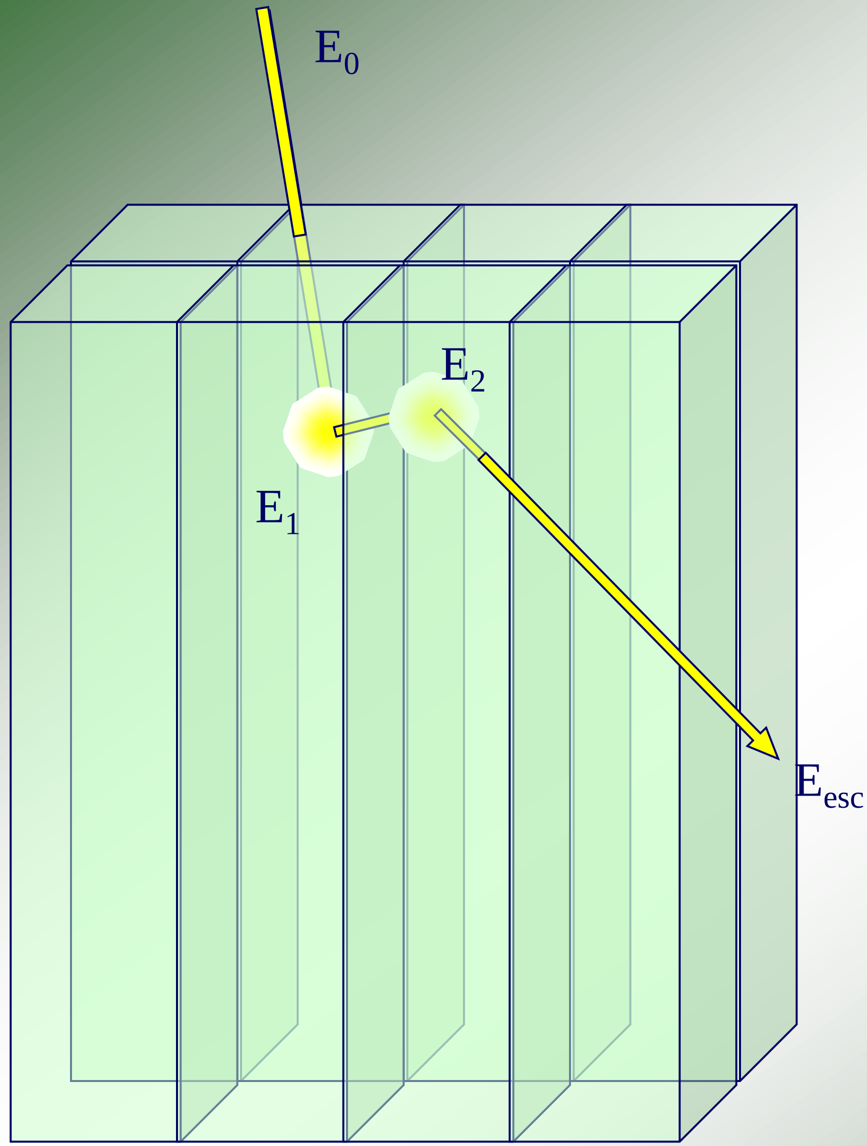


Pixel Array Detector

- **A.** Top electrode
- **B.** Pixellated semiconductor
- **C.** Collection electrodes
- **D.** Bump bonds
- **E.** Input electrode
- **F.** Pixellated ASIC

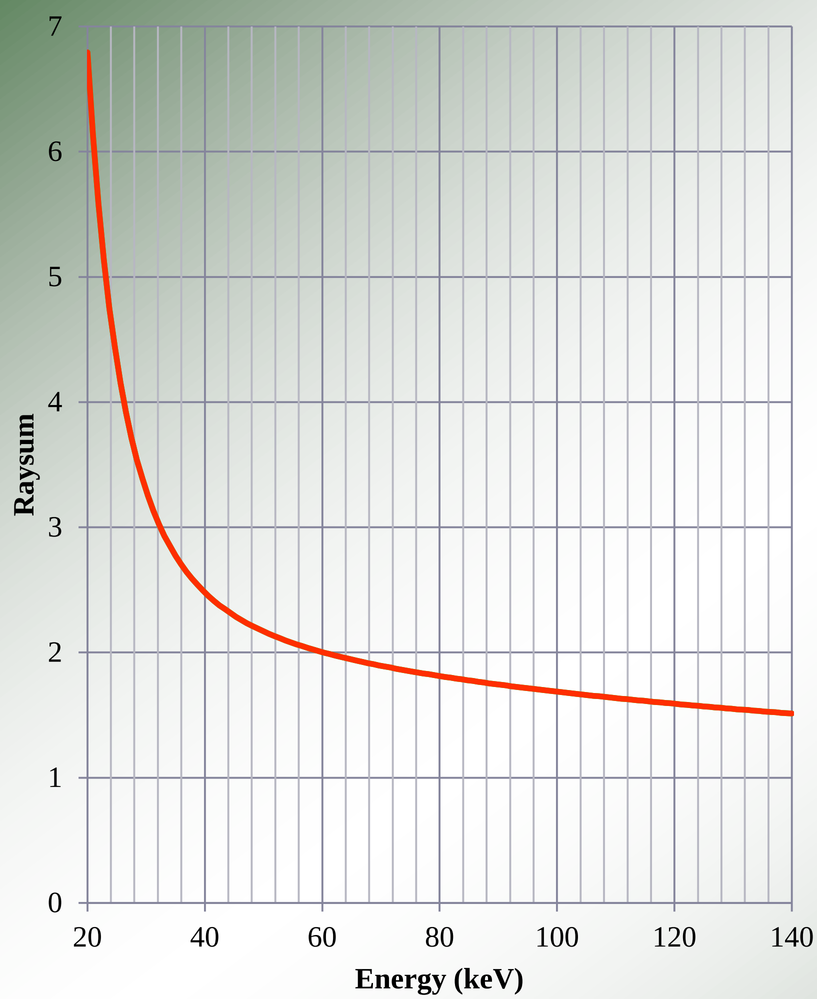


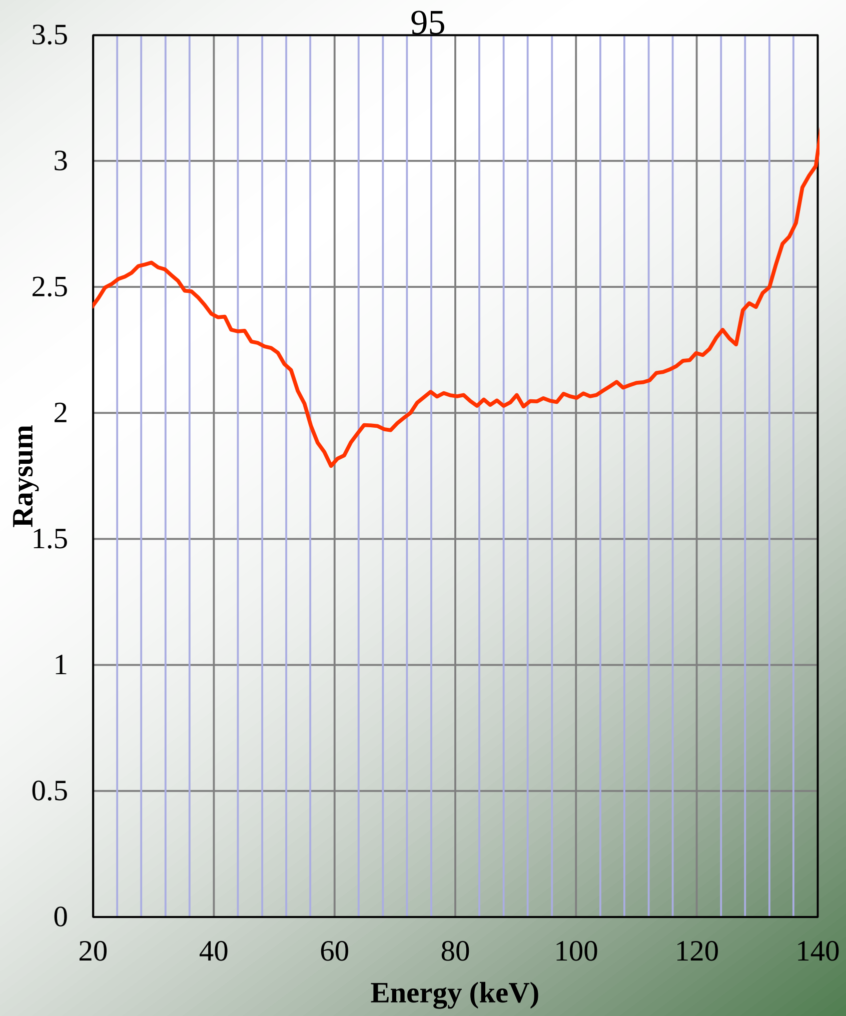
The Problem of Multiple Scatters



- We would like to know E_0 but…..
- $E_0=E_1+E_2+E_{esc}$
- We don't know E_{esc}
- E_1 and E_2 are separate events
- So we must be able to associate multiple energy deposits as single input photon
- We must also minimise E_{esc}
- Not a simple problem!

Spectroscopic Imaging Reality





Detector Considerations

- Intensity Measurement
  - Uniformity across device
  - Ageing, radiation damage
  - Dynamic Range
  - Linearity of Response
  - Stability
- Spatial Measurement
  - Spatial Resolution
  - Spatial Distortion
  - Parallax
- Energy Measurement
  - Spectral Resolution
  - Linearity of Response
  - Uniformity of Response
  - Stability
- Time Measurement
  - Frame Rate
  - Photon Time Resolution
- Others
  - Size and weight
  - Cost

Other Issues

- In addition to detector performance metrics such as
  - Spatial resolution, Spectral resolution, etc.
- Often we need to corollate with other parameters
- Requires that…
  - The detector respond to triggers
  - Be able to synchronise with other systems measuring multiple parameters

Counting Statistics

- Photons are quantised and hence subject to probabilities
- The Poisson distribution expresses the probability of a number of events, k occurring relative to an expected number, n

$$P(n,k) = \frac{n^k e^{-n}}{k!}$$

- The mean of P(n, k) is n
- The variance of P(n, k) is n
- The standard deviation or error (noise) is $\sqrt{n}$
- If signal = n, then SNR = $n/\sqrt{n} = \sqrt{n}$
- As n increases, SNR improves

Performance Measure - DQE

Perfect detector $SNR_{inc} = \sqrt{N_{inc}}$ $\therefore N_{inc} = SNR^2{}_{inc}$

Imperfect detector $SNR_{Non-ideal} < \sqrt{N_{inc}}$

We can define $N_{photons}$ that describes real SNR

$$NEQ = SNR^2{}_{Non-ideal}$$

Ratio of NEQ to N_{inc} is a measure of efficiency

$$DQE = \frac{NEQ}{N_{inc}} = \frac{SNR^2{}_{Non-ideal}}{SNR^2{}_{inc}}$$

Note that DQE is f(spatial and spectral frequencies)

DQE Comparison

DN-5 beam
2.6μGy