Deep Sky Imaging Acquisition Workshop: Electronics

Gabe Shaughnessy

What do you want to achieve?

- Pretty pictures!
  - Color: OSC, RGB, LRGB
  - False color: HaRGB, SHO, HOO, IR-RGB
- Advance what you can image
  - First images of common targets
    - M31, M27, M57, etc.
  - More challenging targets:
    - Veil nebula
    - Dark nebula: Iris nebula, Ghost nebula, etc
  - Pushing the limits of you, your system and your skies
    - Spaghetti nebula
    - Soap bubble nebula
    - Deep integration of galaxy tails
    - IFN
    - The sky is literally the limit
- Science!
  - SN detection, Variable stars, Spectra studies, Exoplanet transit, etc.

Last time...

Mechanics of setting up your rig

- Counterweights
- Mount
- Cable Management
- Focus
- Polar alignment
- Environment sensors
- Dew prevention

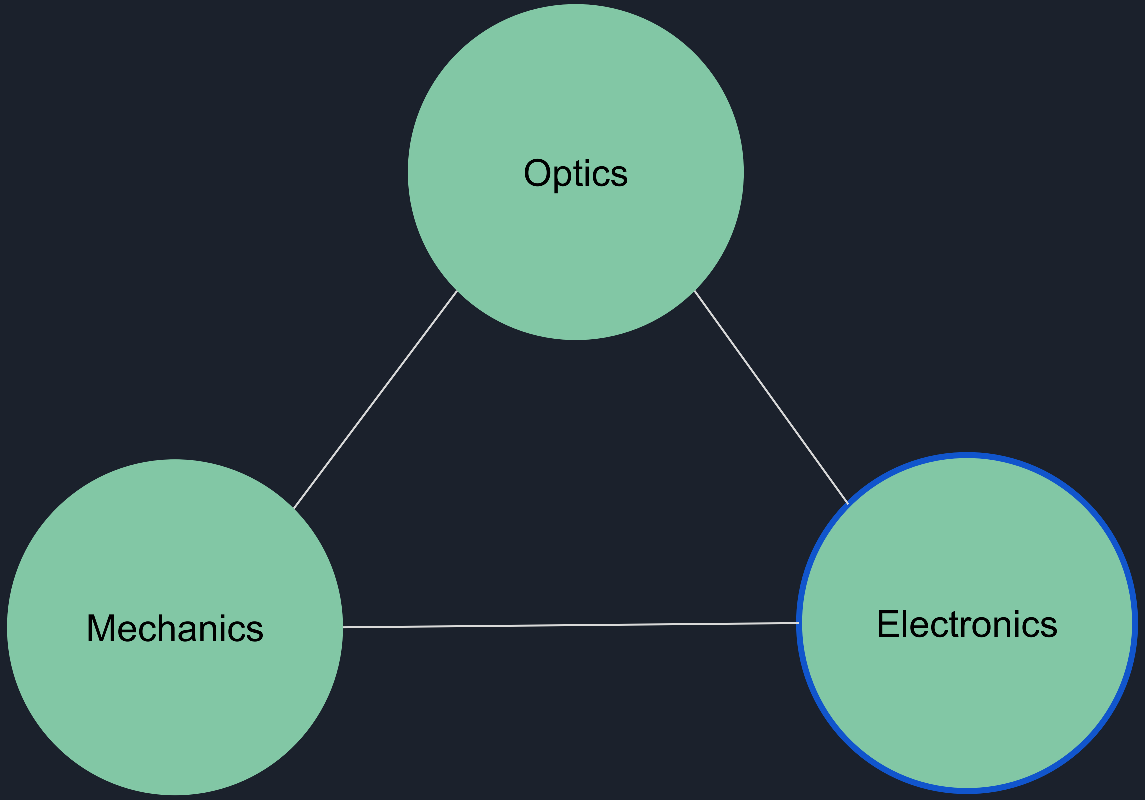
Optical considerations:

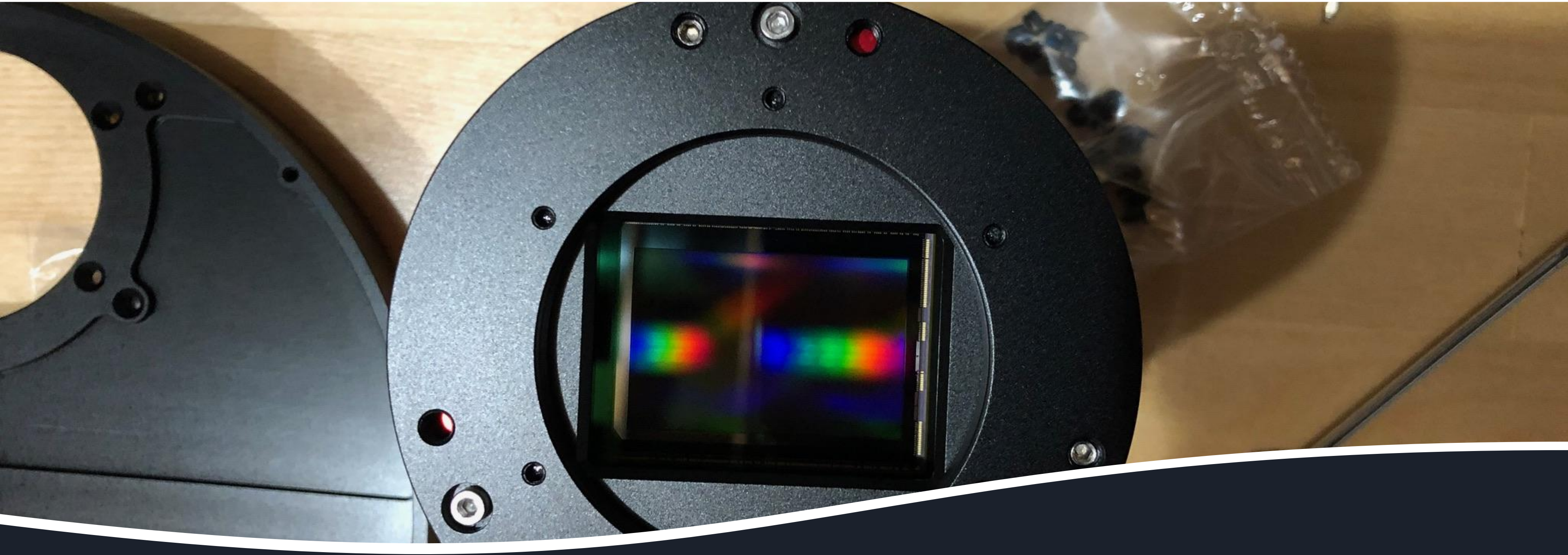
- Telescopes
- Contrast
- Filters
- Aberrations

Guiding:

- Why we guide
- Guiding options/settings

The Trinity of Imaging





Imaging sensors

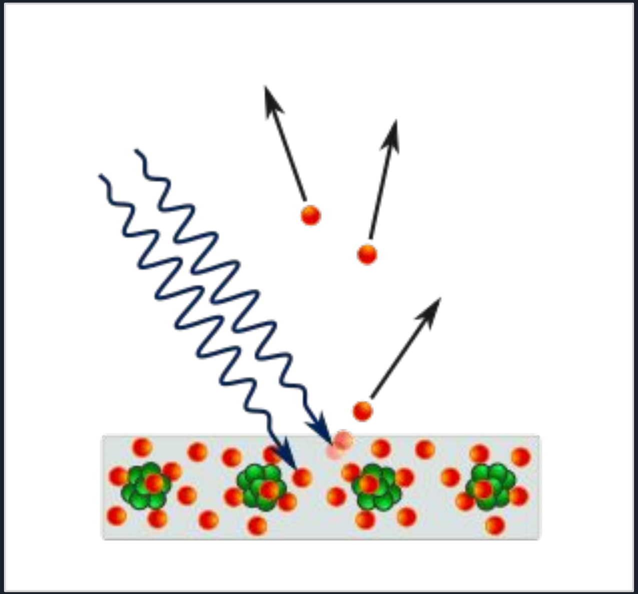
The Photoelectric effect

Incident light can emit electrons off a material

Known since mid-1800s

Albert Einstein proposed explanation in 1905, awarded Nobel Prize in 1921

Principle behind solar cells



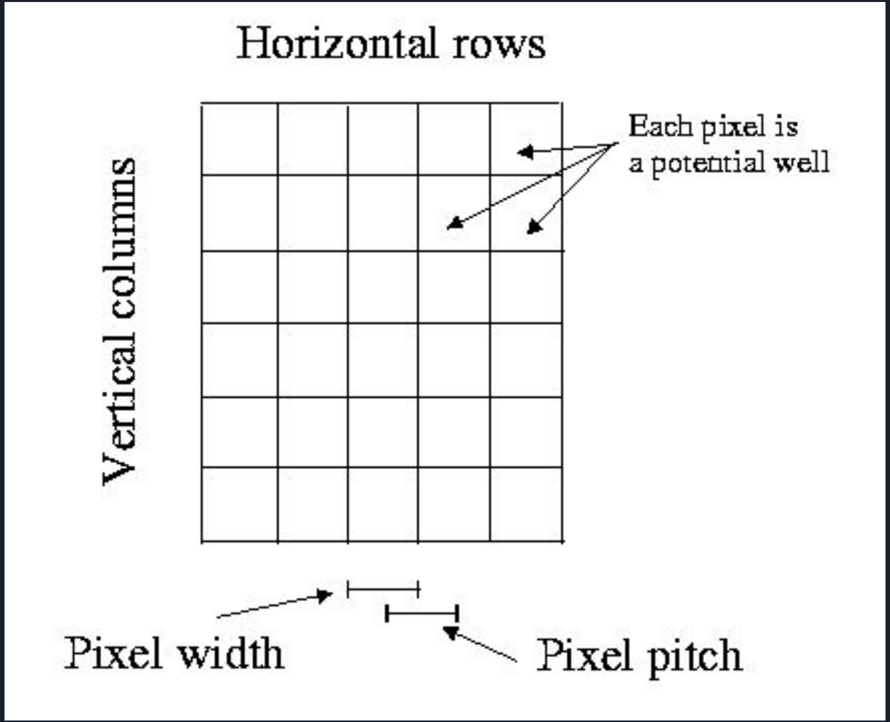
The Pixel

A photoactive unit of material that converts photons to measurable electrical signals.

Millions of pixels form the imaging sensor

Pixel size helps determine imaging scale:

Image scale = 206 * pixel_size / focal_length



The Pixel - A photon bucket

From: https://cloudbreakoptics.com/blogs/news/astrophotography-pixel-by-pixel-part-1

The Pixel - Brightness

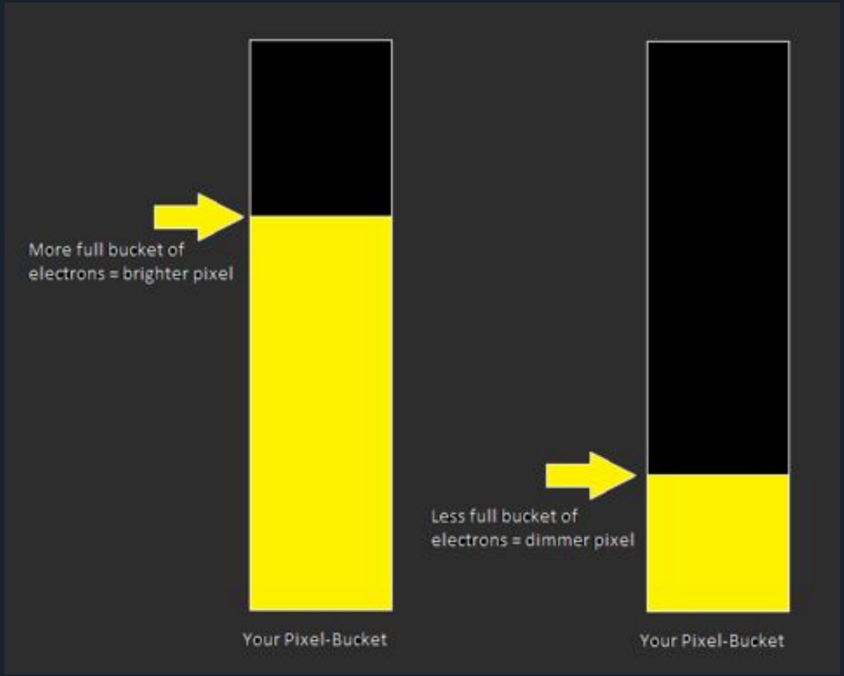
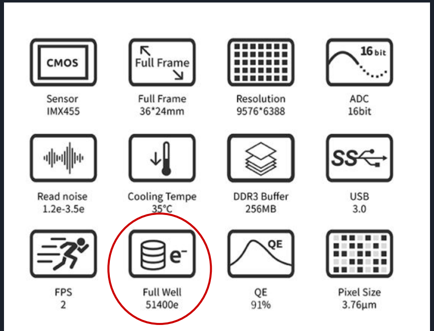


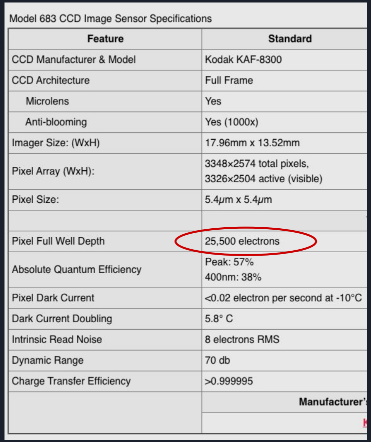
Image brightness directly related to how full the silicon bucket gets

The Pixel - Capacity

Full well capacity

- Measured in Electrons
- How deep is the silicon bucket





Model 683 CCD Image Sensor Specifications

Feature	Standard
CCD Manufacturer & Model	Kodak KAF-8300
CCD Architecture	Full Frame
Microlens	Yes
Anti-blooming	Yes (1000x)
Imager Size: (WxH)	17.96mm x 13.52mm
Pixel Array (WxH):	3348x2574 total pixels, 3326x2504 active (visible)
Pixel Size:	5.4μm x 5.4μm
Pixel Full Well Depth	25,500 electrons
Absolute Quantum Efficiency	Peak: 57% 400nm: 38%
Pixel Dark Current	<0.02 electron per second at -10°C
Dark Current Doubling	5.8° C
Intrinsic Read Noise	8 electrons RMS
Dynamic Range	70 db
Charge Transfer Efficiency	>0.999995
	Manufacturer'

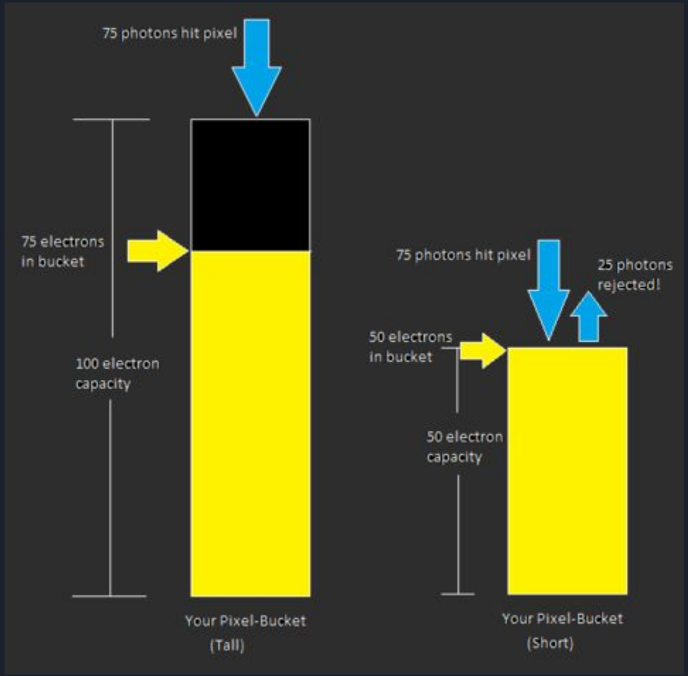
The Pixel - Saturation

Saturated pixels contain no meaningful information:

- Pixel at 100% capacity
- Can cause spill-over in CCDs
    - Blooming

For final image:

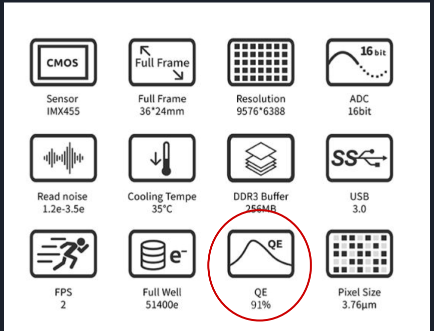
- Affects color saturation
- HDR methods have difficulty with saturated stars

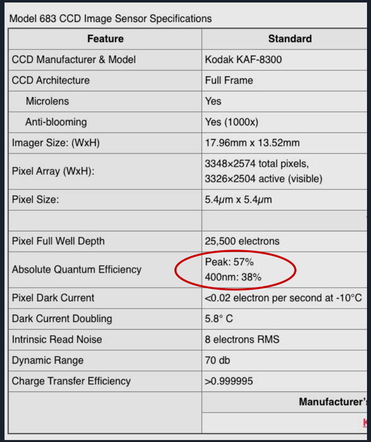


The Pixel - Quantum Efficiency

Measure of how good your chip is at converting photons to electrons

Low QE chips need longer integration times to get the same signal





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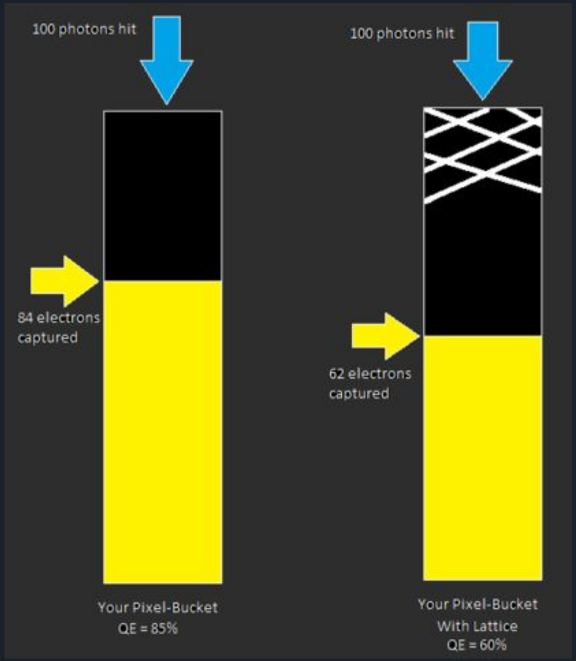
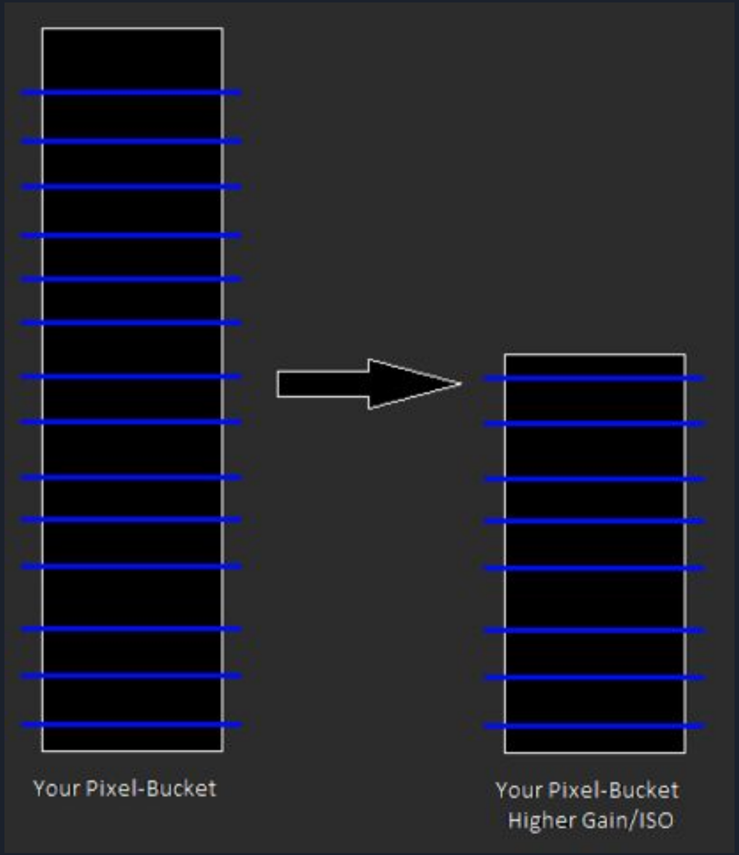


Gain / ISO

High gain effectively shortens the pixel bucket capacity

- Gain increases effect of 1 photon striking the pixel, does not add new data!
- Trade-off:
  - Fills bucket faster
  - Lower dynamic range

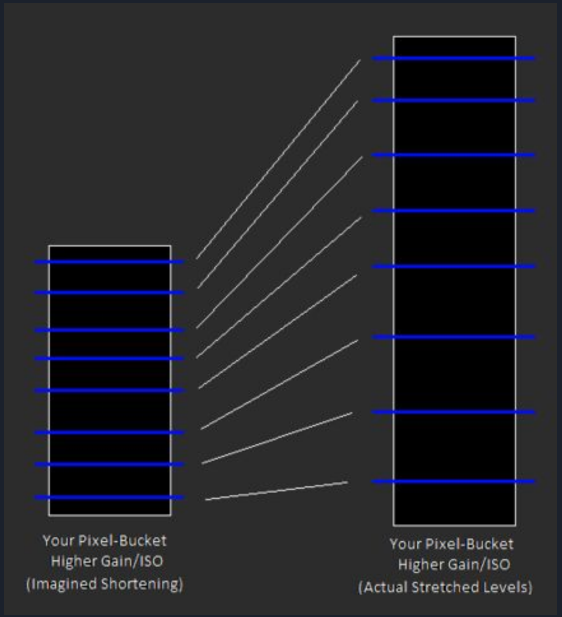
Gain = # electrons / ADU



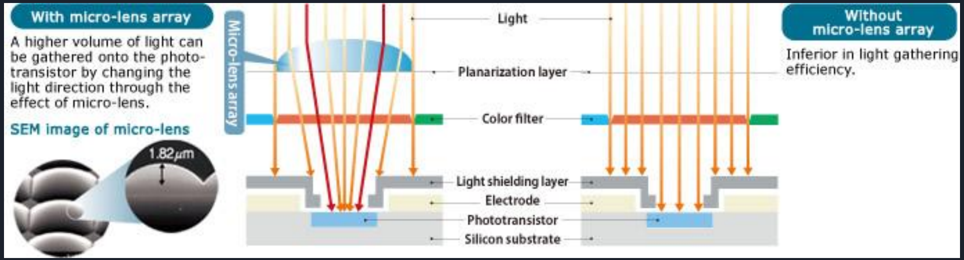
The ADC

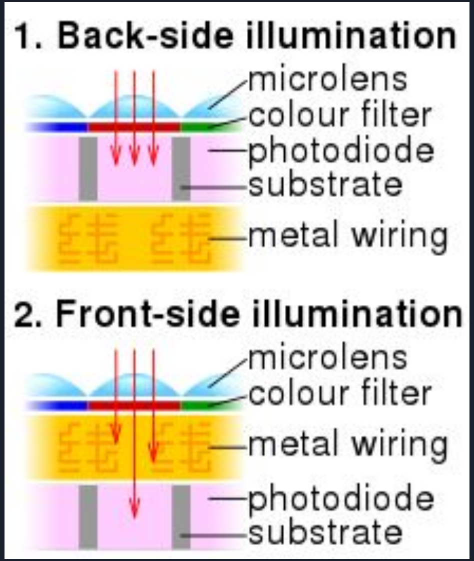
The ADC (Analog to Digital Converter) take the electrons in each bucket and converts them to digital units

- 16-bit: 65536 levels
- 12-bit: 4096 levels



Photon collection improvements

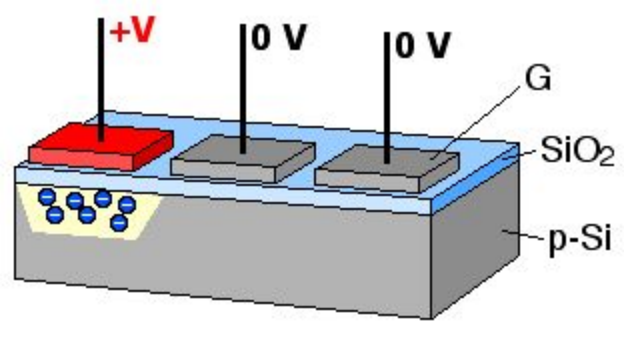


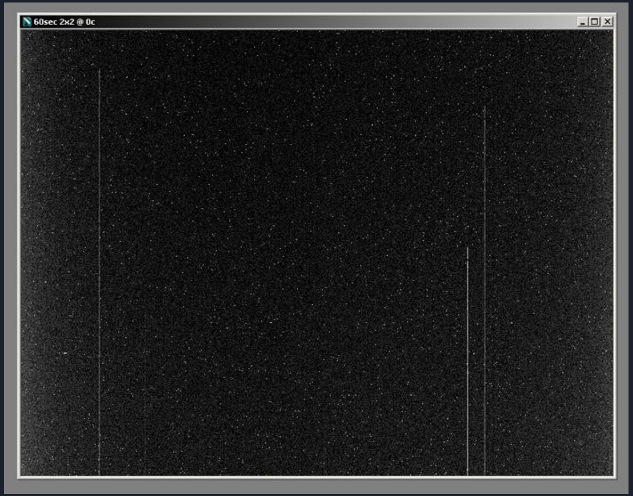


CCD

CCD - Charge-coupled device

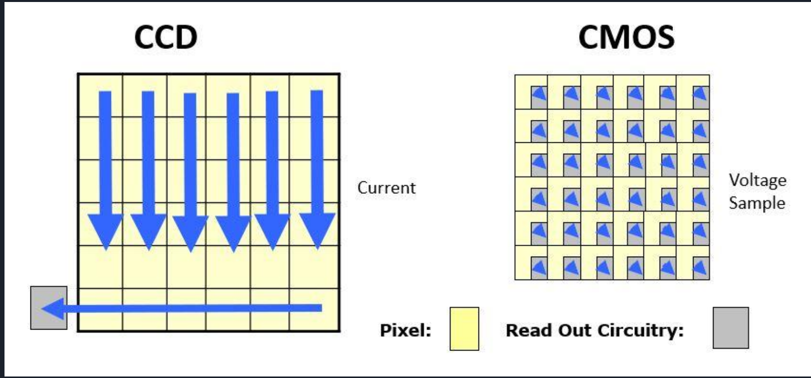
- First popular form of electronic imaging
- Global shutter
- Columns defects
- Binning without extra read noise





CMOS

- Each pixel has its own readout
    - Generally run warmer than CCDs
- Newer technology
- Rolling shutter
- Read noise typically lower
- Amp glow prevalent in some sensors
- Digital binning - higher read noise

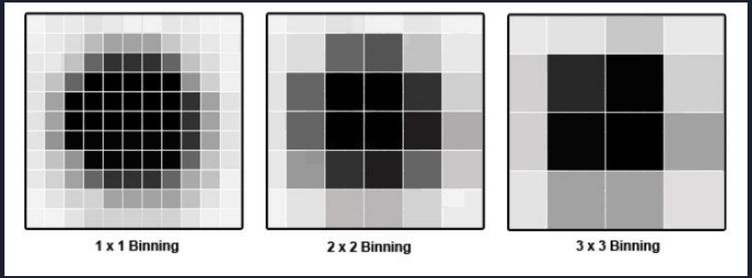


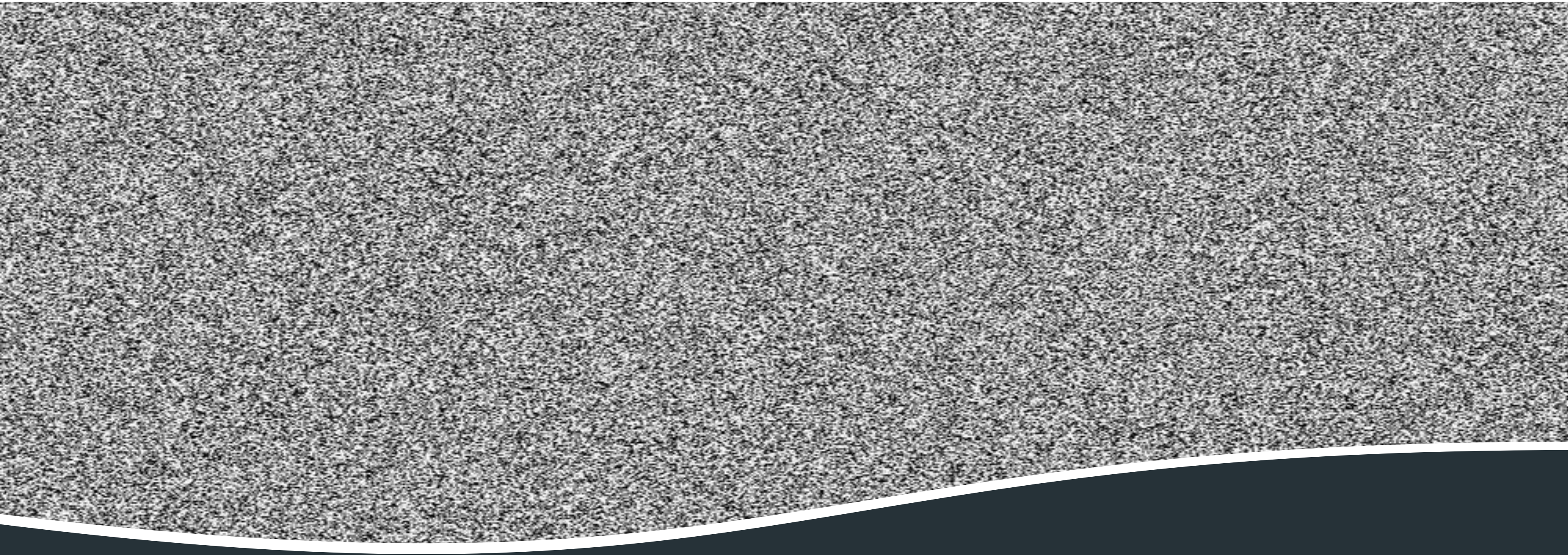
Binning

Binning can increase signal at expense of resolution

Read noise impacts:

- Increases if binning done at software level (CMOS)
- Stays the same if binning done at hardware level (CCD)





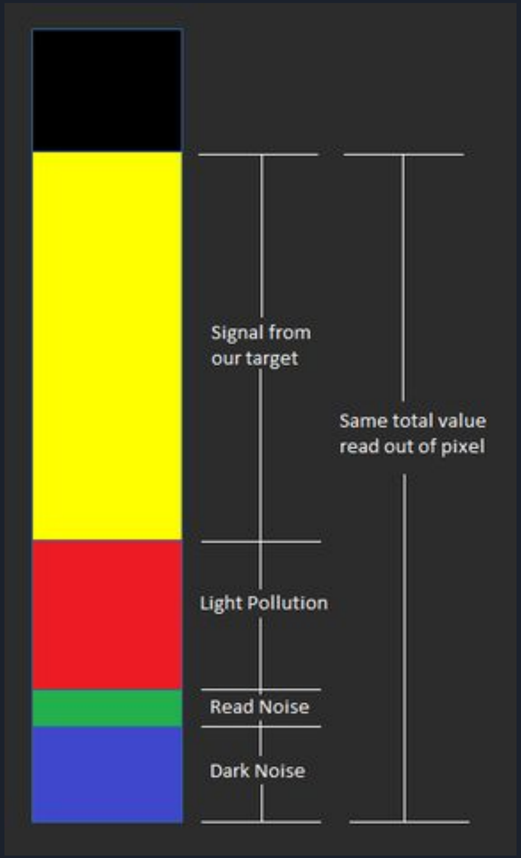
Noise

What is noise?

Noise sources have two components:

- Average amplitude (this can be removed with subtraction)
- Dispersion (this is the random part)
  - Can be reduced by stacking many subframes

Noise: random fluctuations in data that cannot be calibrated out



Dynamic Range

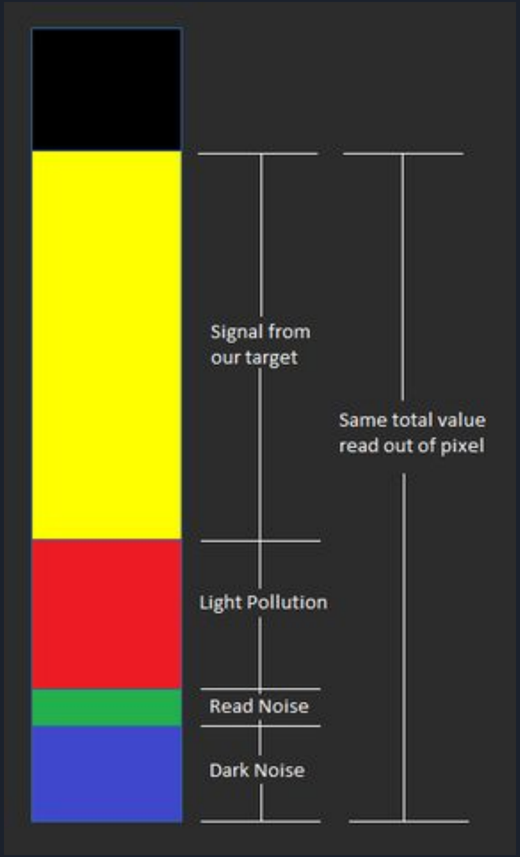
Total capacity of pixel divided by noise (typically just read noise)

Reducers of DR:

- Added noise
- Shallow well depth

$$\text{Dynamic Range in dB} = 20\log_{10}\left(\frac{\text{FullWellCapacity } (e^-)}{\text{ReadNoise } (e^-)}\right)$$

$$\text{Dynamic Range in stops} = \log_{2}\left(\frac{\text{FullWellCapacity } (e^-)}{\text{ReadNoise } (e^-)}\right)$$



Read Noise

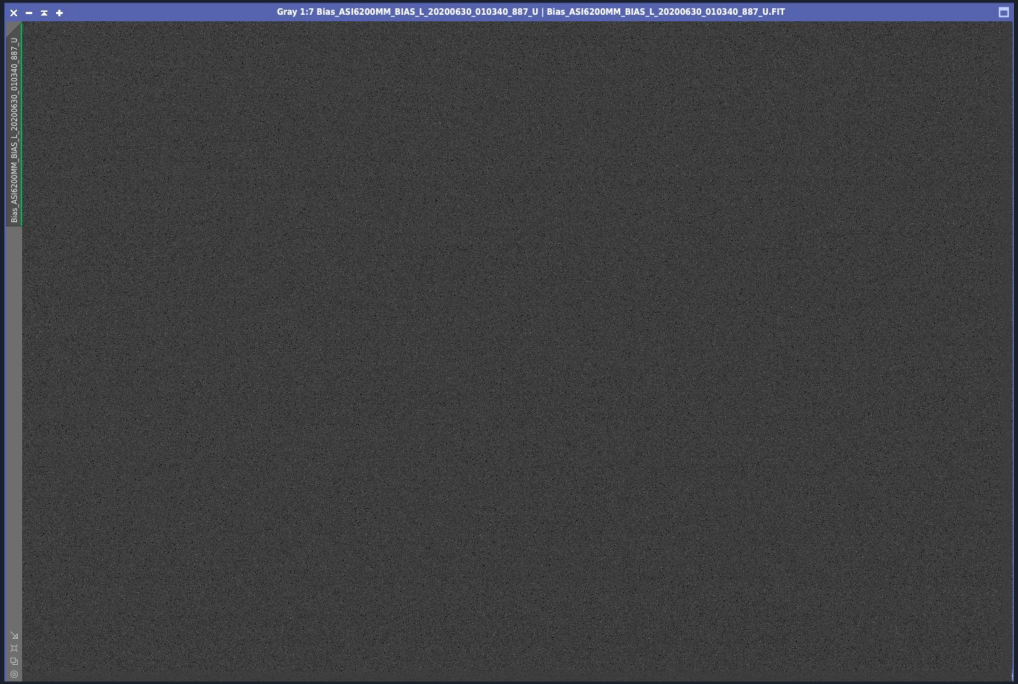
Noise added when the signal from each pixel is measured and converted to digital unit

- Specific to camera electronics

How to measure read noise:

$$\text{Read Noise (ADU)} = \frac{Std(\text{Bias}_1 - \text{Bias}_2)}{\sqrt{2}}$$

$$\text{Read Noise } (e^-) = gain \cdot \frac{Std(\text{Bias}_1 - \text{Bias}_2)}{\sqrt{2}}$$



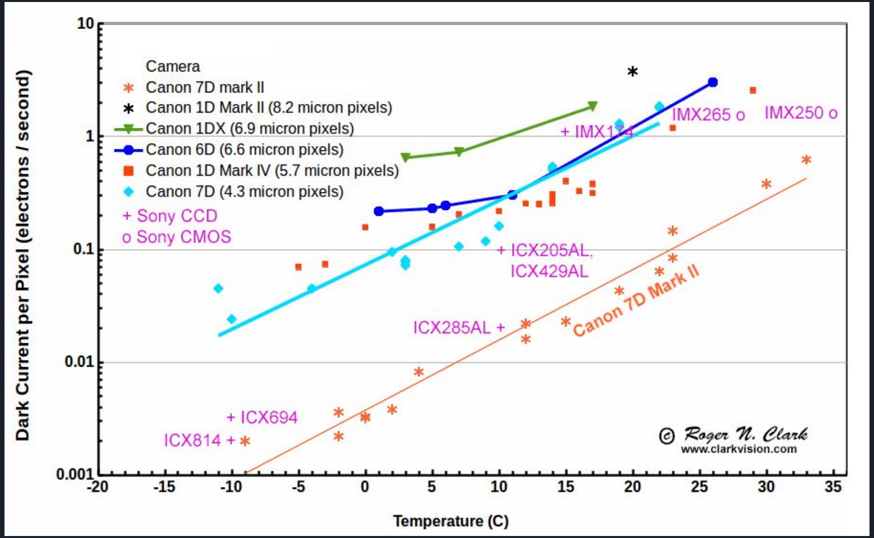
Thermal Noise - Dark Current

Added noise from thermal fluctuations of electrons

Units of electrons / second

- Increases with time

Decreases with temperature



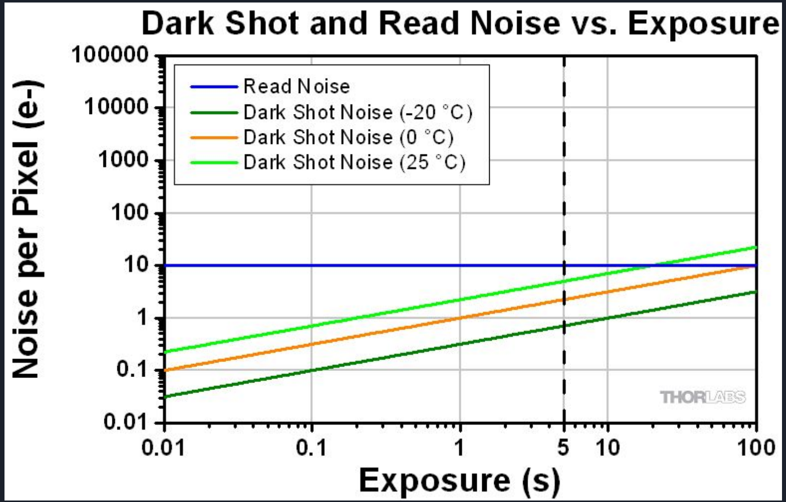
Read Noise vs. Dark Current

Summary:

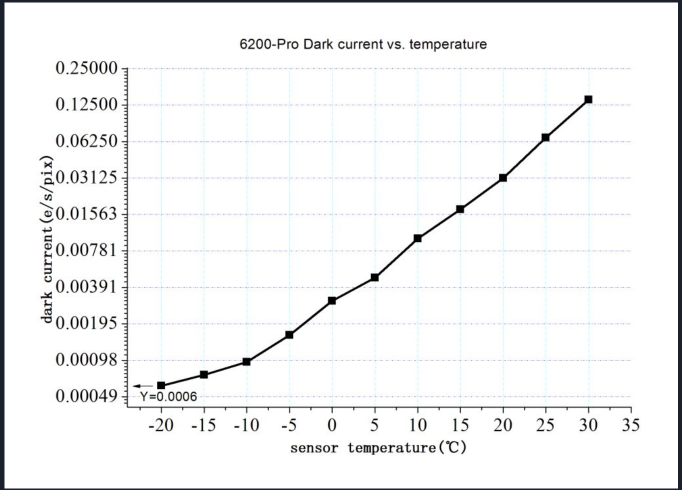
Read noise is fixed

Dark current increases with time and temperature

Best case scenario is reduce dark current below read noise



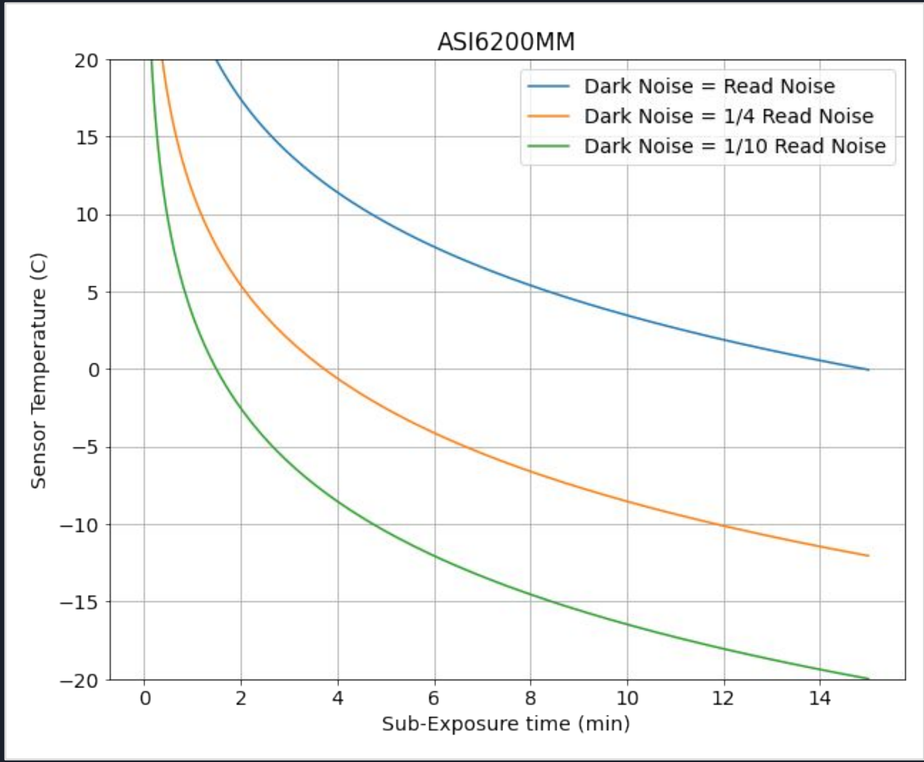
Example: ASI6200MM



ASI6200MM:

Read Noise $= 3.5e^-$

Dark Noise $\sim 0.00311 \frac{e^-}{s \cdot pix} \cdot 2^{T/6}$



Example: QSI683

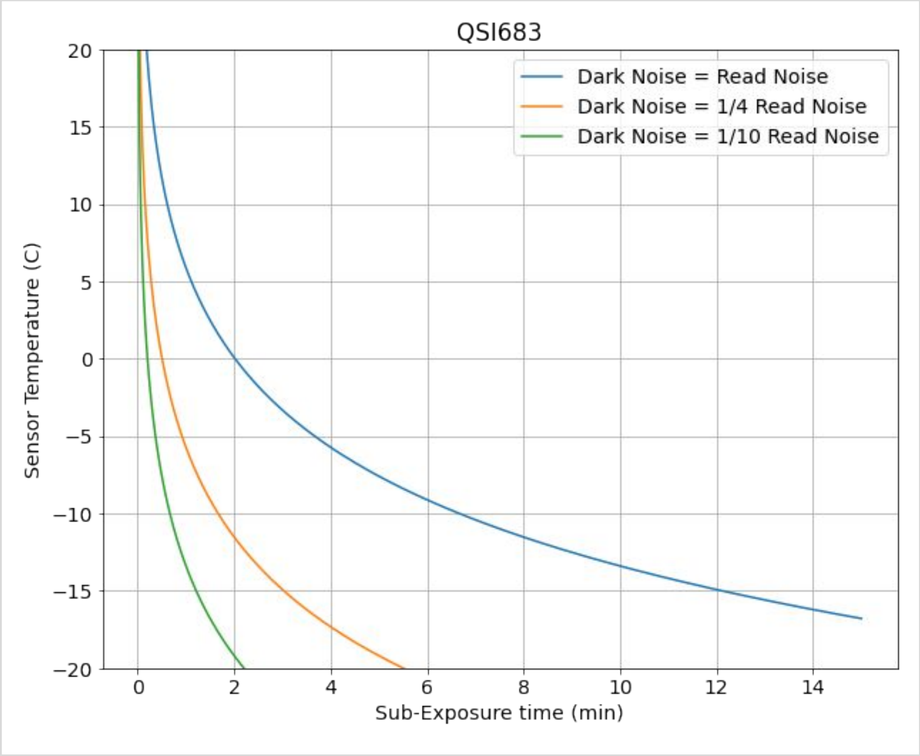
Model 683 CCD Image Sensor Specifications

Feature	Standard	Optional
CCD Manufacturer & Model	Kodak KAF-8300	Kodak KAF-8300 (no coverglass)
CCD Architecture	Full Frame	Full Frame
Microlens	Yes	No
Anti-blooming	Yes (1000x)	Yes (1000x)
Imager Size: (WxH)	17.96mm x 13.52mm	17.96mm x 13.52mm
Pixel Array (WxH):	3348x2574 total pixels, 3326x2504 active (visible)	3348x2574 total pixels, 3326x2504 active (visible)
Pixel Size:	5.4μm x 5.4μm	5.4μm x 5.4μm
	Typical Values	
Pixel Full Well Depth	25,500 electrons	25,5000 electrons
Absolute Quantum Efficiency	Peak: 57% 400nm: 38%	Peak: 60% 400nm: 40%
Pixel Dark Current	<0.02 electron per second at -10°C	
Dark Current Doubling	5.8° C	5.8° C
Intrinsic Read Noise	8 electrons RMS	8 electrons RMS
Dynamic Range	70 db	70 db
Charge Transfer Efficiency	>0.999995	>0.999995
	Manufacturer's CCD Imager Specifications	
	KAF-8300 (PDF)	

QSI683:

$$\text{Read Noise} = 8e^-$$

$$\text{Dark Noise} \sim 0.02\frac{e^-}{s \cdot pix} \cdot 2^{(T+10)/5.8}$$



Shot Noise - Poisson

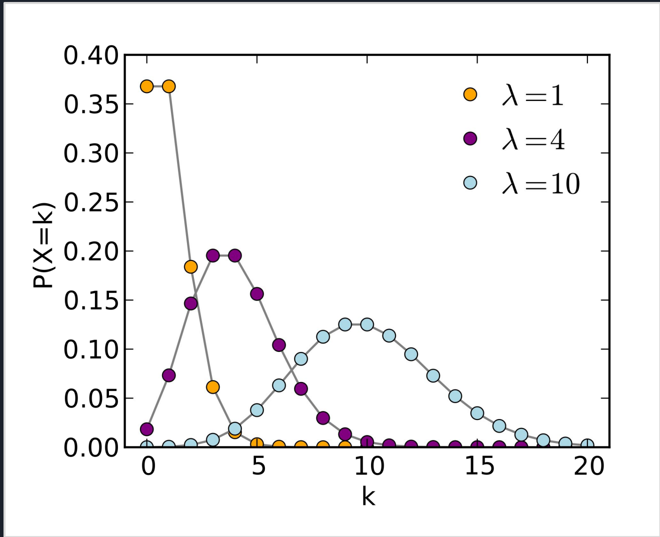
Poisson probability distribution describes counts:

- Photons / s
- Raindrops / min
- Blue cars / hour

For a Poisson distribution:

$$\text{Std. Dev.} = \sqrt{\text{Mean}}$$

$$\text{SNR} = \frac{\text{Signal}}{\text{Noise}} = \frac{\text{Mean}}{\sqrt{\text{Mean}}} = \sqrt{\text{Mean}}$$



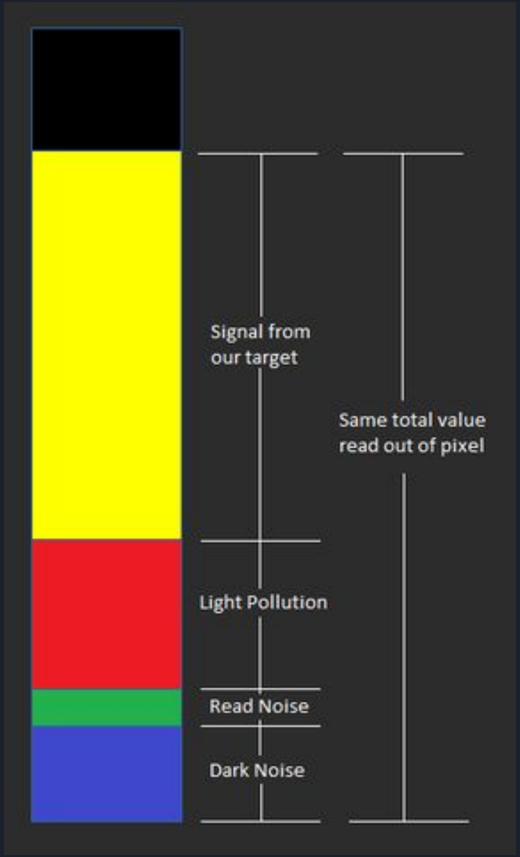
Signal to Noise Ratio

Uncalibrated single frame:

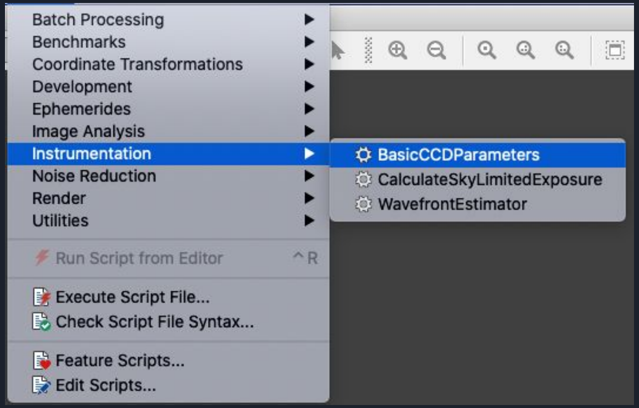
$$\mathrm{SNR}_{\mathrm{Pixel}} = \frac{S_{\mathrm{object}}}{\sqrt{S_{\mathrm{object}} + S_{\mathrm{sky}} + \mathrm{Dark\ Current} + \mathrm{RN}^2}}$$

Calibrated single frame:

$$\mathrm{SNR}_{\mathrm{Pixel}} = \frac{S_{\mathrm{object}}}{\sqrt{S_{\mathrm{object}} + S_{\mathrm{sky}} + \mathrm{Dark\ Current} + \mathrm{RN}^2 + \mathrm{Dark\ Frame\ Noise}^2 + \mathrm{Flat\ Frame\ Noise}^2}}$$



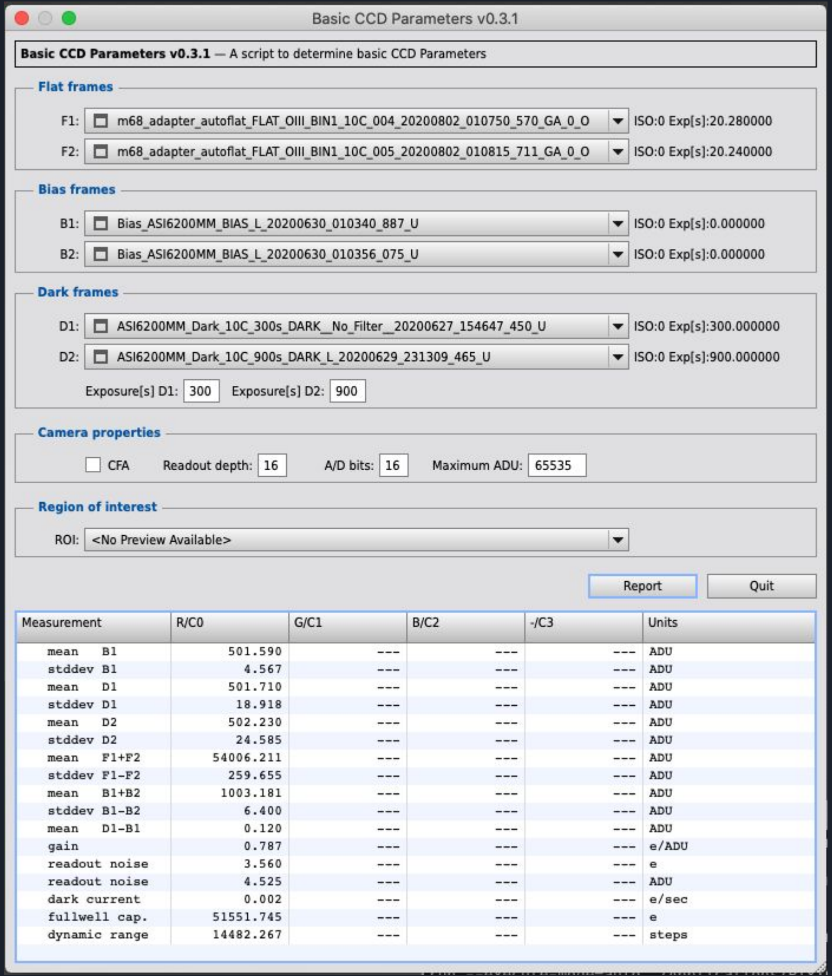
Measuring Your Camera



$$\text{Gain}\ \left(\frac{e^-}{ADU}\right) = \frac{Mean(\text{Flat}_1 + \text{Flat}_2)}{Var(\text{Flat}_1 - \text{Flat}_2)}$$

$$\text{Read Noise (ADU)} = \frac{Std(\text{Bias}_1 - \text{Bias}_2)}{\sqrt{2}}$$

$$\text{Read Noise}\ (e^-) = gain \cdot \frac{Std(\text{Bias}_1 - \text{Bias}_2)}{\sqrt{2}}$$



Measurement	R/C0	G/C1	B/C2	-/C3	Units
mean B1	501.590	---	---	---	ADU
stddev B1	4.567	---	---	---	ADU
mean D1	501.710	---	---	---	ADU
stddev D1	18.918	---	---	---	ADU
mean D2	502.230	---	---	---	ADU
stddev D2	24.585	---	---	---	ADU
mean F1+F2	54006.211	---	---	---	ADU
stddev F1-F2	259.655	---	---	---	ADU
mean B1+B2	1003.181	---	---	---	ADU
stddev B1-B2	6.400	---	---	---	ADU
mean D1-B1	0.120	---	---	---	ADU
gain	0.787	---	---	---	e/ADU
readout noise	3.560	---	---	---	e
readout noise	4.525	---	---	---	ADU
dark current	0.002	---	---	---	e/sec
fullwell cap.	51551.745	---	---	---	e
dynamic range	14482.267	---	---	---	steps

Sky Limited Exposure

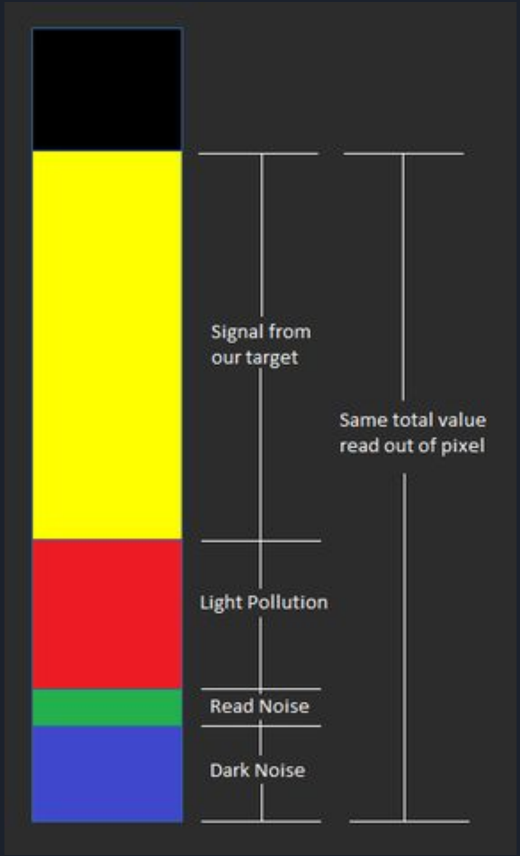
Read noise is unavoidable

- When does the photon flux overwhelm read noise?
- Light pollution is big factor

$$\text{Read Noise}^2 + tE_{\text{sky}} = tE_{\text{sky}} \cdot (1+p)^2$$

$$\implies t = \frac{\text{Read Noise}^2}{E_{\text{sky}} \cdot \left((1+p)^2 - 1\right)}$$

$$E_{\text{sky}} = \frac{(\text{Test Image ADU} - \text{Pedestal}) \cdot \text{Gain}}{t_{\text{exposure}}}$$

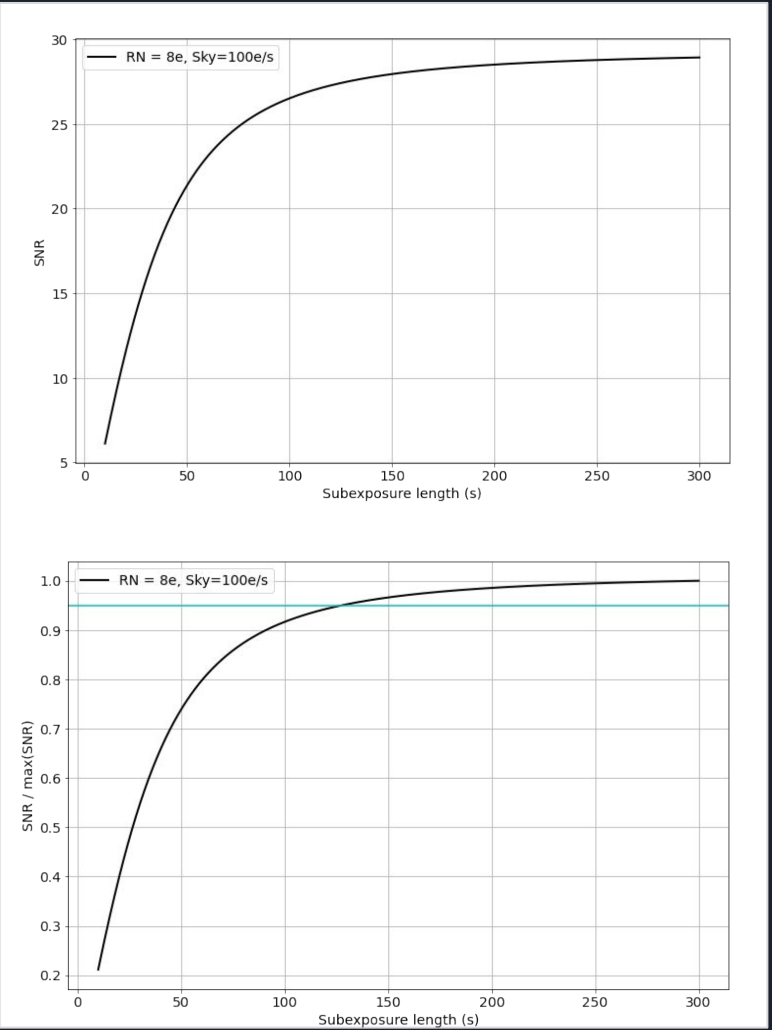


Subexposure length

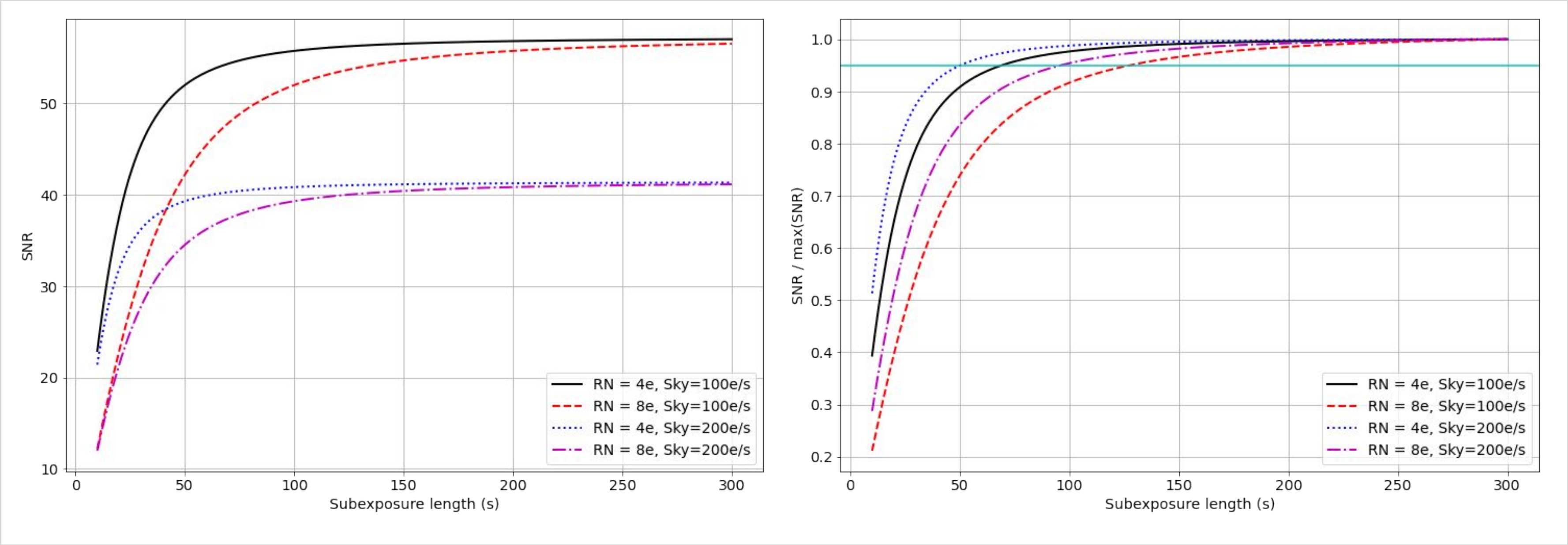
Considerations:

- Total exposure length
- Read noise
- Sky limited exposure
- Temperature changes
- Cosmic-ray hits
- Airplanes
- Satellites
- Disk drive space

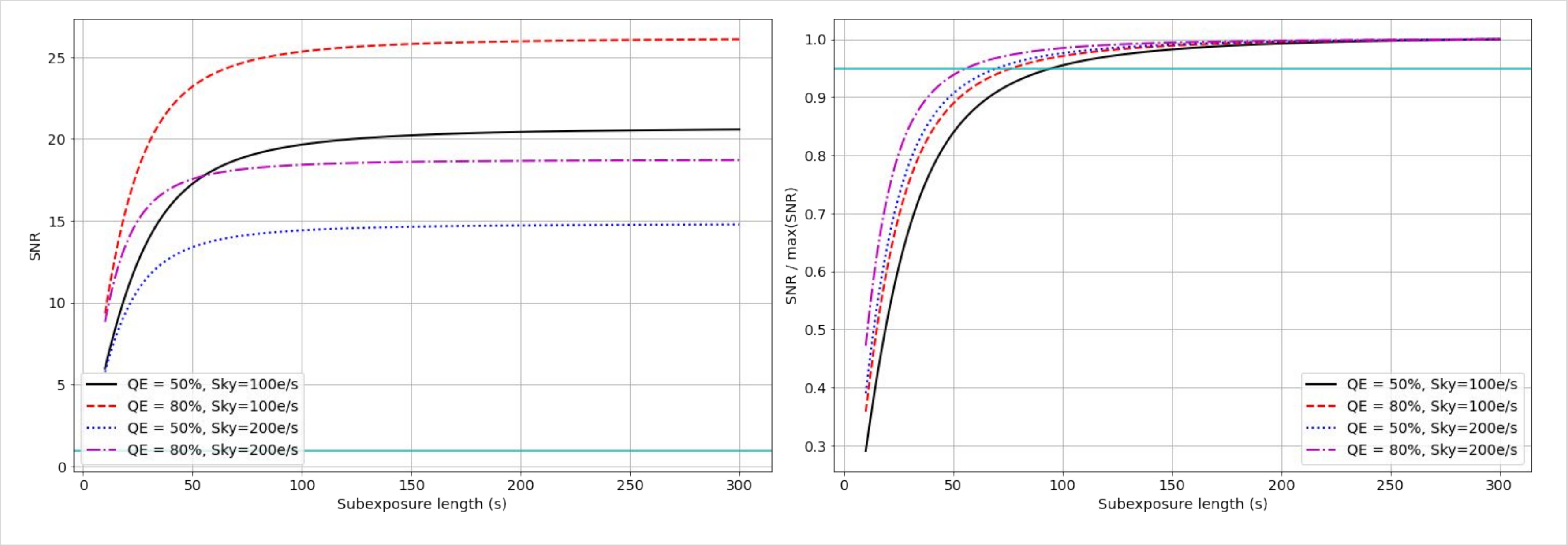
$$\mathrm{SNR}_{\mathrm{Pixel}} = \frac{S_{\mathrm{object}} t_{\mathrm{sub}} n_{\mathrm{sub}}}{\sqrt{S_{\mathrm{object}} t_{\mathrm{sub}} n_{\mathrm{sub}} + S_{\mathrm{sky}} t_{\mathrm{sub}} n_{\mathrm{sub}} + \text{Dark Current } t_{\mathrm{sub}} n_{\mathrm{sub}} + n_{\mathrm{sub}}^2 (\mathrm{RN}^2 + \text{Dark Frame Noise}^2 + \text{Flat Frame Noise}^2)}}$$



Effect of Read Noise



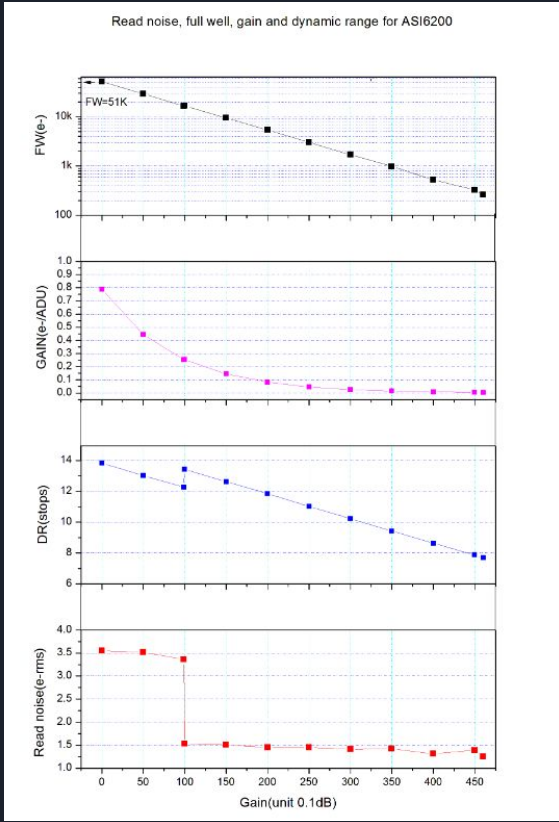
Effect of Quantum Efficiency

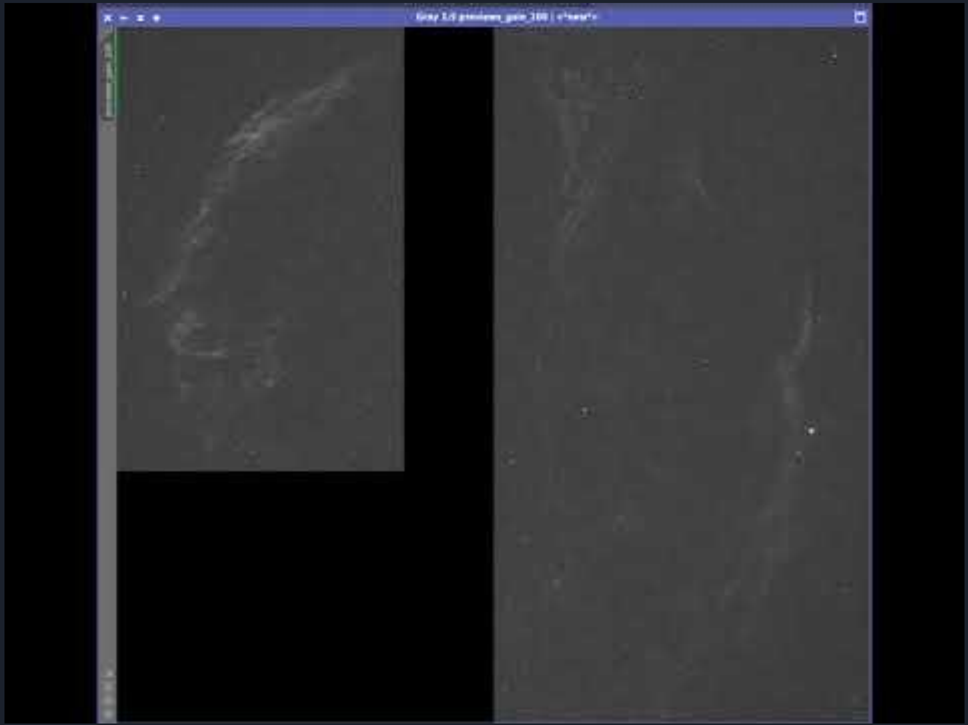


Comparisons: QHY16200A vs. ASI6200MM

QHY16200A SPECIFICATION	
Model	QHY16200A
CCD Sensor	KAF16200 APS-H (Default: Grade 2) Full Frame CCD
Pixel Size	6.0um*6.0um
Resolution	4540 (H) *3630 (V)
Effective Pixels	16.2 mega
Effective Image Area	27.0mm*21.6mm APS-H format
Readout Type	Progressive Scan
Readout Noise	Typical 10 e
System Gain	0.7e-/ADU at lowest Gain
Full Well Capacity	41ke-
Anti-Blooming Gate	2000x Saturation
Exposure Time Range	1ms-10000sec
AD Sample Depth	16bit
Sensor Size	APS-H Format
Pixel Binning	1x1,2x2,4x4

High Conversion Gain switch





Down the road

- Cameras and settings
- Calibration frames
- Acquisition software (SGP, etc.)
- Target planning/sequencing
- Data management
- Weather resources
- Observatory topics
- More processing topics
  - PS/PI

Looking for volunteers for some of these topics

Next time:

Open date, options:

- Pixinsight?
- Photoshop?
- Open forum?
- Additional imaging topics?