Properties of a Detector

Quantum Efficiency

- fraction of photons detected
- wavelength and spatially dependent

Dynamic Range

- difference between lowest and highest measurable flux

Linearity

- detection rate should scale linearly with photon flux

Noise:

- low noise on measured signal
- low background noise

Stability

- repeatable measurements and calibration

Spatial dynamic range

- want to see fine detail but also want large field of view
- combination of pixel size and detector area

The Perfect Detector

- Counts every photon it receives.
- Notes the photon's position and energy.
- Has uniform wavelength and spatial response.
- Has a linear response.
- Has no noise.
- Has a high dynamic range.

Does such a thing exist?

The Perfect Detector

- Counts every photon it receives.
- Notes the photon’s position and energy.
- Has uniform wavelength and spatial response.
- Has a linear response.
- Has no noise.
- Has a high dynamic range.

Human Eye?

integration time: 1/30 second

The Perfect Detector

- Counts every photon it receives.
- Notes the photon's position and energy.
- Has uniform wavelength and spatial response.
- Has a linear response.
- Has no noise.
- Has a high dynamic range.

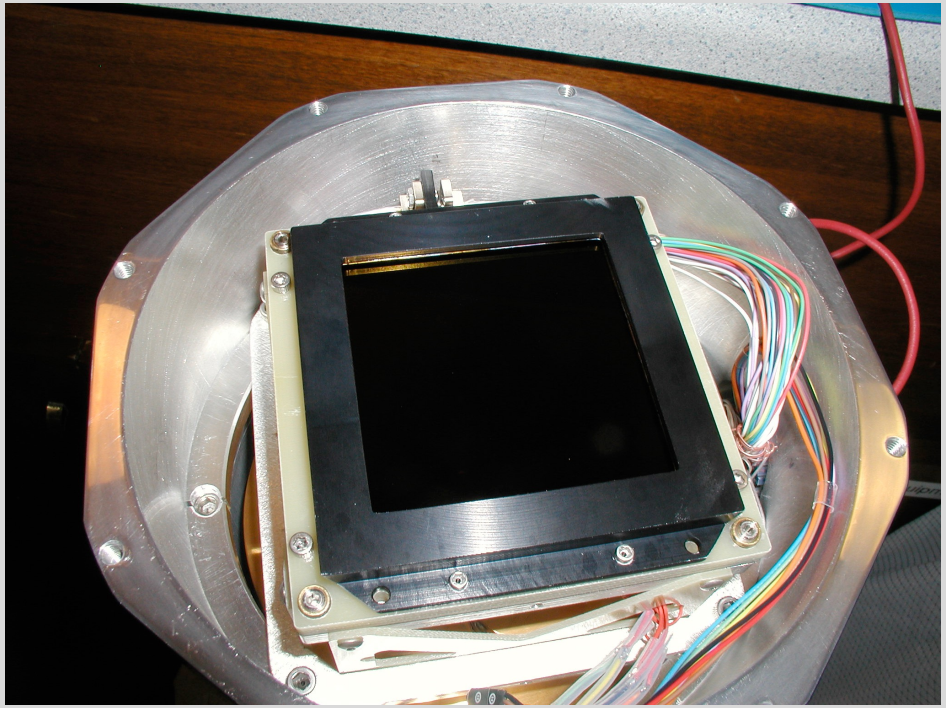
Photographic Film?

integration time: hours

The Perfect Detector

- Counts every photon it receives.
- Notes the photon's position and energy.
- Has uniform wavelength and spatial response.
- Has a linear response.
- Has no noise.
- Has a high dynamic range.

Modern Solution:
Charge Coupled Device (CCD)



integration time: 15-20 min
but images can be stacked

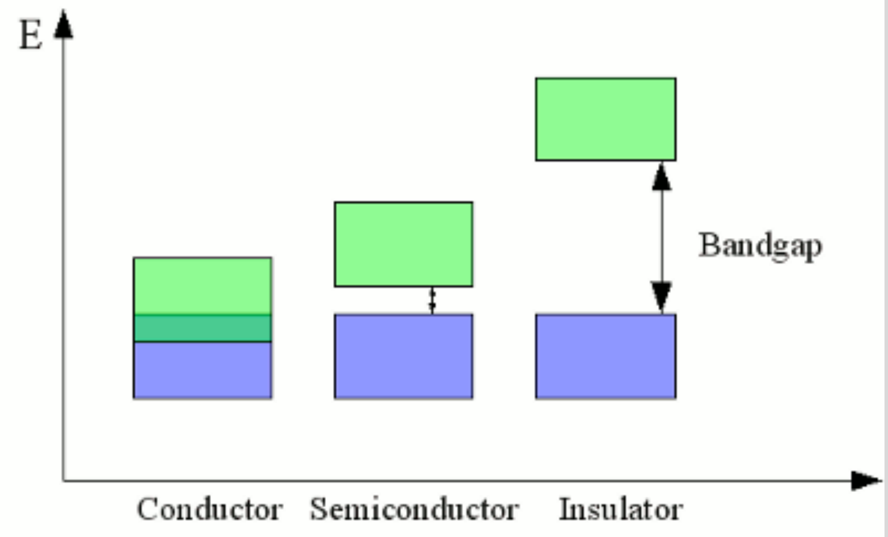
Charge Coupled Devices (CCDs)

Consider a silicon crystal semiconductor, where the electrons live in discrete energy bands.

Electrons in the low energy valence bands are locked in place in the crystal lattice and cannot move.

If you add energy (ie absorb a photon), an electron can jump into the conduction band, where it is free to move around the lattice.

Only photons above a minimum energy will be absorbed and detected.

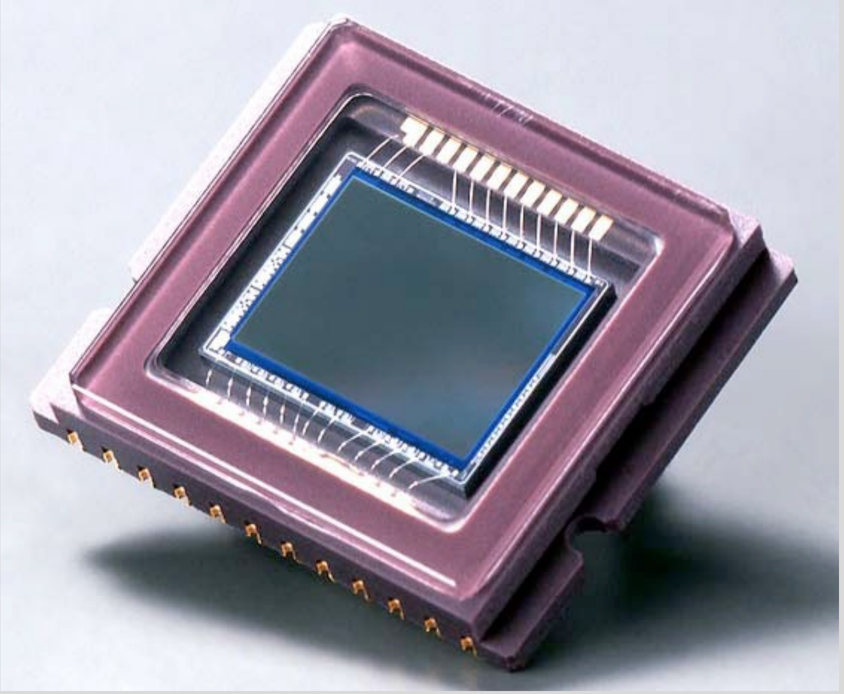


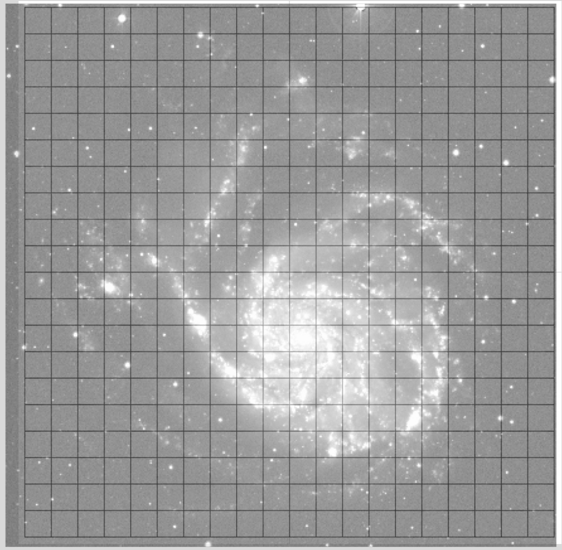
Material	Bandgap	λ_{max}
Silicon	1.1 eV	11,000 Å (1.1μ)
Germanium	0.67 eV	18,000 Å (1.8μ)
InSb (Indium Antimonide)	0.18 eV	6.7μ

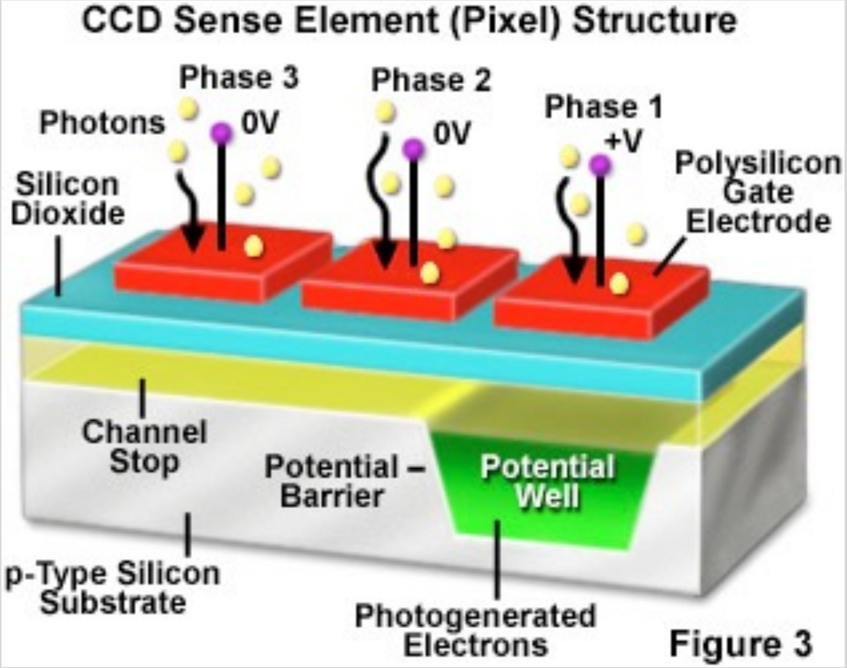
thermal noise: electrons can jump from the valence band to the conduction band on their own, depending on the temperature. CCDs are typically cooled to −125C or lower to reduce thermal noise.

So the material used sets the wavelength coverage and noise characteristics of the CCD.

CCD pixels







When a CCD is exposed to light, photons hit the detector and causing an electron to jump into the conduction band at the spot each photon was absorbed.

A CCD is divided into pixels, which consist of a set of gates where voltages are applied to keep the electrons in place during the exposure.

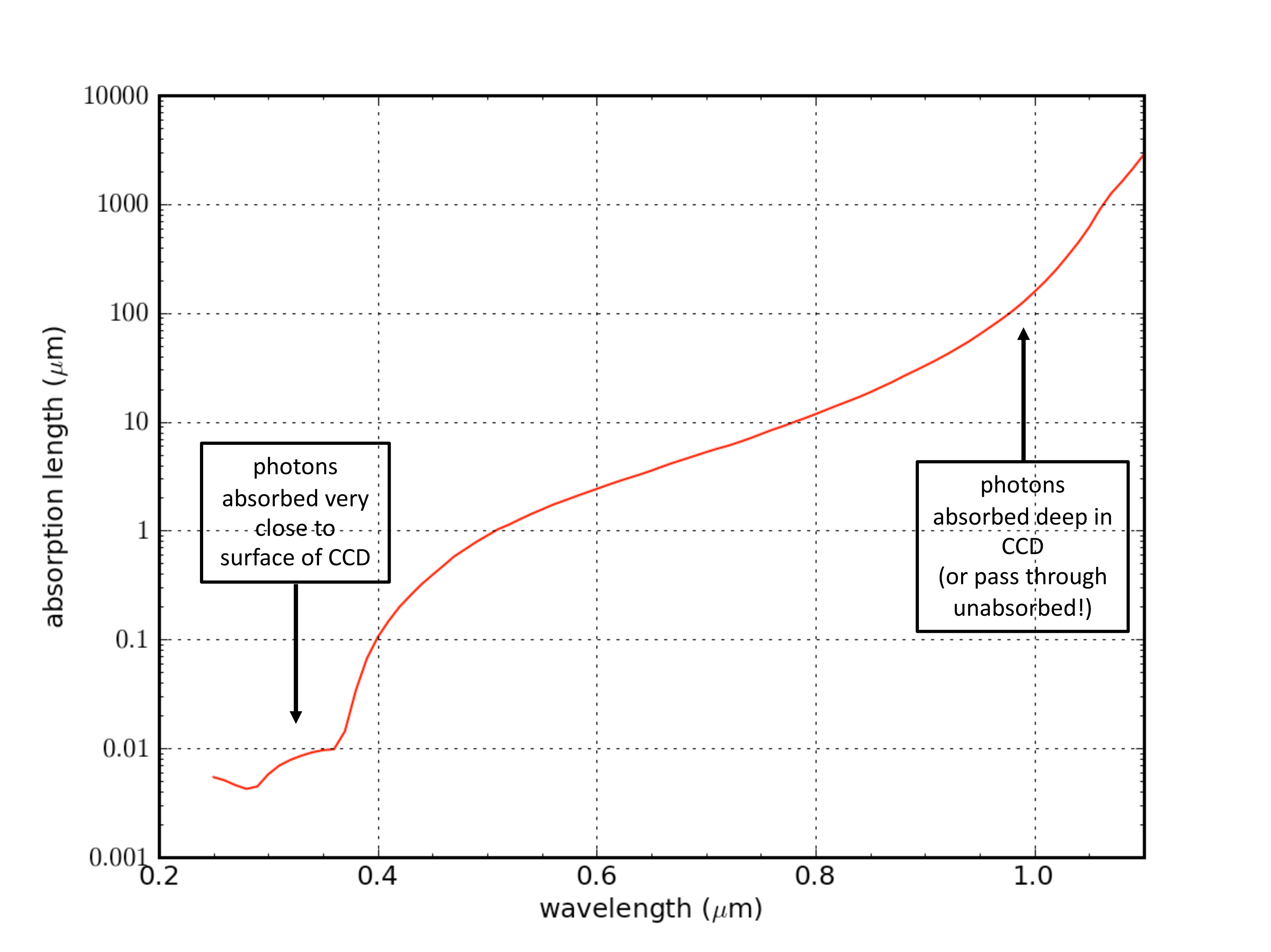
Silicon absorption

How far into the silicon CCD will photons travel before being absorbed?

Depends on the wavelength of the photon.

This determines **quantum efficiency** (the fraction of photons detected).

You want the photons absorbed close to the surface, where they can be captured and controlled by the pixel gates.



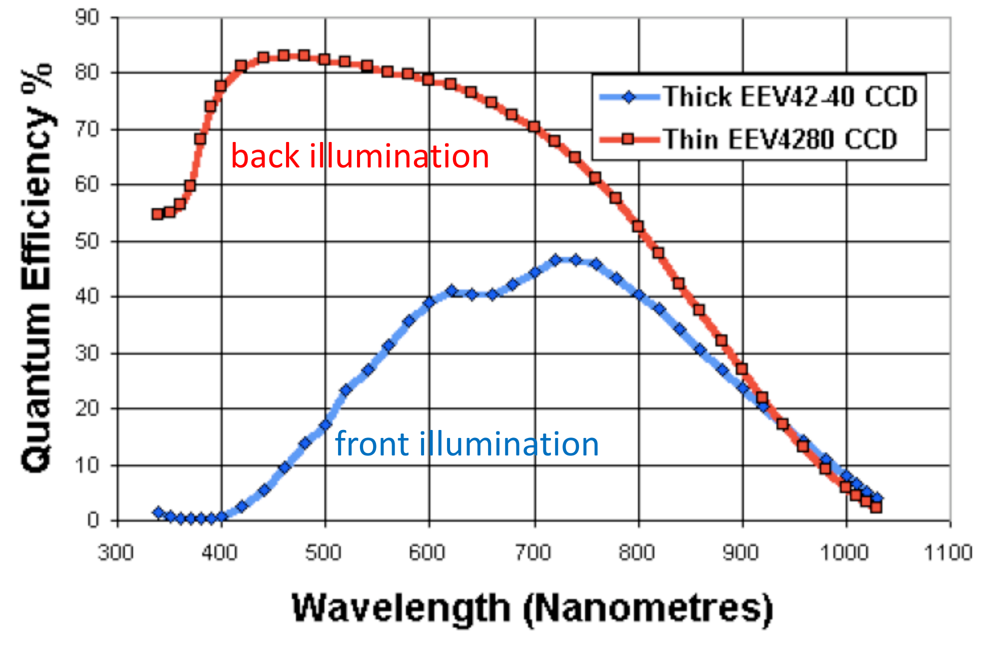
Front and Back Illuminated CCDs

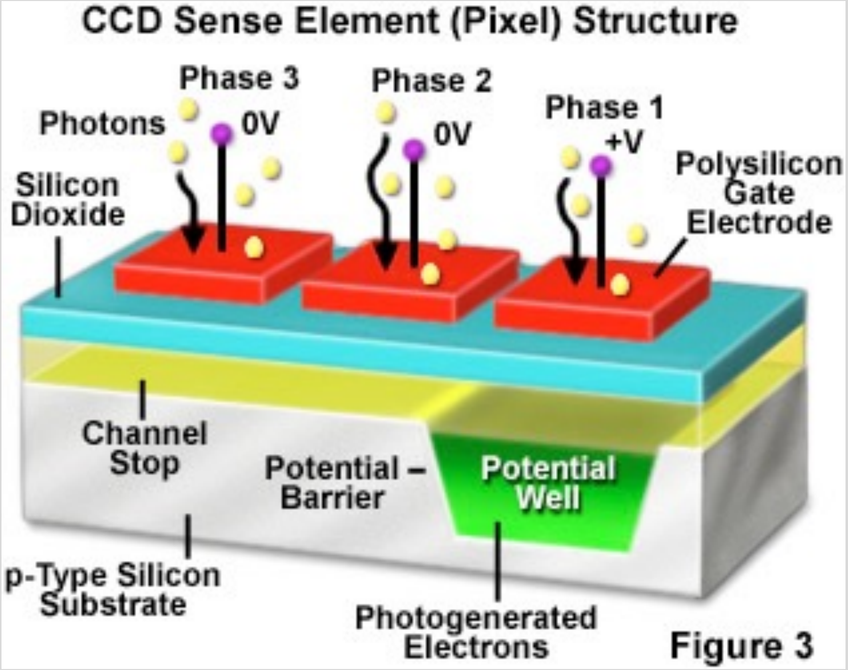
front illumination

CCD consists of a layer of nearly pure silicon covered on one side (front) by electronic gates that control the movement of the photoelectrons.

In front illuminated chips, the photons go through the gate structures before being absorbed. This lowers the quantum efficiency, particularly in the blue.

In back illuminated chips, the photons avoid the gates (raising QE), but they need to be thinned so that the absorption happens close to the gates.



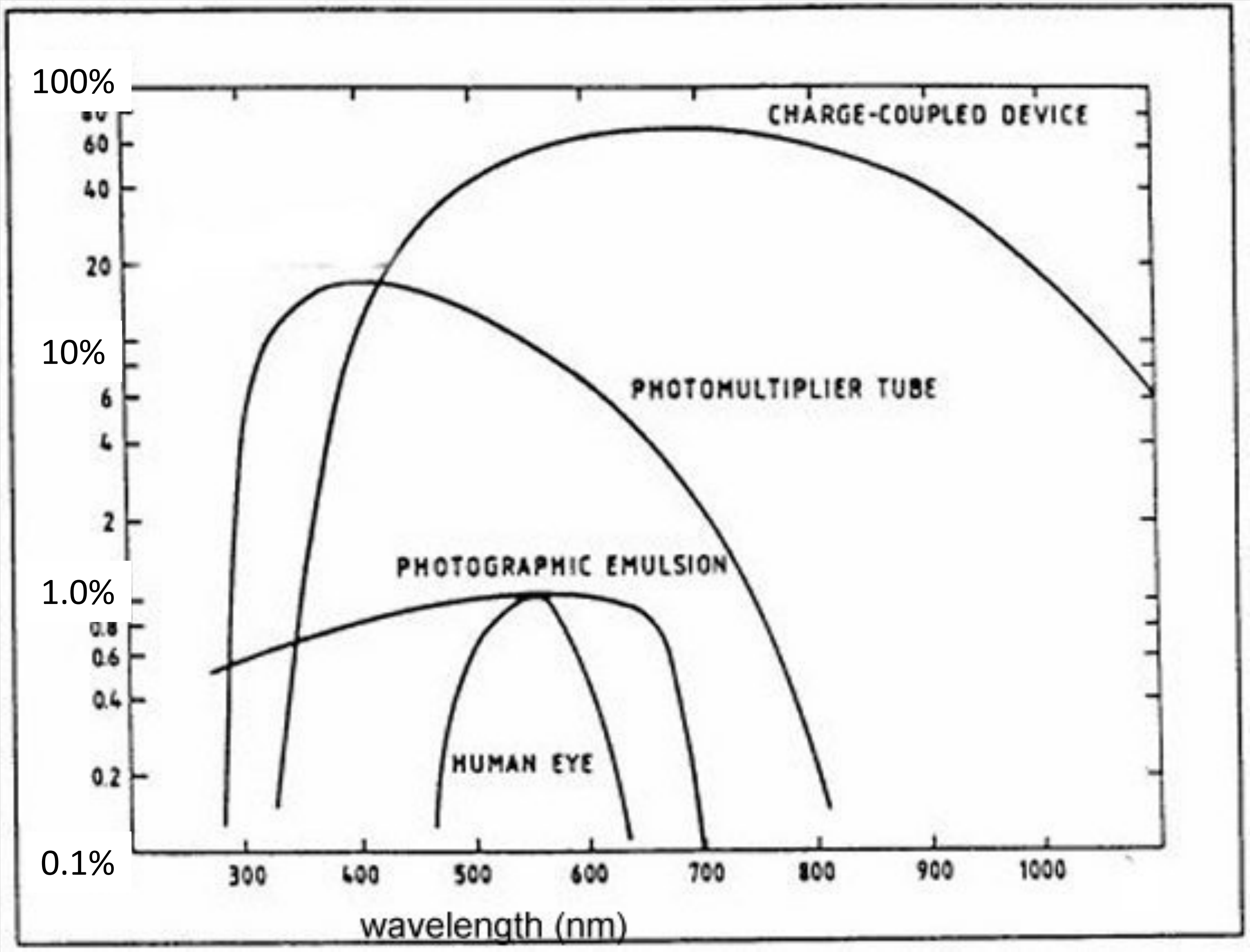


back illumination

Quantum efficiency comparison

A factor of 10 in detection efficiency is like having a telescope that is 3x bigger!

However, you can't go above 100%.....



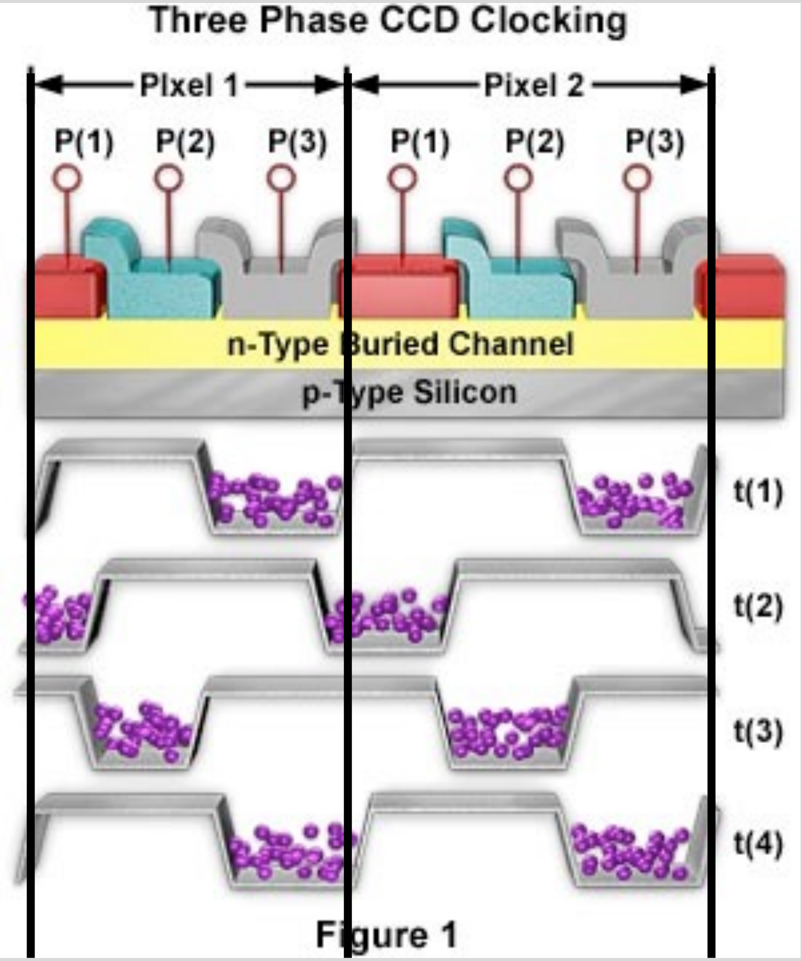
CCD “Read-out”

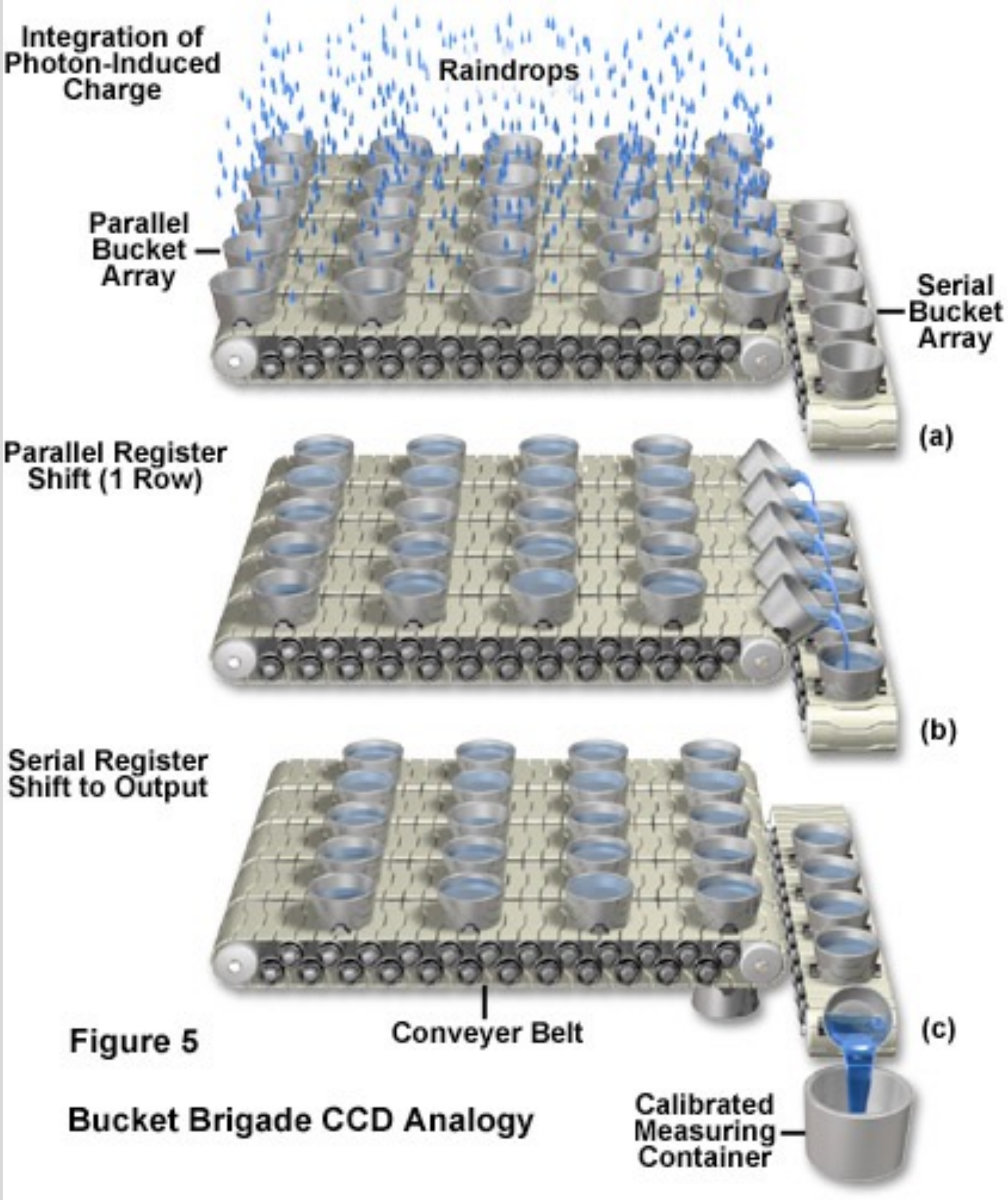
Once the exposure is over, the voltages on the pixel gates can be altered in a pattern that moves the charge across the CCD to be collected.

Reading out a CCD takes time. More pixels (bigger CCD), more time.

Schmidt 4Kx4K CCD: ~ 60 seconds

Readout can be done faster, but then more errors: higher **readout noise**.





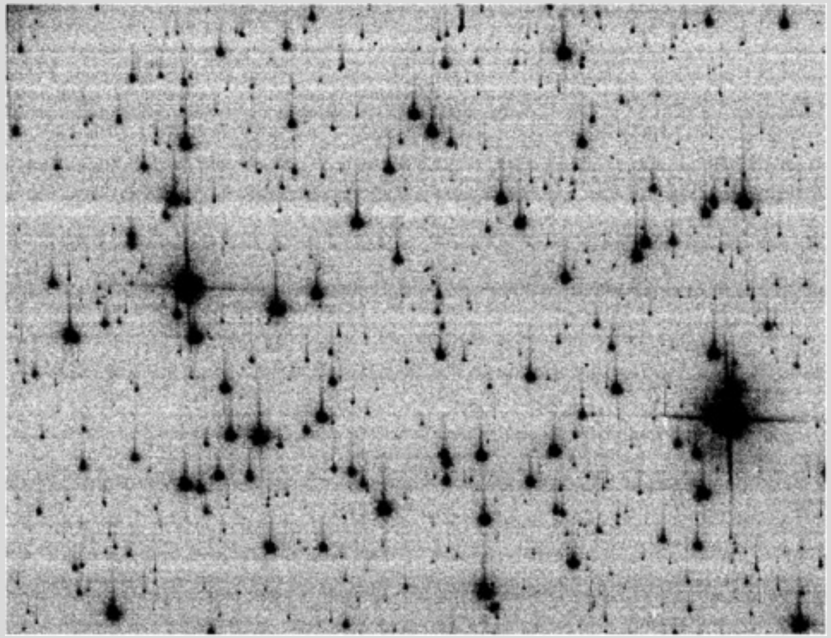
CCD pixel problems: misbehaving electrons

Charge transfer efficiency (CTE)

CTE: The fraction of electrons which are successfully transferred at each step. If you leave electrons behind (poor CTE)

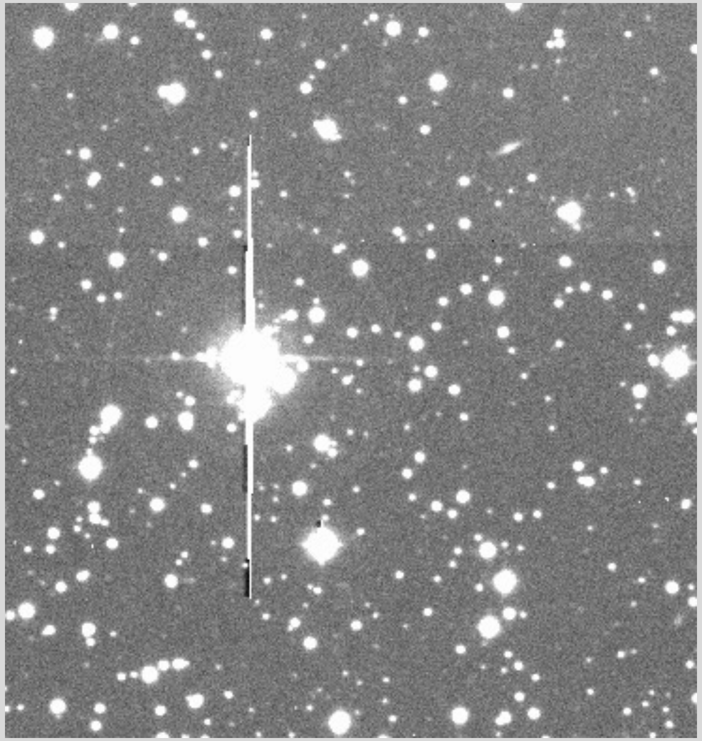
You want CTE ≥ 0.99999 or so!

Hubble ACS CTE effects (Anderson & Bedin 10)



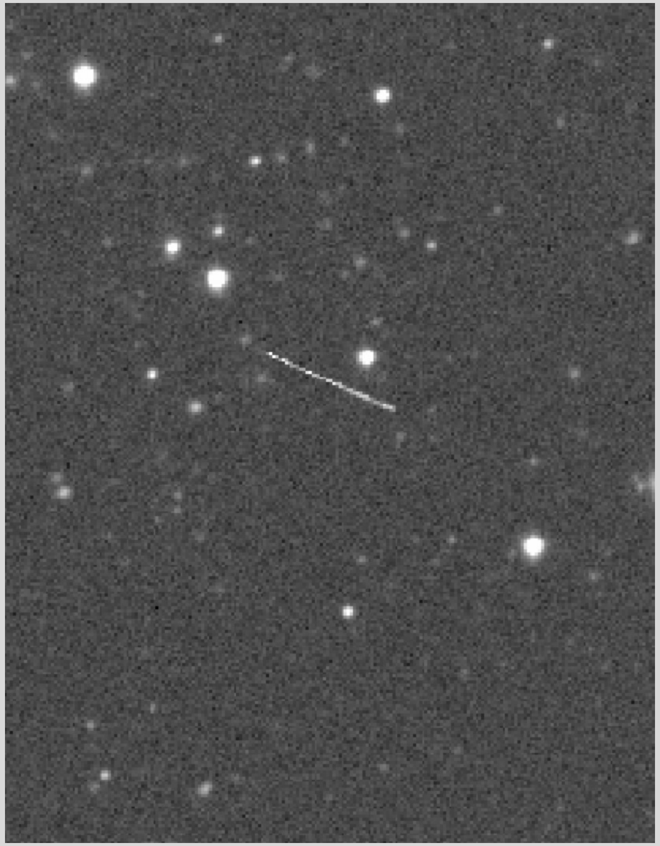
Saturation/Bleeding

A pixel can hold a maximum accumulated charge (full well capacity or saturation). If exceeded, photons will no longer be accurately counted and charge will bleed out to adjacent pixels.



Cosmic rays

Charged particles hit the detector, freeing electrons. Limits exposure times to ~ 15-20 minutes.



CCD Readout Electronics

Amplifier(s)

- converts the read-out charge to a voltage
- adds a **bias** or **pedestal** value to the signal

Analog to Digital Converter(s) (A/D Converters)

- turns output voltage into **counts**, aka “analog/digit units” (**ADU**)
- characterized by a **gain:** how many electrons does each count correspond to? (for example, 3 e^-/ADU)

Readout Noise

- CCD electronics inserting spurious electrons into the stream.
- conversion from analog signal to digital number is not perfectly repeatable.
- *faster readout usually produces higher readout noise*
- characterized as a certain number of electrons (e^-) per pixel

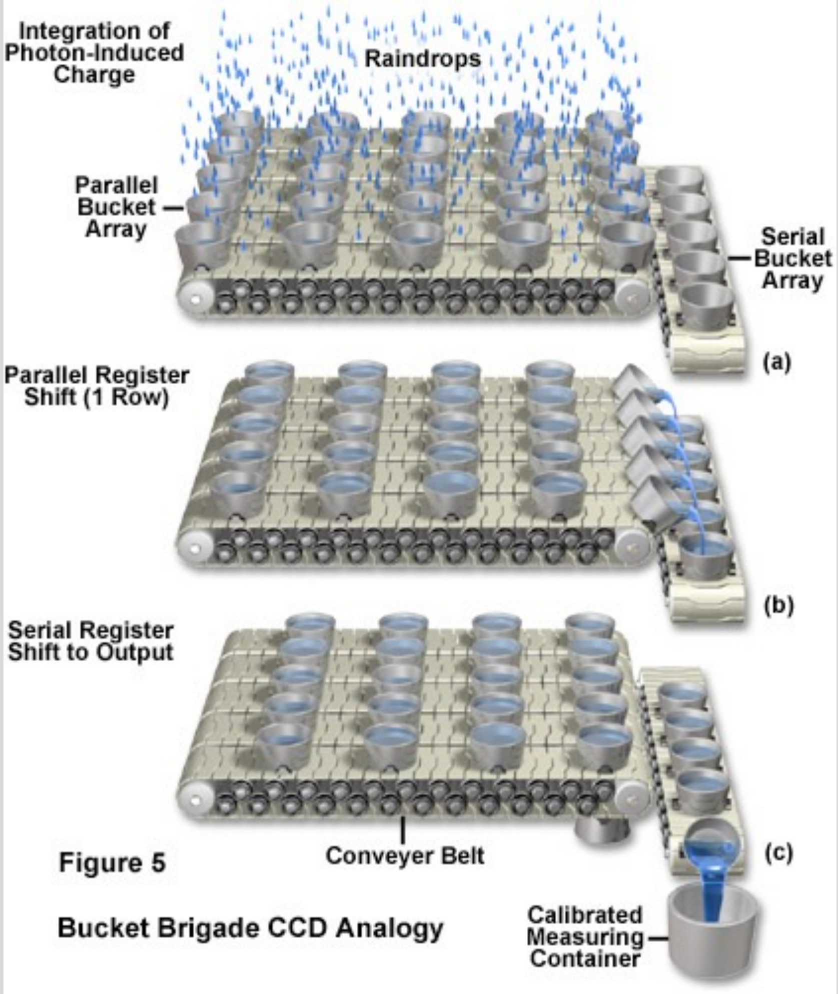
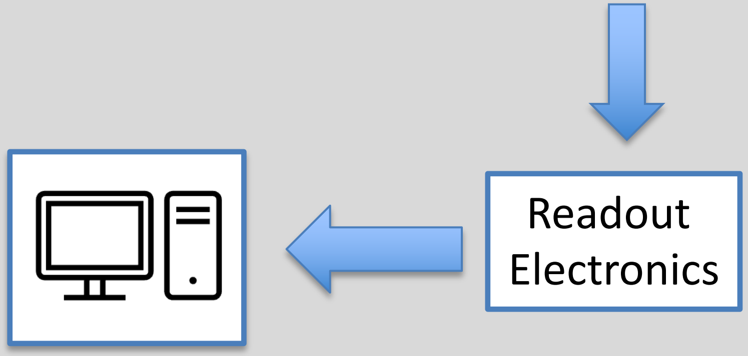


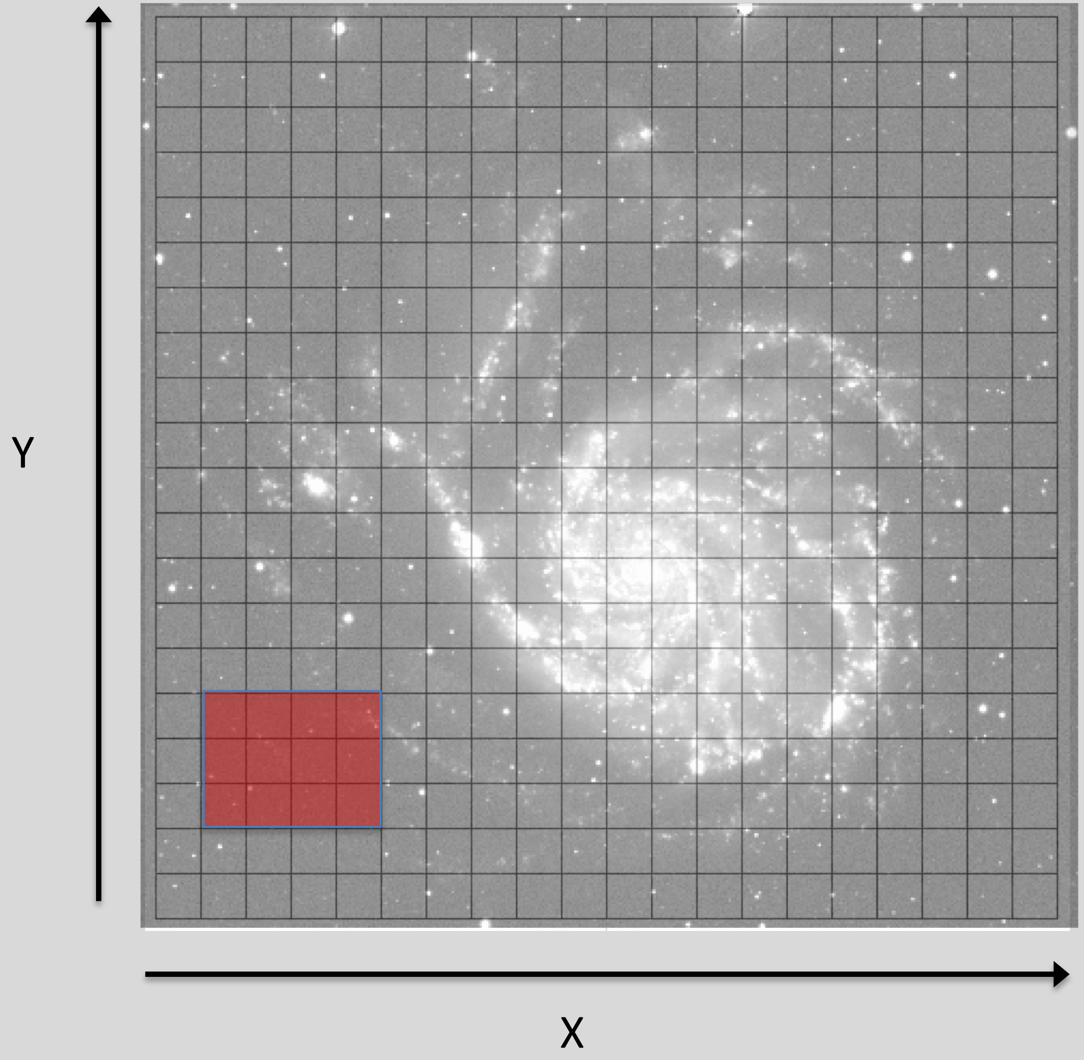
Figure 5

Bucket Brigade CCD Analogy

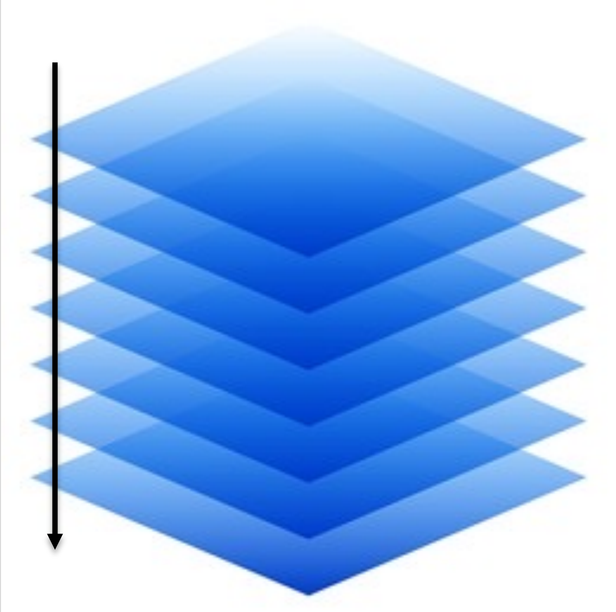


Concept of ”image math”

Images can be thought of mathematically as 2D arrays of intensity.



pixel-by-pixel math
along a multiple images.

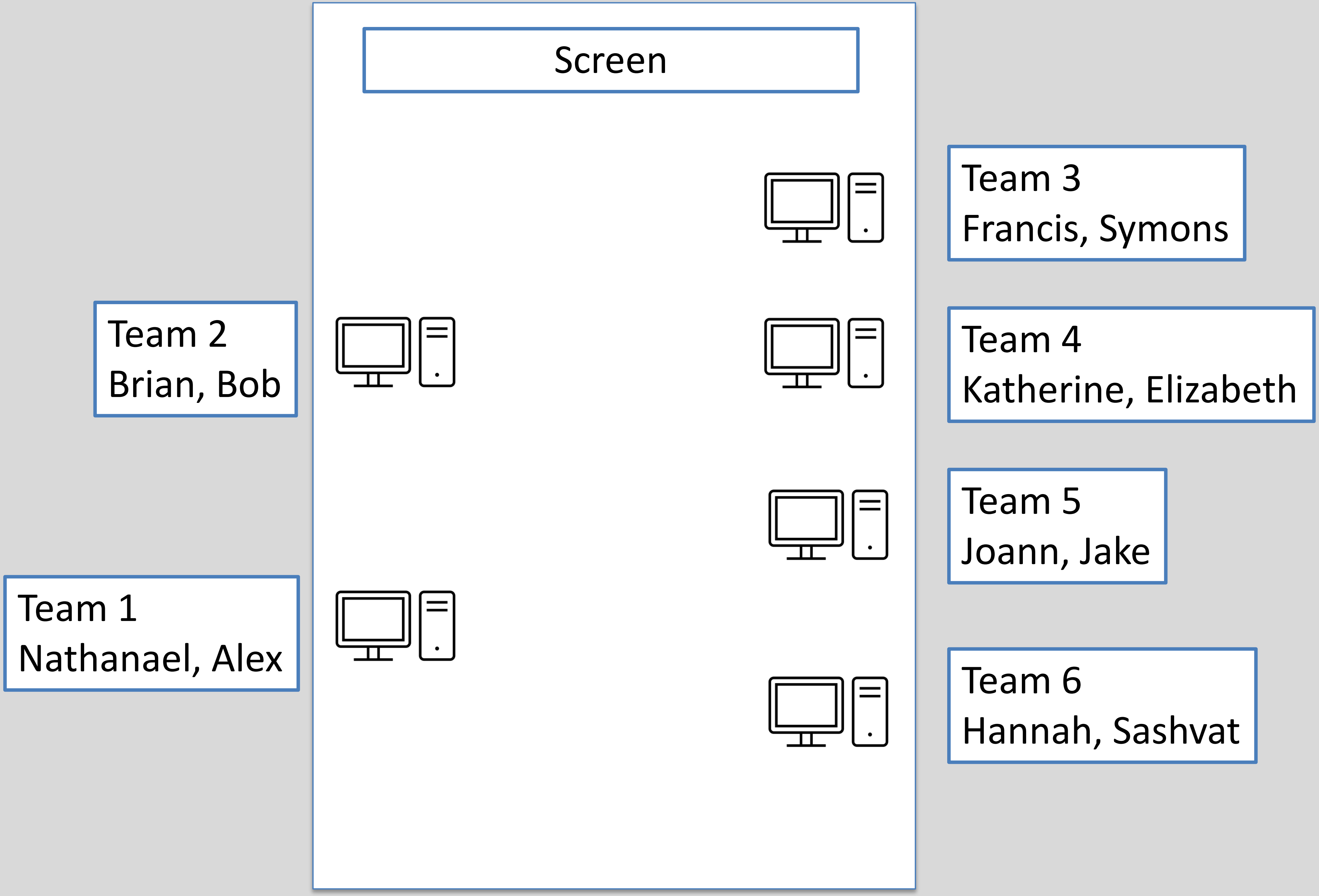


Images can be:

- added or subtracted
- multiplied or divided
- averaged or medianed

You can also do statistical analysis of regions:

- sums (measures total flux in a region!)
- standard deviation (measures flux variation in a region)


Screen
Team 3
Francis, Symons
Team 2
Brian, Bob
Team 4
Katherine, Elizabeth
Team 5
Joann, Jake
Team 1
Nathanael, Alex
Team 6
Hannah, Sashvat

CCD Data Reduction: Conceptual Steps

First question: what patterns does the readout process imprint on the image? In other words, what does an image look like if you don't expose the CCD to any light?

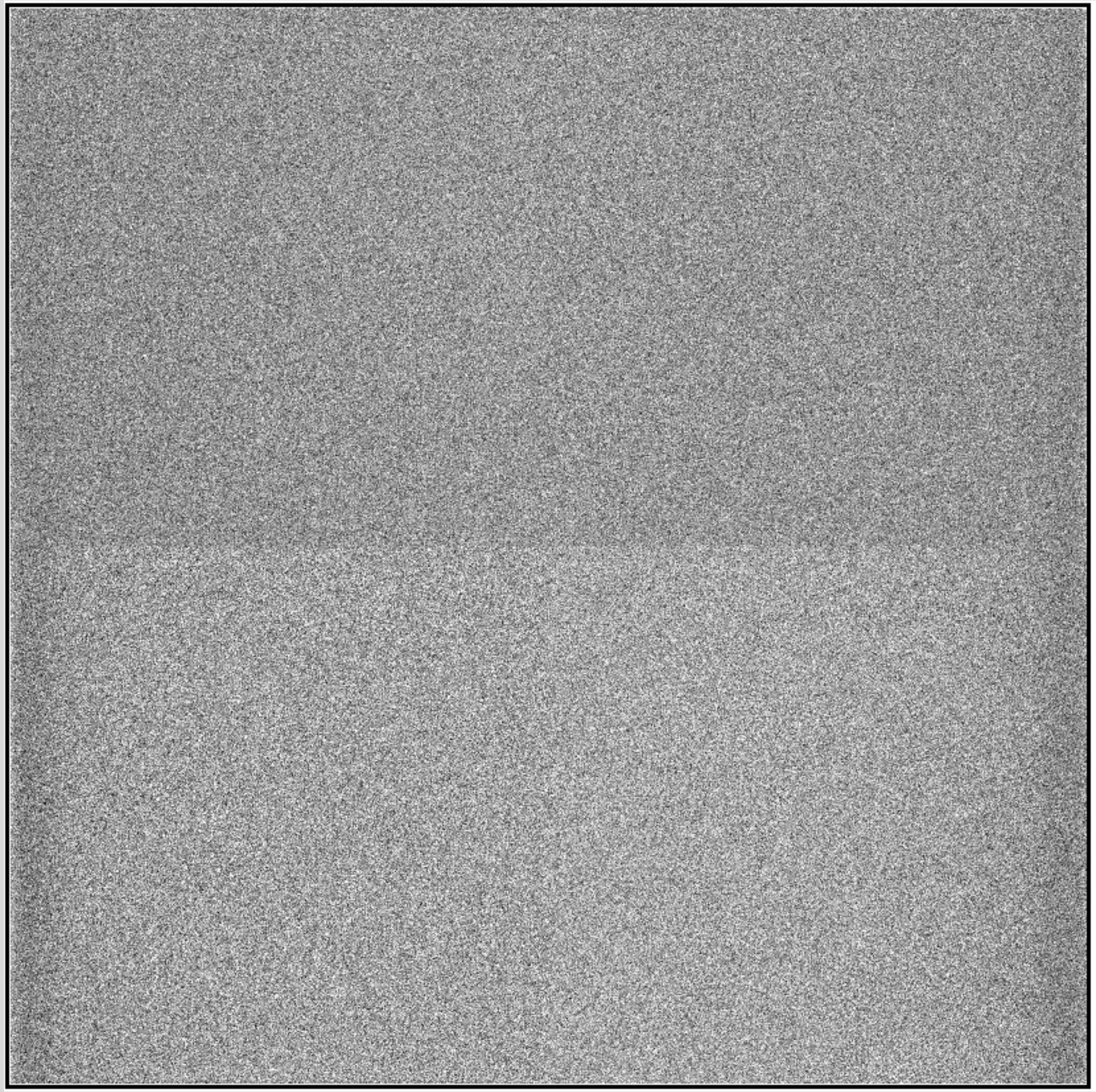
Zero images and Zero Subtraction

Read out the CCD without exposing it to light. This shows the readout noise and any systematic spatial pattern associated with it.

Every readout adds a **random noise signal** (the readout noise) to each pixel an image. This is random, and different, for every image.

It sets a "floor" to the noise level in a single image.

Schmidt CCD readout noise is 3.6e^{-} or about 1.4 ADU.



Schmidt 4Kx4K CCD zero image, showing fluctuations at the +/- 5 ADU level.

CCD Data Reduction: Conceptual Steps

First Concern: what patterns does the readout process imprint on the image? In other words, what does an image look like if you don't expose the CCD to any light?

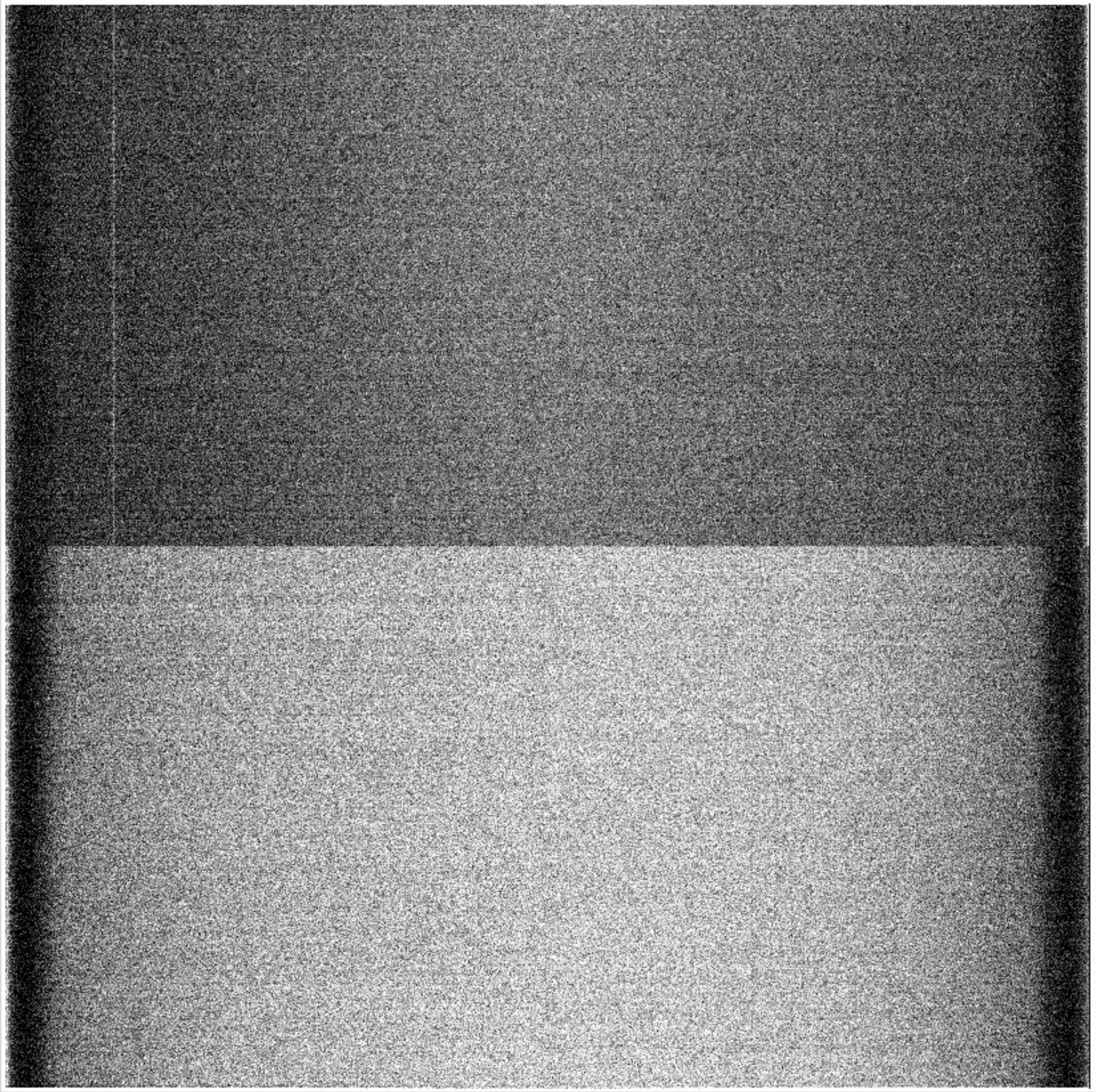
Zero images and Zero Subtraction

Read out the CCD without exposing it to light. This shows the readout noise and any systematic spatial pattern associated with it.

Schmidt CCD readout noise is 3.6e$^-$ or about 1.4 ADU.

By co-adding many zero images, you can beat down the readout noise (hopefully by $\sqrt{N}$) and see the underlying systematic pattern: **fixed pattern noise**

This pattern can be removed by **subtracting the co-added zero** from every image taken, but the basic readout noise of each pixel will remain.



25 co-added Schmidt 4Kx4K CCD zero images, showing fluctuations at the +/- 1 ADU level.

CCD Data Reduction: Conceptual Steps

Second Concern: Is there a noise component that grows with time, so that longer exposure have more noise? The longer you expose the more problematic these noise sources will be.

Dark subtraction

Over the course of a long exposure, thermal electrons can jump from the valence band to the conduction band and introduce a **thermal or dark current**.

Also may have scattered light or “**light leaks**” in the telescope: light getting to the detector from extraneous sources.

To correct for this, take long exposures (**dark frames**) with the CCD blocked from being exposed to light. This dark frame can then also be subtracted from all your images.

Most modern optical CCDs have very low dark current, but the problem is much worse with infrared CCDs (which have a narrow energy gap between valence and conduction bands).

CCD Data Reduction: Conceptual Steps

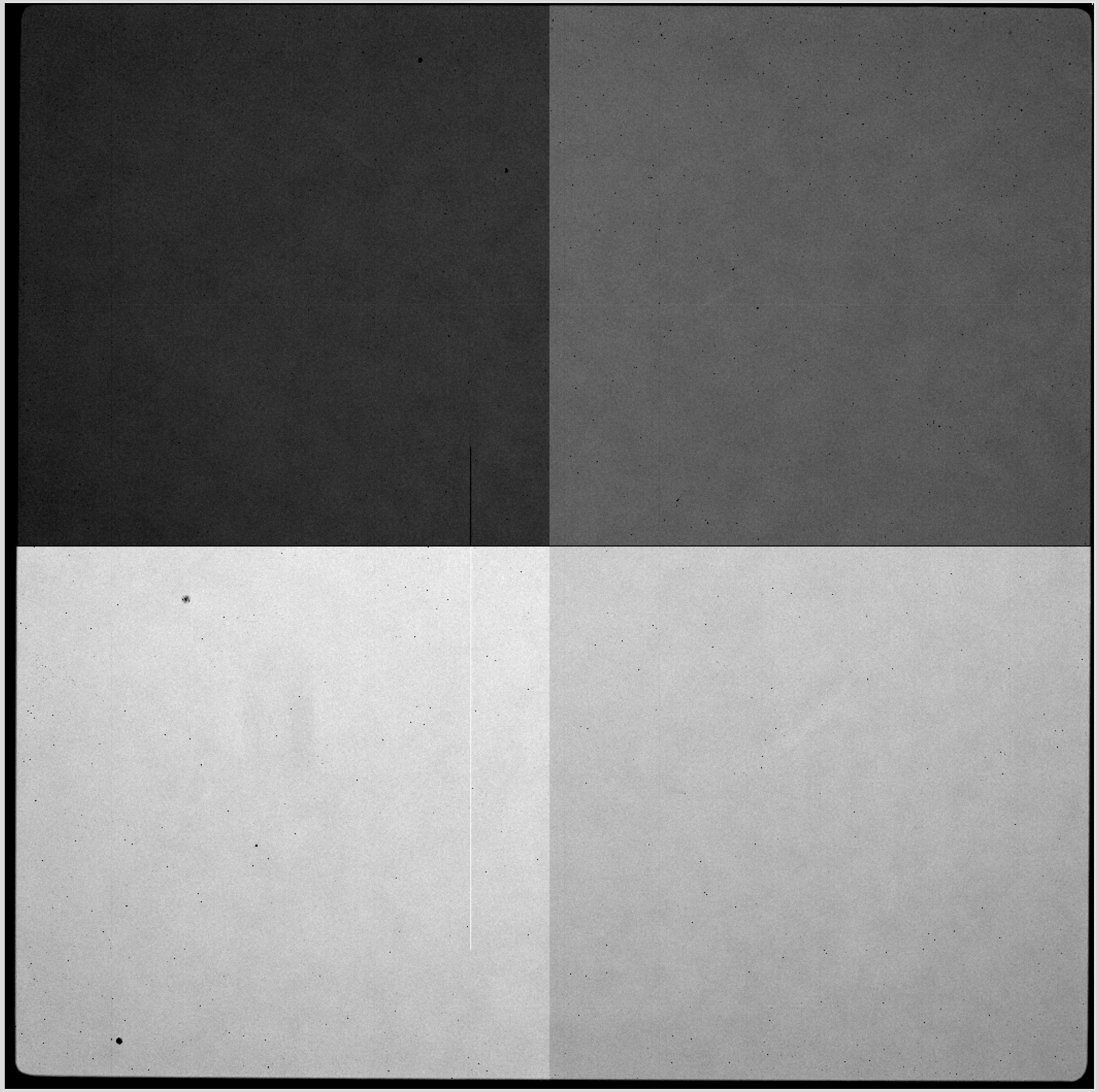
Schmidt 2019 flat field

Third Concern: The sensitivity of the detector may not be unform across the field of view, or the gain (e^-/ADU) may differ in different parts of the detector.

Flat fielding

Expose the CCD to a source of illumination that is uniform across the field. These **flat field** images can be made using various techniques:

- **dome flat**: pointing telescope at a white screen on the dome
- **twilight flat**: pointing telescope at the twilight sky
- **dark sky flat**: co-adding many images of sparsely crowded night sky.



Notice variations in gain in different quadrants

CCD Data Reduction: Conceptual Steps

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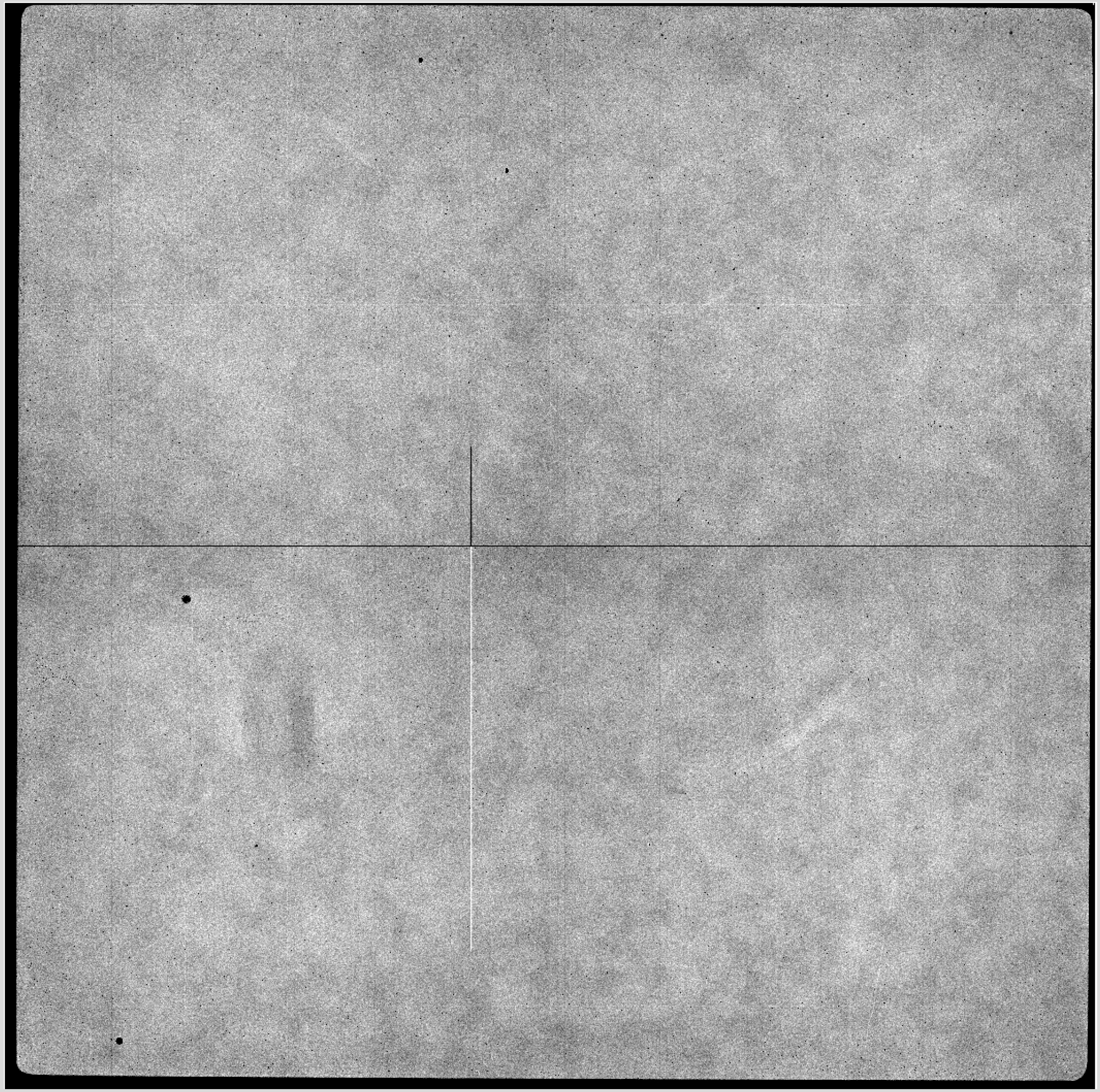
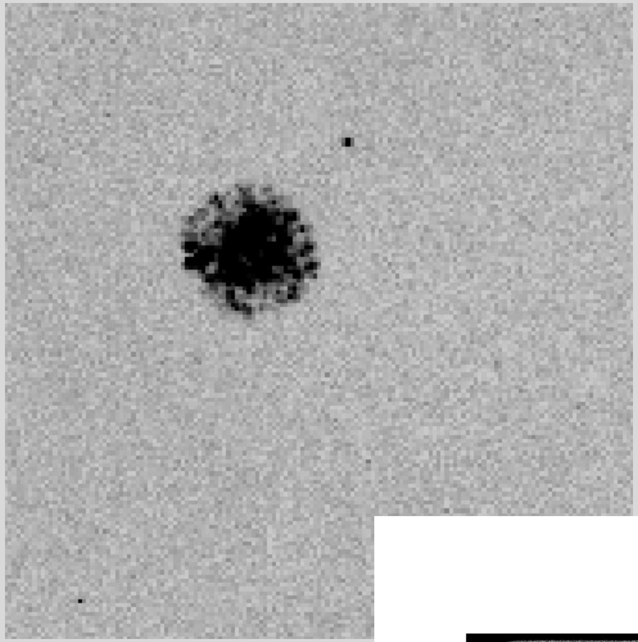
Schmidt 2019 flat field

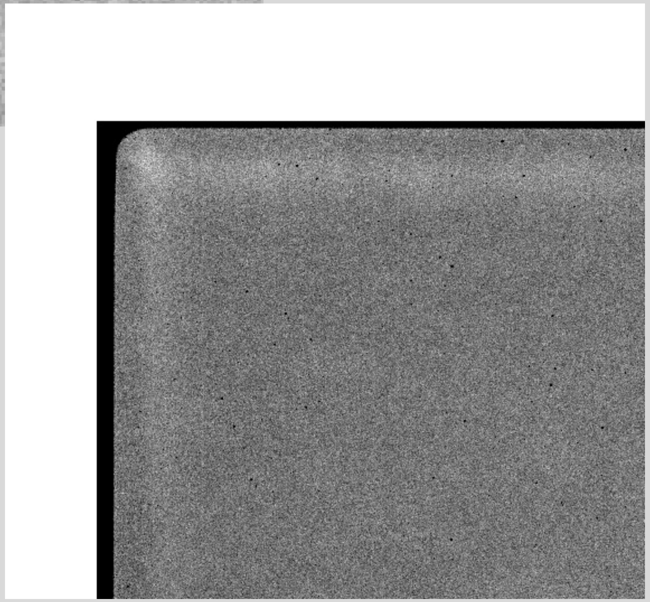


After removing gain variations we see sensitivity variations

CCD Data Reduction: Flat field features

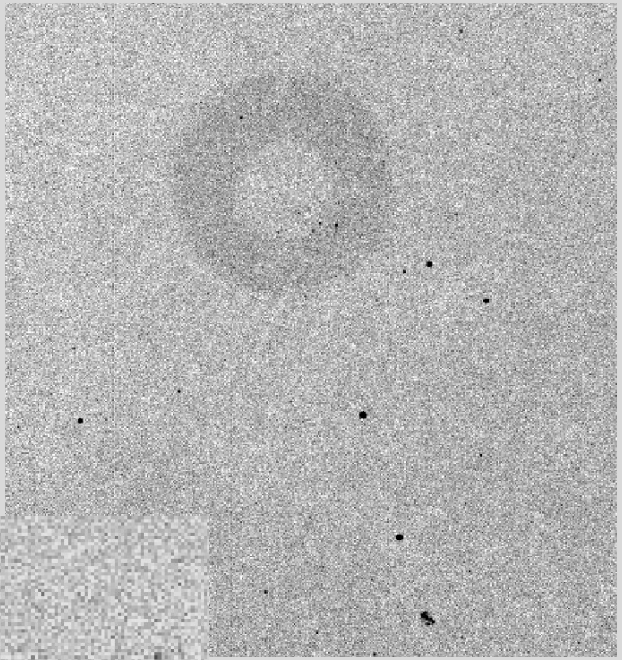


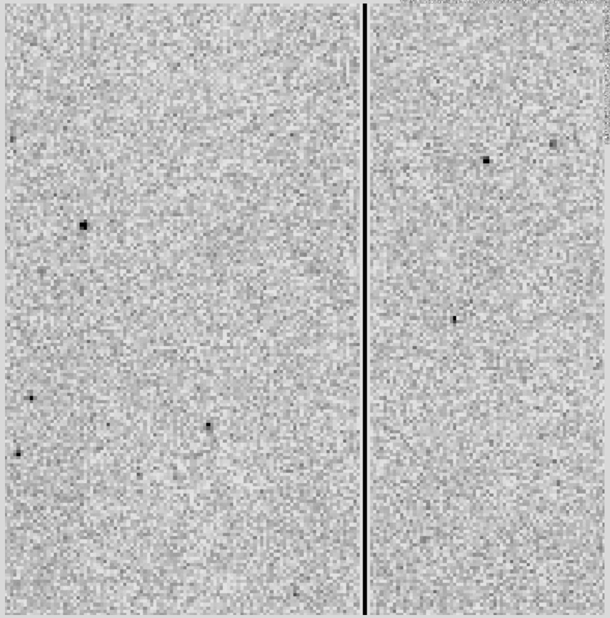
CCD blemish



vignetting and large scale features

dust spot





bad columns

CCD Data Reduction: Conceptual Steps

Third Concern: The sensitivity of the detector may not be unform across the field of view, or the gain (e^-/ADU) may differ in different parts of the detector.

Flat fielding

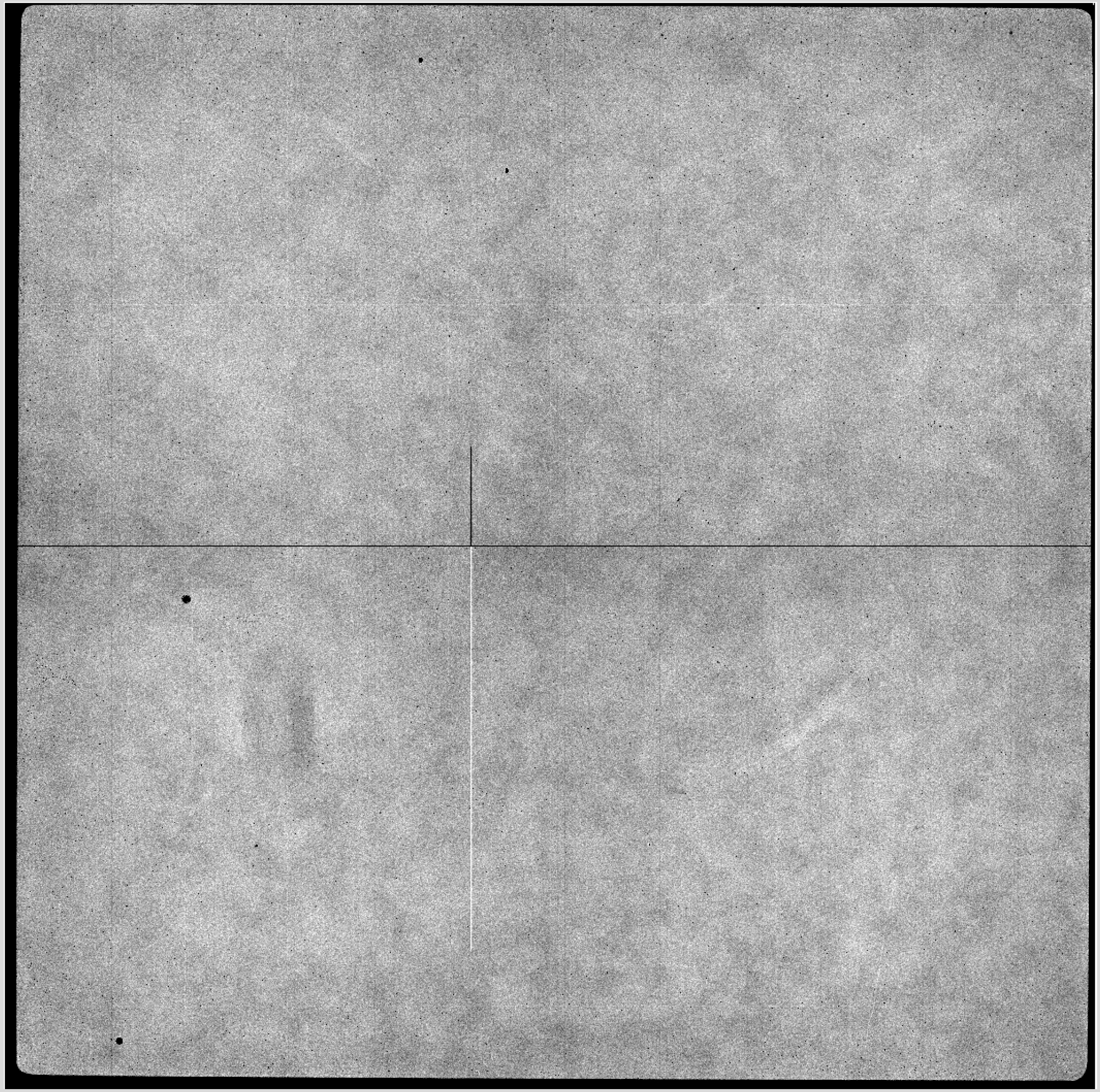
Expose the CCD to a source of illumination that is uniform across the field.

Normalize (rescale) the flat field image so that it has an average value of 1.0 across the image – some pixels will be higher than one (more sensitive) and some will be lower than one (less sensitive).

Then ***divide*** your science images by the flat field.

These sensitivity variations are wavelength dependent, so you must have a flat field taken through every filter you are observing with!

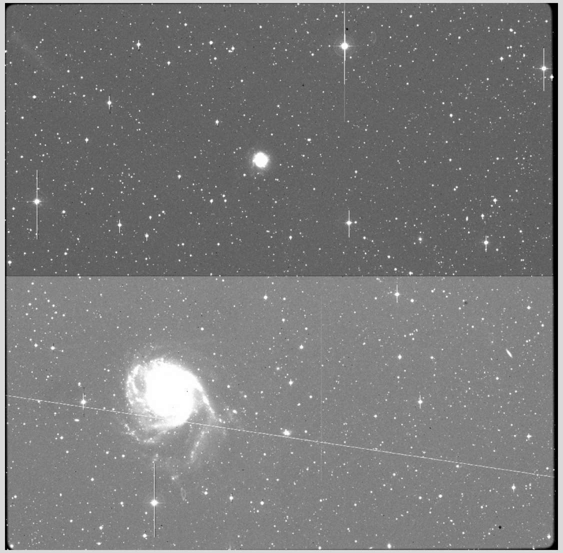
Schmidt 2019 flat field



After removing gain variations we see sensitivity variations

CCD Data Reduction: Conceptual Steps

Reduced Image = (Raw image – Master Zero [– Dark]) / Flat



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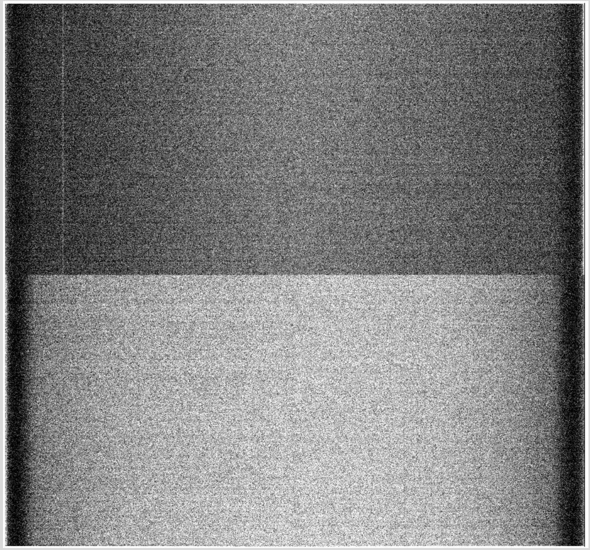

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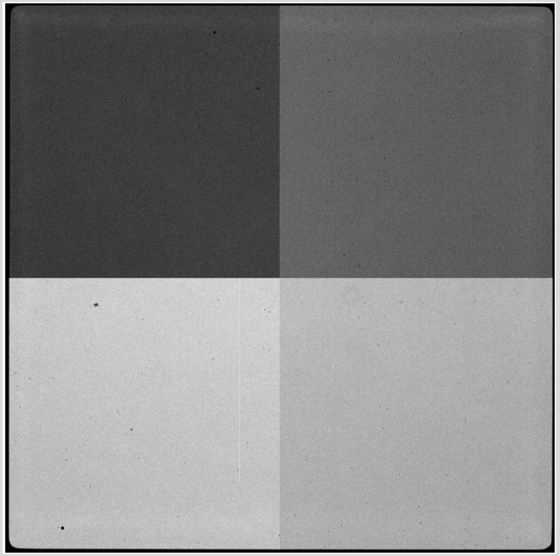

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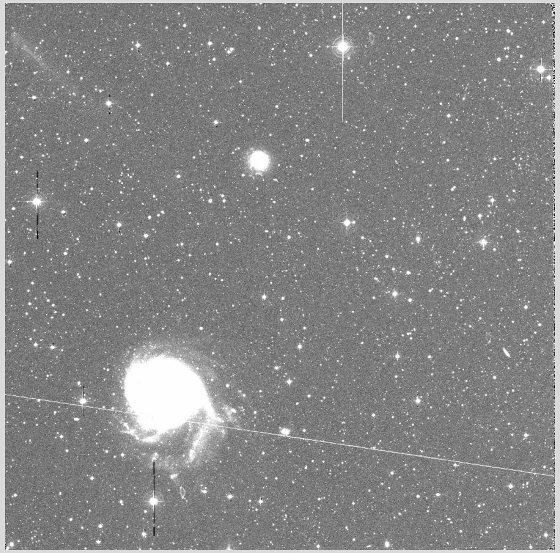
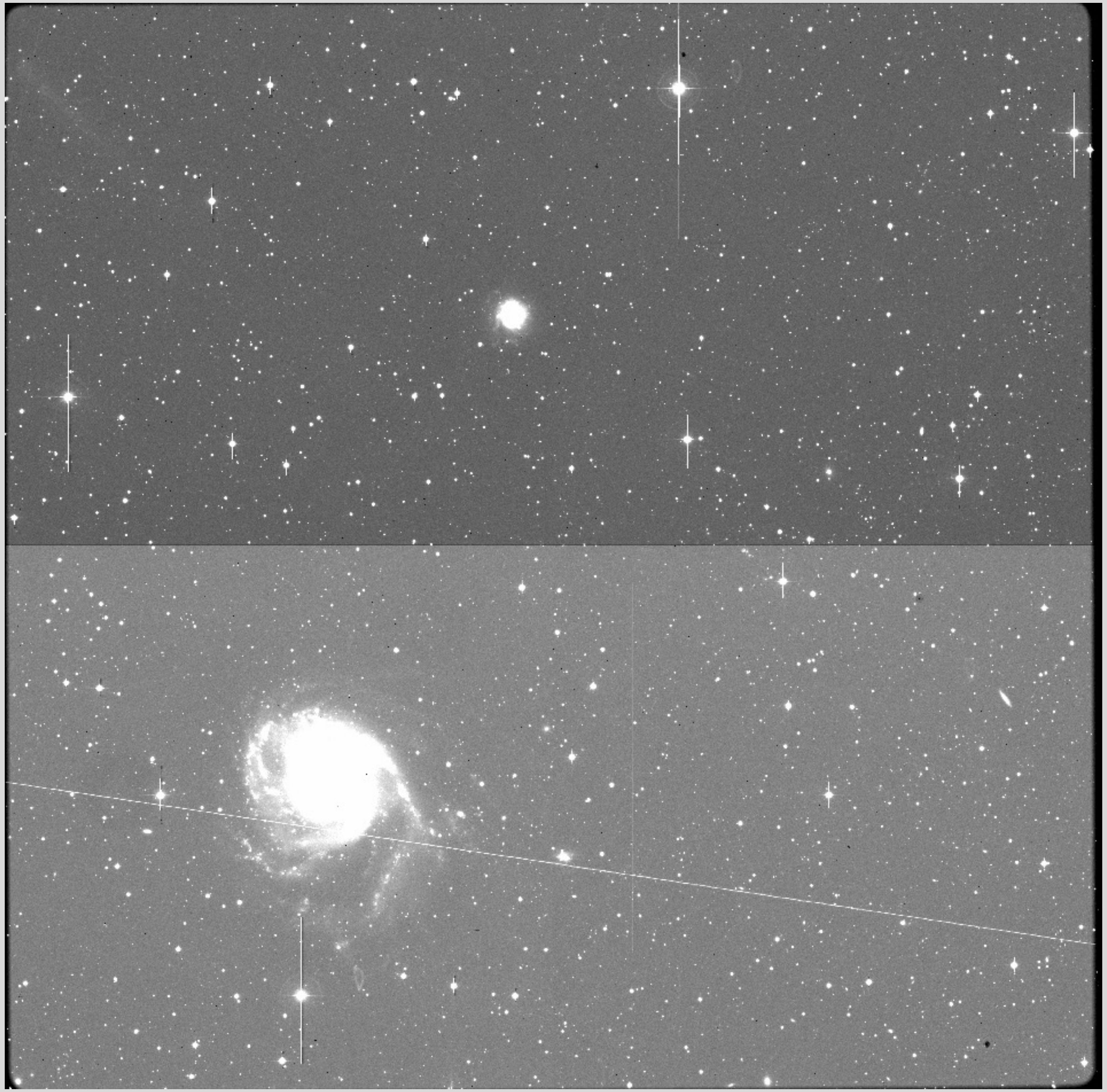


CCD Data Reduction: Conceptual Steps

Raw image



Reduced Image