

# Lecture 3

September 20, 2018

Telescopes and CCD Camera

# News

- Rutgers Astronomical Society (RAS)
  - Help with public observing nights (tonight is cancelled) + other activities.
- Society of Physics Students (SPS)
  - Listen to talks + other activities.
- 2019 APS Conference for Undergraduate Women in Physics: Friday, Jan 18 through Sunday, Jan 20
  - The College of New Jersey (TCNJ)

# News

- Note there are a few changes in lab assignments.
- Note the importance of being prepared for your lab period – 2 hours is not much time.
  - Carefully read the lab before showing up!
  - Is there any prior planning that you need to do?

# News

- Lab 2 is **now due October 4.**
  - Maintain 7:30 – 9:30 and 9:30 – 11:30 PM lab periods
  - **Observing will continue in the coming week... but start work on writing up what you can.**
    - Friday: clear – visual observing; cloudy – flats/biases lab
    - Sunday: clear – finish visual observing; cloudy – flats/biases
    - Monday: clear – visual observing; cloudy – no lab
    - Tuesday: clear – no lab; cloudy – flats/biases
    - Wednesday: clear – visual observing; cloudy – no lab
  - Analysis part of “cloudy lab” now available. Work on that if you don’t have visual observations to write up.
- Lab 3 will be handed out next week.

# Schommer Obs. Telescope Properties

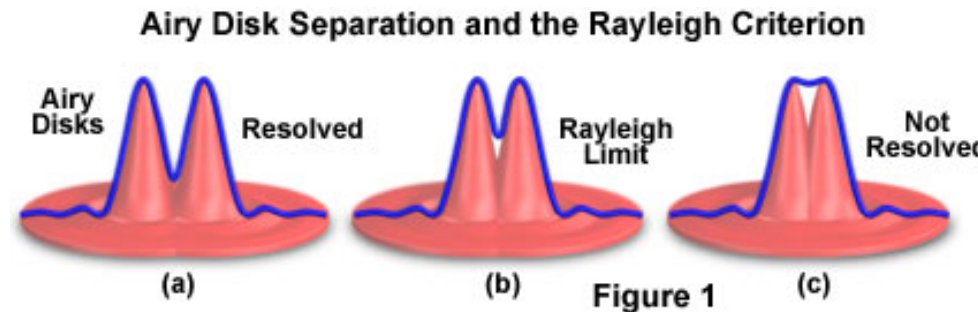
- **Light-collecting area:**

- $Area = \pi(d / 2)^2 = \pi(0.5m / 2)^2 = 0.20m^2$

- Minus the  $\sim 20\%$  central obscuration

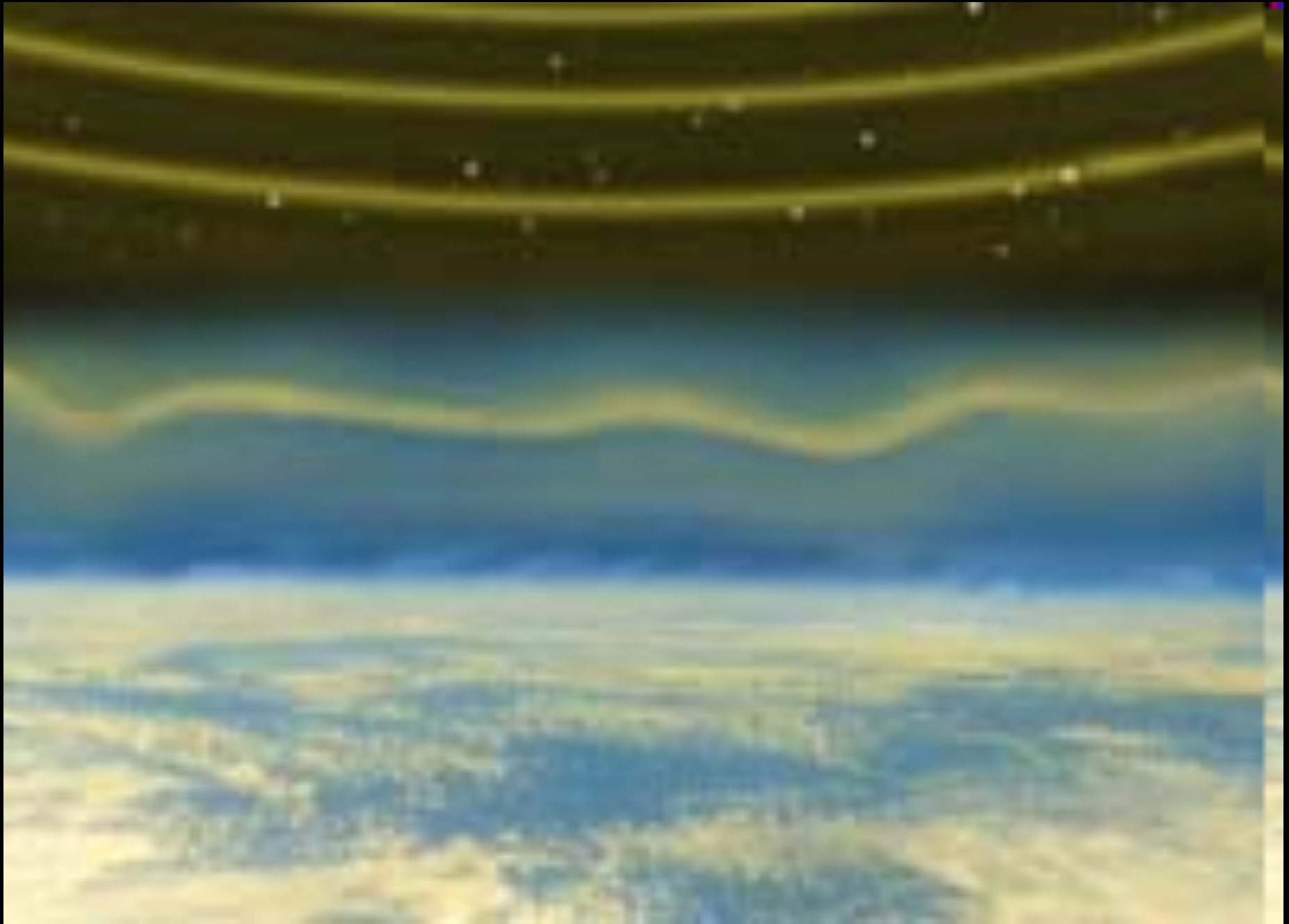
- **Angular resolution:**

- $$\theta_{Rayleigh} = 1.22 \left( \frac{\lambda}{d} \right)$$
$$= 1.22 \left( \frac{500nm}{0.5 \times 10^9 nm} \right) = 1.2 \times 10^{-6} rad = 0.25''$$



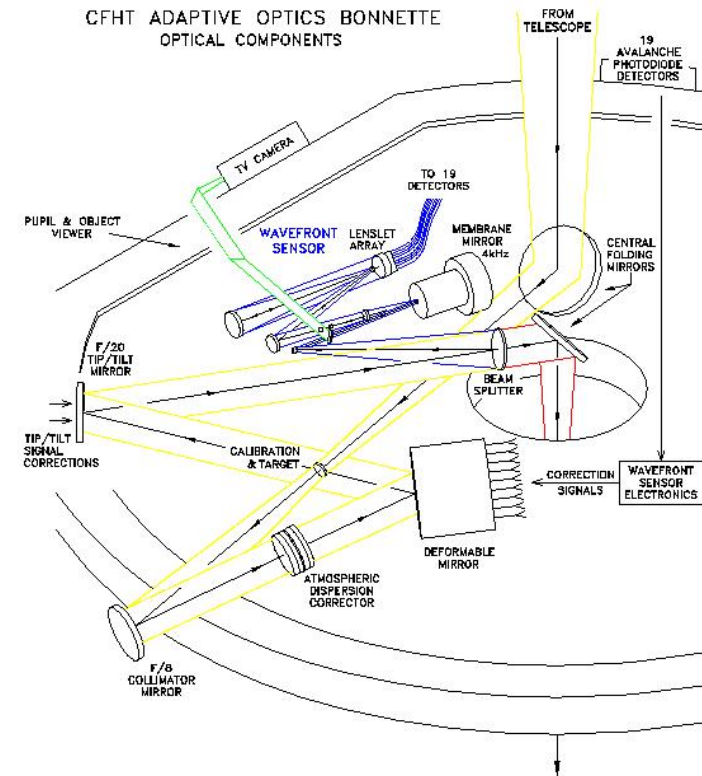
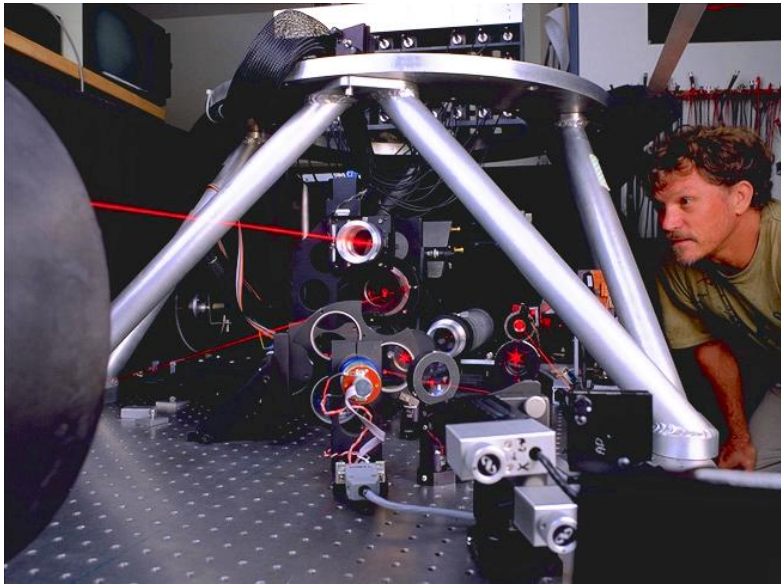
- Limited to 1–2 arcsec by atmospheric turbulence (can be as good as 0.5 arcsec at best sites).

The atmosphere acts like many lenses, bending incoming light rays.

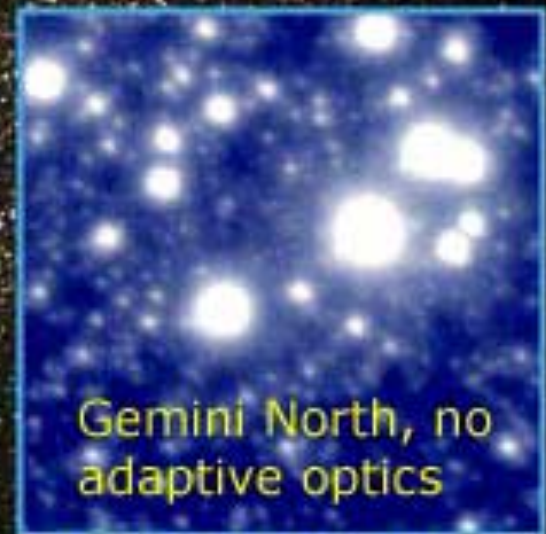
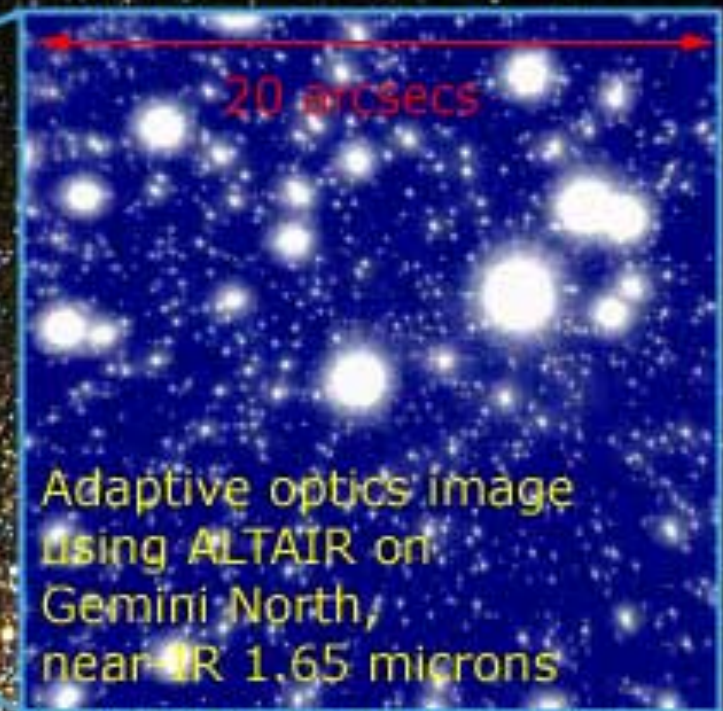
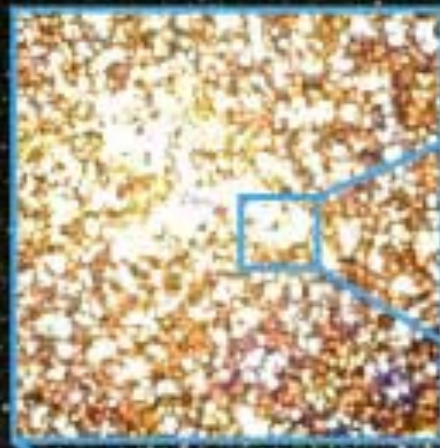


# Angular Resolution

- A solution to atmospheric distortion: *adaptive optics*
  - Bend your telescope mirror to remove the deflections introduced by the atmosphere.
  - Significantly increases complexity of telescope and needs fast computer processing.
  - Not perfect, but does help.



# Example of adaptive optics on globular cluster M13



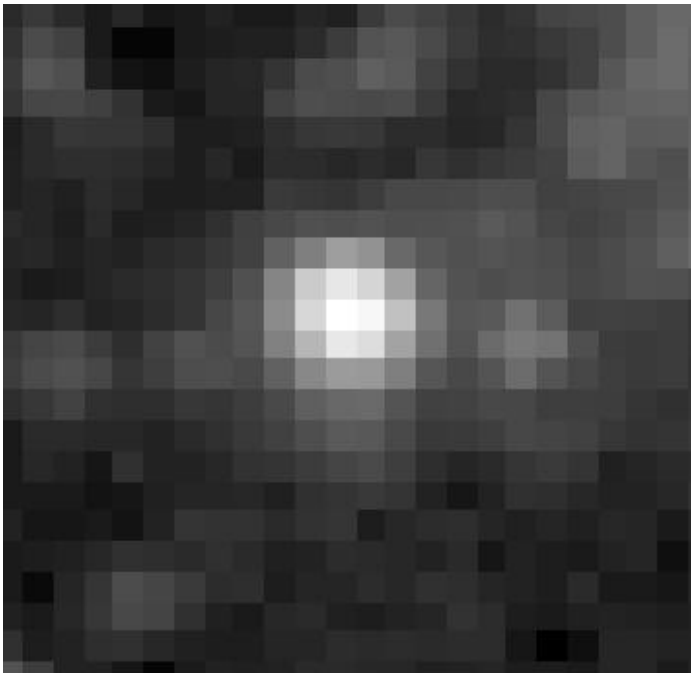
Wide-field image of M13 by  
Canada-France-Hawaii Telescope



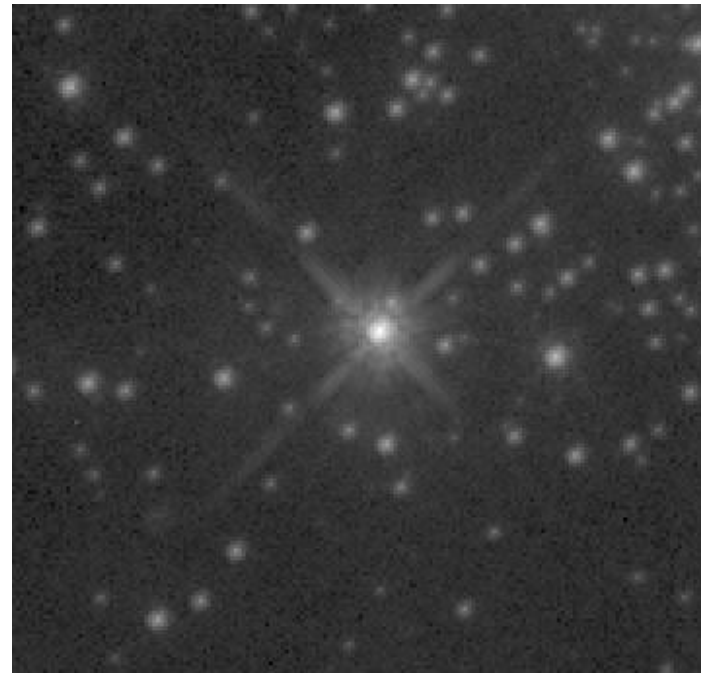
Another solution: put your telescope in space, above the atmosphere



Main problem: very expensive. Hubble cost \$1.5 billion to launch and requires \$100 million/yr to run.



Bright star viewed with  
ground-based telescope

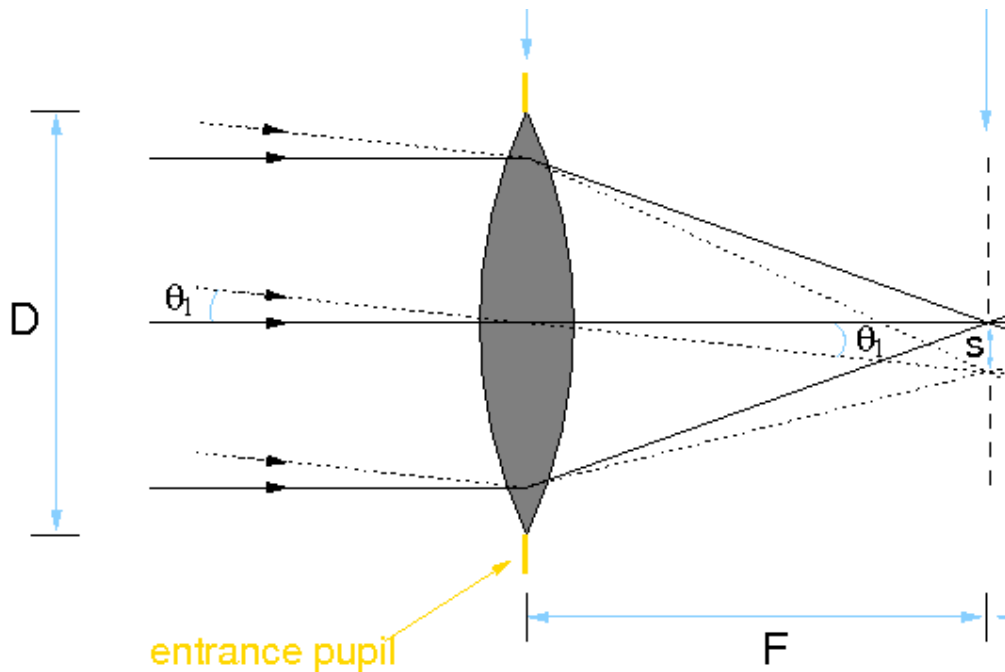


Same star viewed with  
Hubble Space Telescope

There is another reason for putting telescopes in space ... observing wavelength of light that are not transmitted by the atmosphere.

# Other Telescope Properties

- **Image Scale:** The relation between angular size on the sky and linear size in the image plane ( $\theta_1$  and  $s$  below).
  - Generally not exactly constant across the image.
  - Units are often arcseconds/mm or arcseconds/pixel.



For  $\theta_1 \ll 1$ :

$$s = \theta_1 \times F$$

$$\rightarrow \text{scale} = \theta_1/s = 1/F$$

Example: Our 0.5 m telescope has  $F = 4.0$  m.

$$\rightarrow \text{scale} = 0.25 \text{ rad/m} \\ = 52 \text{ arcsec/mm}$$

Note  $206265 \text{ arcsec} = 1 \text{ rad}$

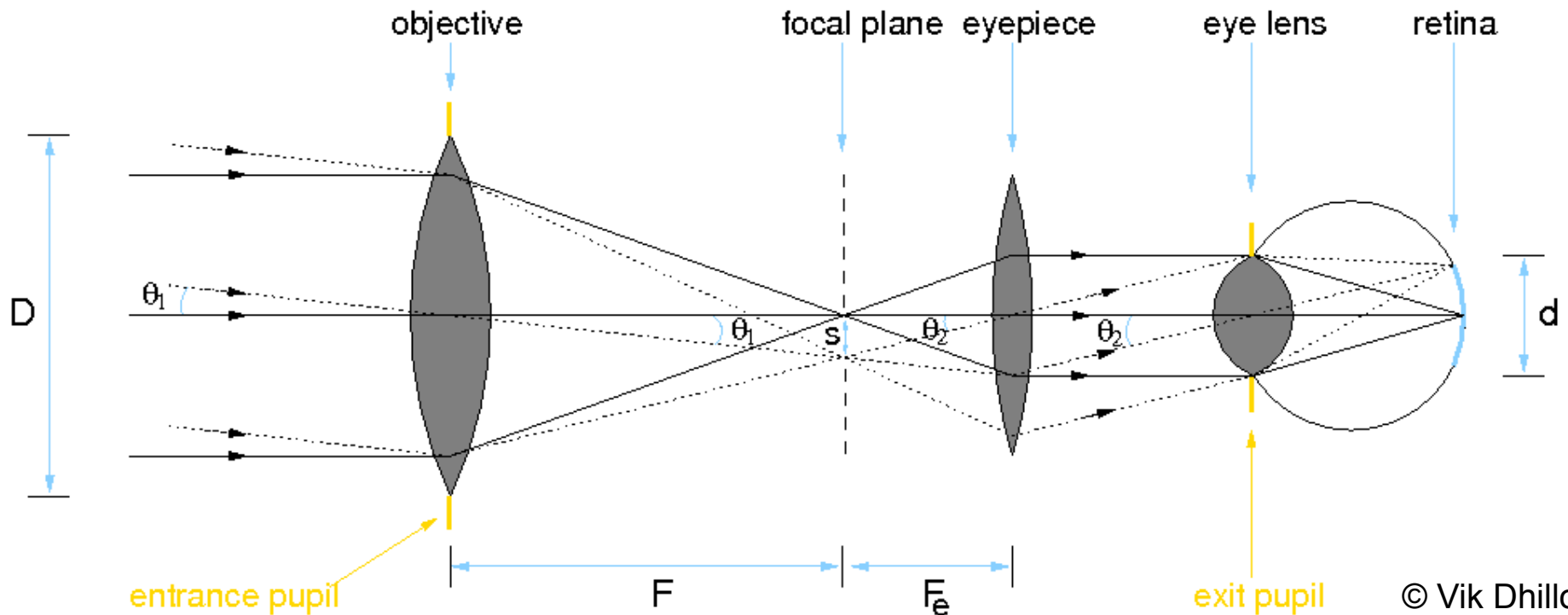
# Other Telescope Properties

- **Focal ratio:**  $f/ = F/d$ 
  - Our telescope has  $F/d = (4.0 \text{ m})/(0.5 \text{ m}) \rightarrow f/8$ .
    - Typical of Cassegrain configurations. Large research telescopes are typically  $f/2$  at prime focus.
  - Brightness of *extended* images depends only on  $f/$ .
    - Light collected proportional to  $d^2$ . More light implies a brighter image.
    - Image area proportional to  $F^2$ . A larger image spreads the light over a bigger area, so the image is fainter.
  - For unresolved objects (like stars), the brightness depends only on collecting area.

# Other Telescope Properties

- **Magnification:** Only applies to telescopes used visually. It is the increase in the apparent angular size of objects.

$$\text{magnification} = \theta_2 / \theta_1 = F_{\text{telescope}} / F_{\text{eyepiece}}$$



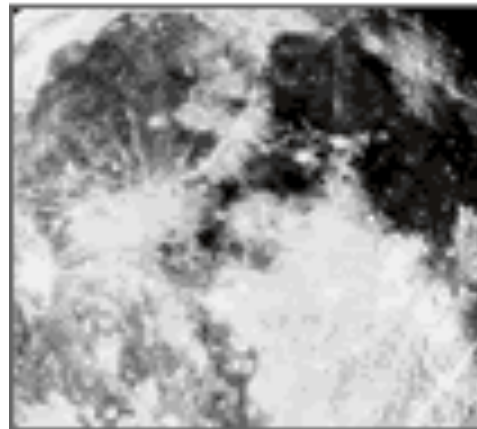
# Other Telescope Properties

- The diagram shows the typical use of an eyepiece in an astronomical telescope.
  - Diverging light rays from the image plane are made parallel, accommodating the resting focus of the normal eye (which is at  $\infty$ ).
  - Formula for magnification comes from  $\theta_1 F_t = s = \theta_2 F_e$ .
  - Note the the eyepiece forms an image of the entrance aperture of the telescope – the *exit pupil*.
    - Placing the pupil of the eye at the exit pupil ensures that all of the light from the telescope enters the eye.
    - If the exit pupil is larger than the eye's pupil, some light is lost. Avoiding this imposes a minimum useful magnification.

# Other Telescope Properties

- **Field of View:** The size of the region in the focal plane that is (nearly) fully illuminated and has good image quality.
  - Fundamental limit is usually off-axis image aberrations.
  - Size of the eyepiece or detector is also important.

**Small field of view**

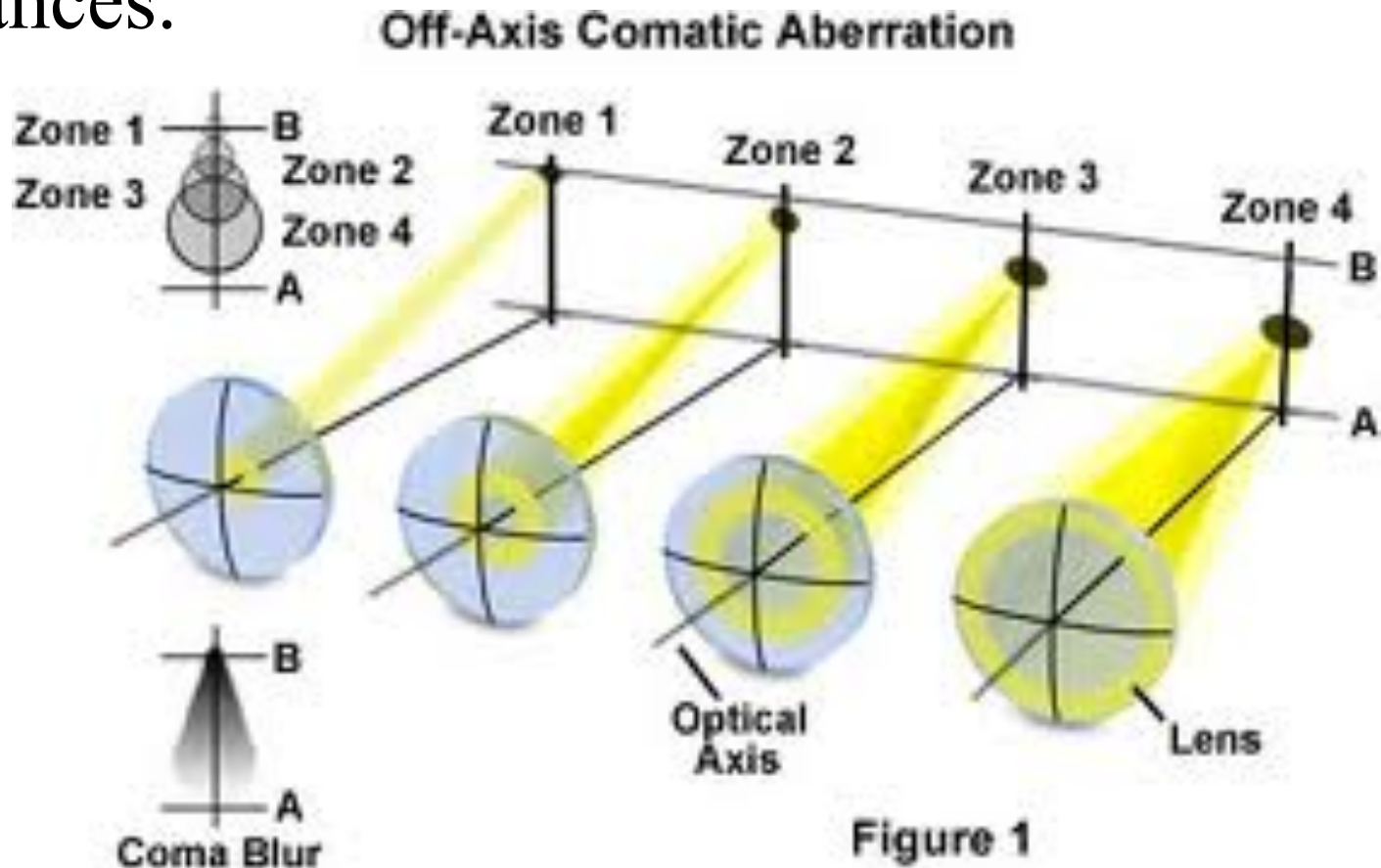


**Large field of view**



# Off-Axis Aberrations

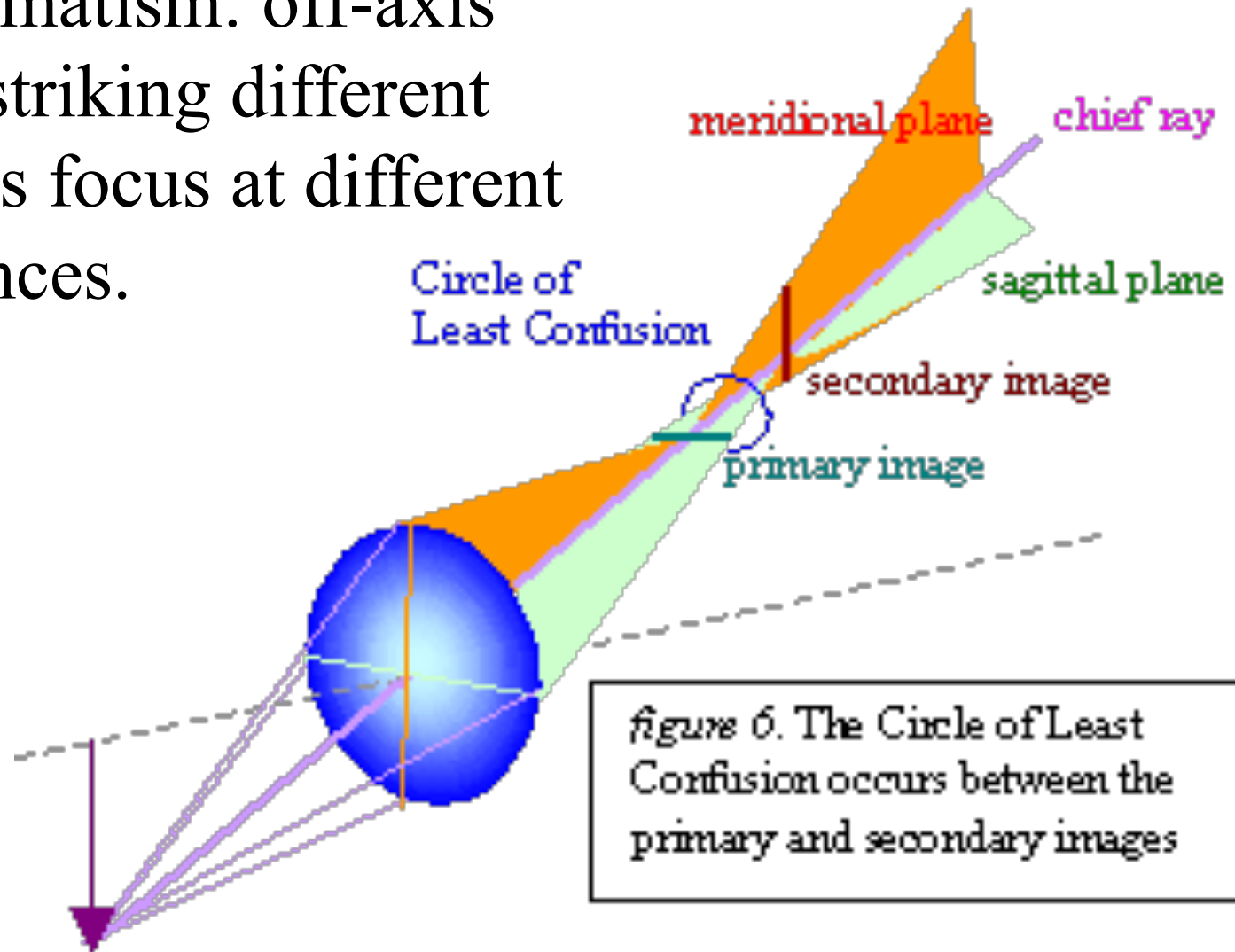
- Coma: rays striking different zones of lens or mirror focus at different locations and distances.





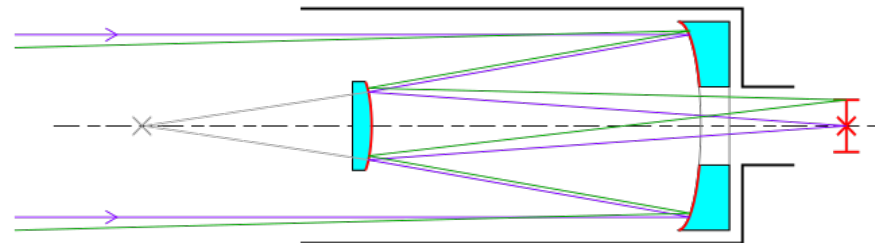
# Off-Axis Aberrations

- Astigmatism: off-axis rays striking different planes focus at different distances.



# Ritchey-Chretien Telescope

- Has hyperbolic surfaces on both the primary and secondary. This extra degree of freedom allows a reduction in off-axis aberrations.

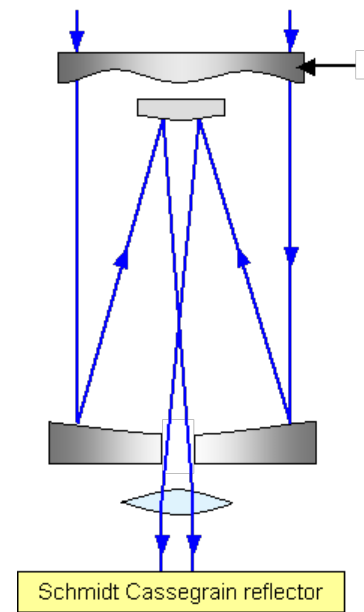
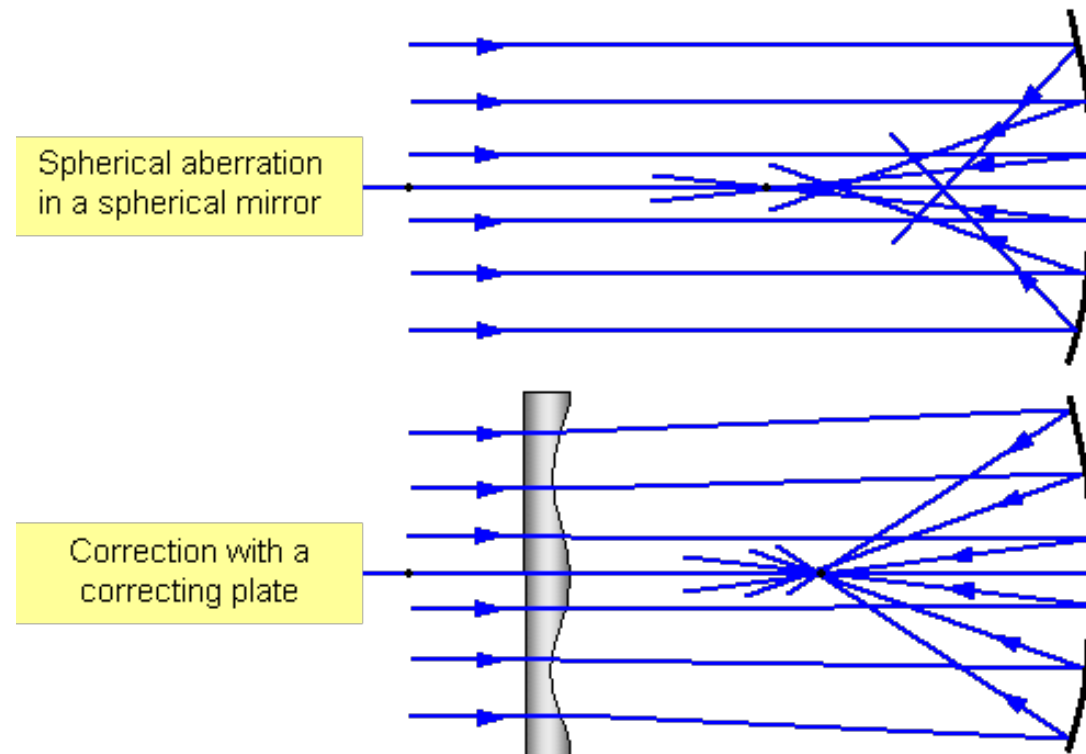


Is close to this classical Cassegrain light path (Krishnavedala; Wikimedia).

- Eliminates coma (to 1<sup>st</sup> order), which causes asymmetric images. Still has astigmatism, which does not (at circle-of-least-confusion focus).
  - Images better suited for measuring positions – astrometry.
- Does have *field curvature* (a curved focal plane).
- Most large professional telescopes use the RC design.

# Schmidt Telescope

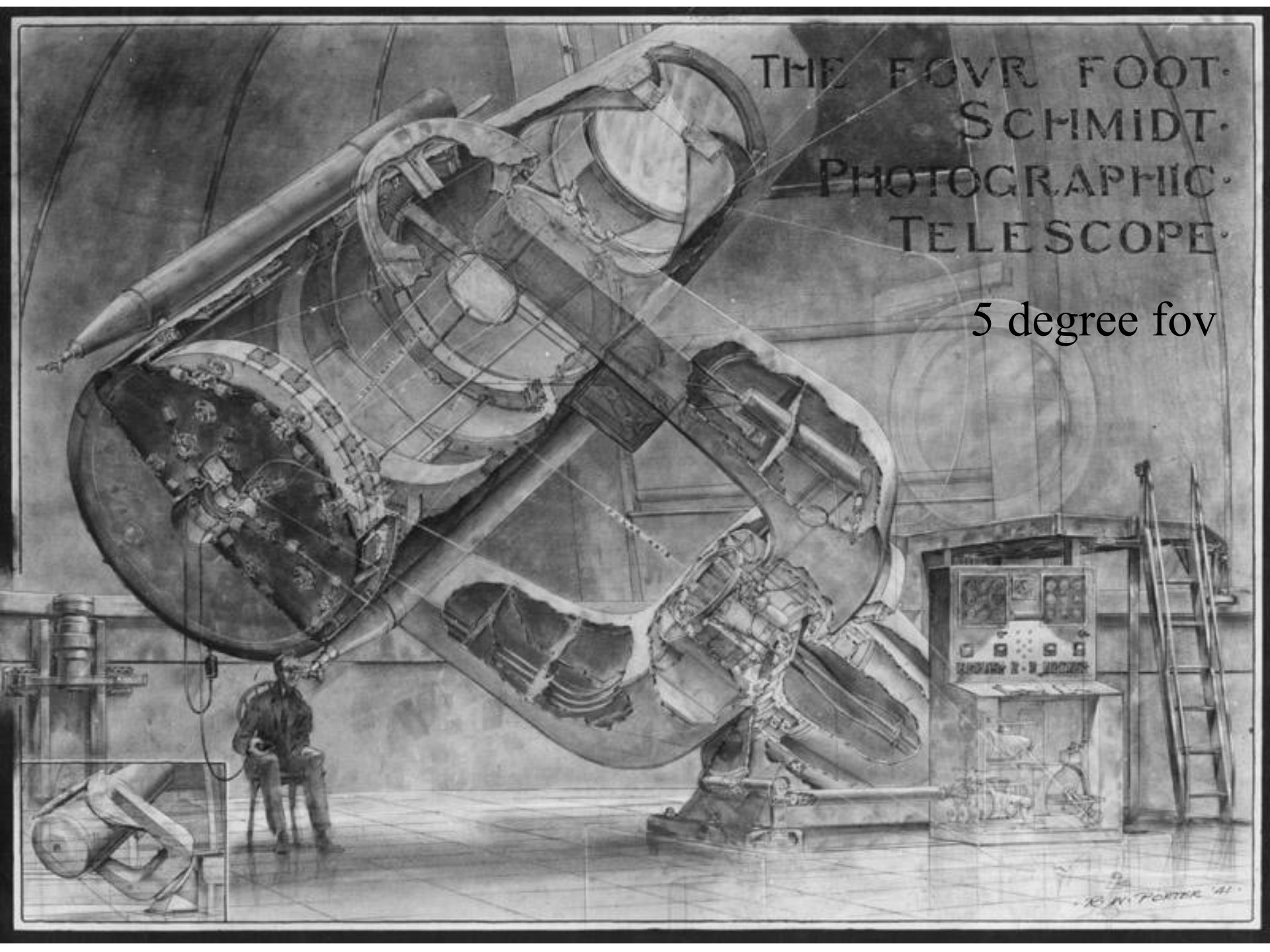
- Uses a spherical primary mirror to get a wide field of view, but suffers from spherical aberration which must be corrected (along with off-axis aberrations).



Our 8-inch telescopes have this design. The corrector reduces off-axis aberrations.

THE FOUR FOOT-  
SCHMIDT-  
PHOTOGRAPHIC-  
TELESCOPE.

5 degree fov



R. W. PORTER '41

# Large Synoptic Survey Telescope (LSST):

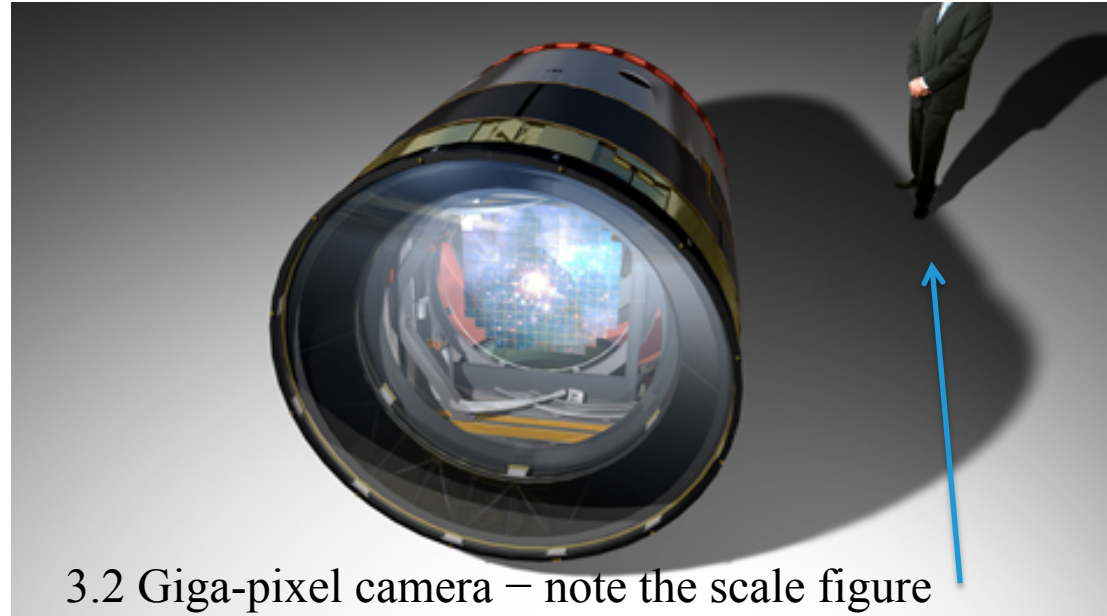
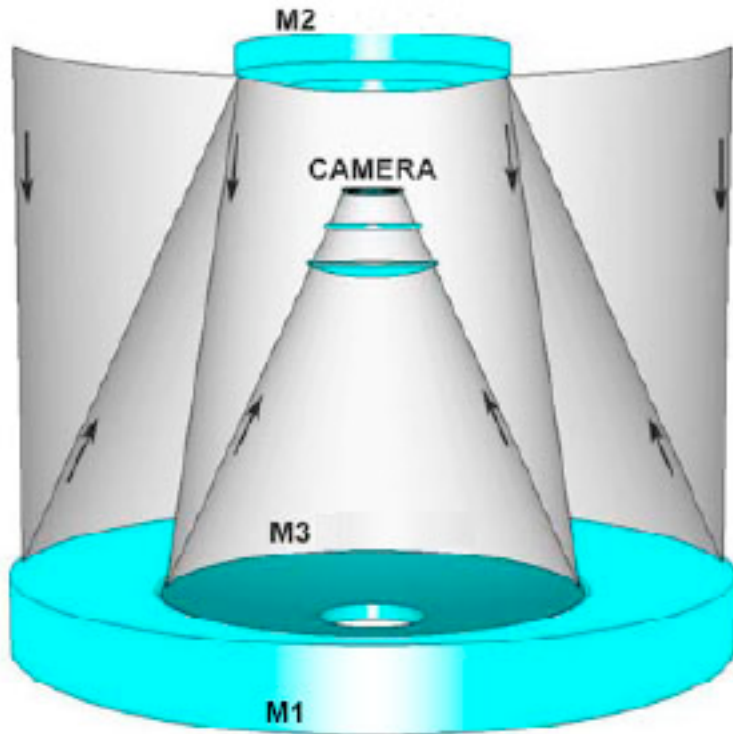
8.4 m primary mirror;

the 3-mirror + lenses

design gives a  $3.5^\circ$  fov.

Survey to begin in 2022

(first light late 2020?).



3.2 Giga-pixel camera – note the scale figure

# Vignetting

- Not all off-axis rays make it to the focal plane  
– generally hit baffles or stops.

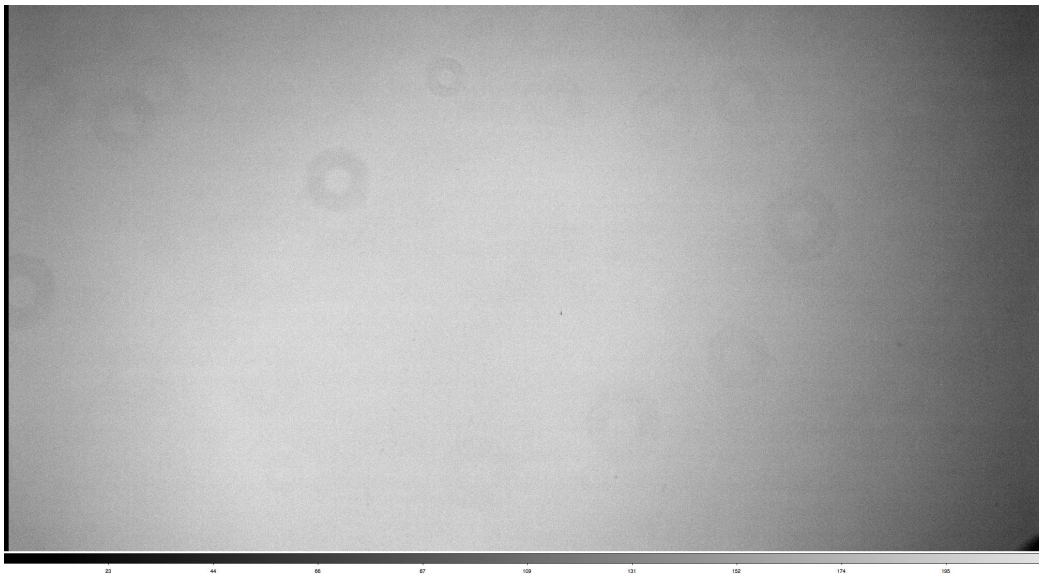
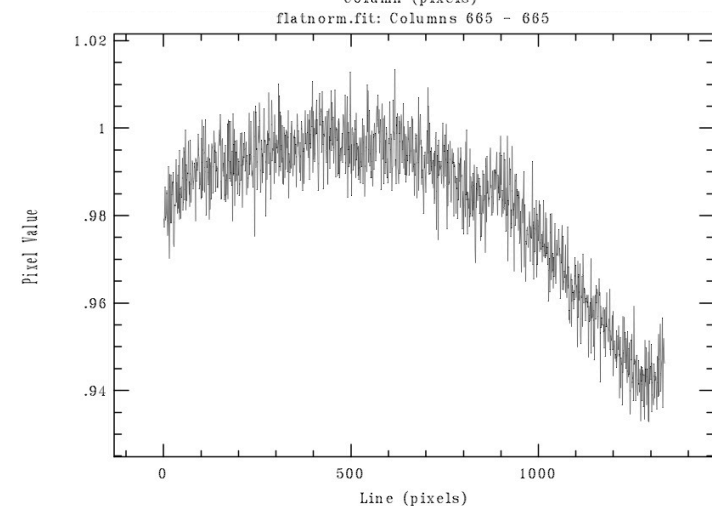
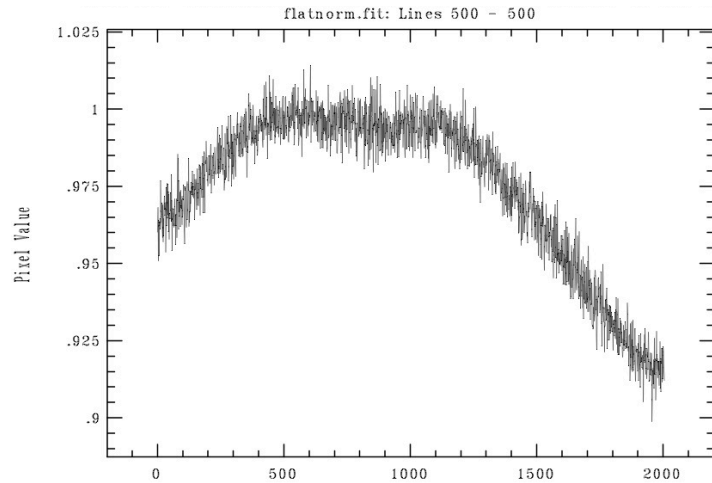


Image of uniformly illuminated field taken with the CCD camera on the 0.5m telescope. Plots of image intensity along central row and column show reduction in signal  $<10\%$ .

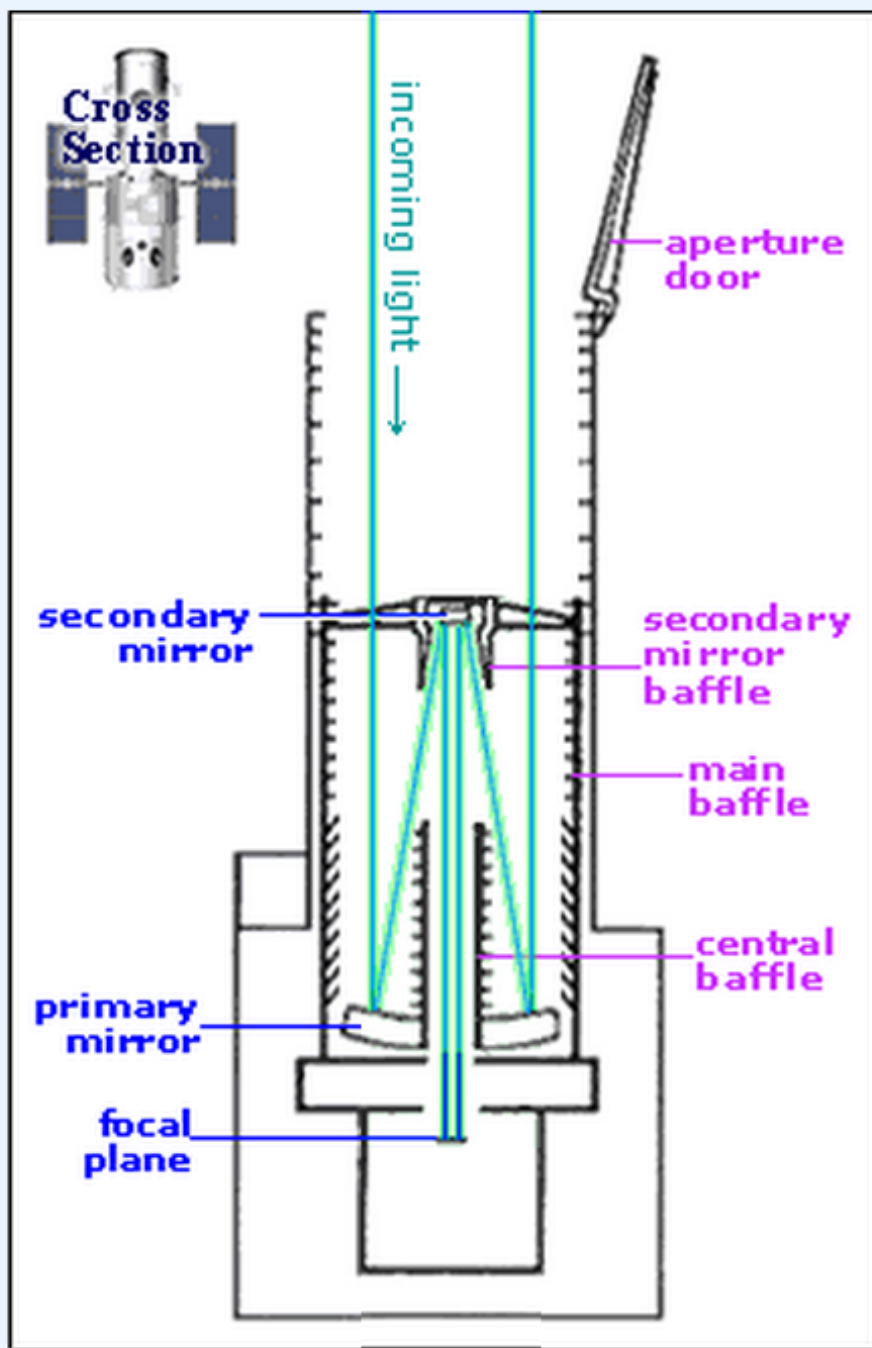


1 Light enters Hubble's **aperture** and travels down the **main baffle**. A baffle is a surface which eliminates stray light.

2 Light is reflected by the **primary mirror** which measures about 8 feet (2.4 meters) in diameter. Because of the concave shape, the primary mirror converges the light to the secondary mirror through a **secondary baffle**.

3 The **secondary mirror**, measuring about 1 foot (0.3 m) in diameter receives the light. It in turn reflects the still-converging light back toward the primary mirror through a **central baffle**.

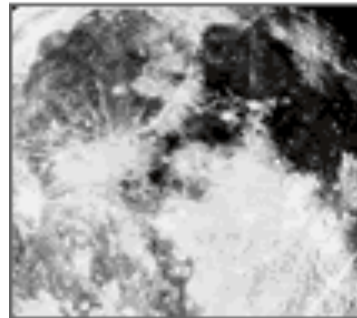
4 **The light travels through a** the primary mirror, to reach the **focal plane**, where the science instruments examine the light.



# Other Telescope Properties

- **Field of View:** The size of the region in the focal plane that is (nearly) fully illuminated and has good image quality.
  - Usually determined by off-axis image aberrations.
    - 0.5 degrees for our telescope's Ritchey-Chretien optics

**Small field of view**



**Large field of view**



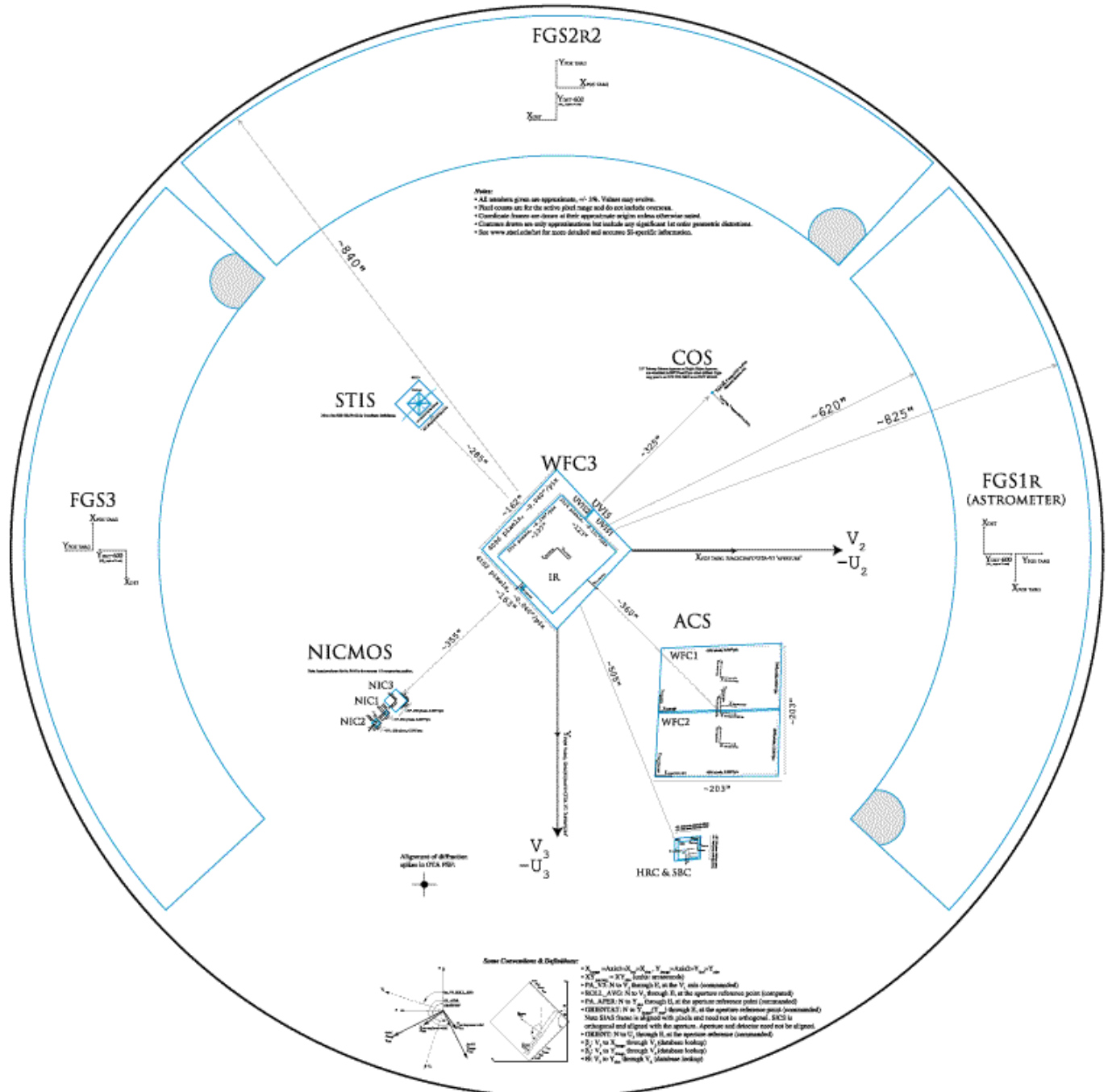
- Other limits:
  - Baffles inserted to eliminate scattered light.



# Other Telescope Properties

- Field of View: The size of the region in the focal plane that is (nearly) fully illuminated and has good image quality.
  - Usually determined by off-axis image aberrations.
    - 0.5 degrees for our telescope's Ritchey-Chretien optics
  - Other limits:
    - Baffles inserted to eliminate scattered light.
    - Size of the detector (the cameras on our telescope and on the Hubble Space Telescope).

HUBBLE SPACE TELESCOPE FIELD OF VIEW  
POST-SM4 CONFIGURATION



HST focal plane is about 0.5 degree across. But the individual cameras cover only a small fraction of it.



FOV of the Kepler space telescope: about 10 degrees across. Is an 0.95m diameter Schmidt telescope.

Detector pixels are so large on the sky that defocus the telescope so that stars are sampled by a few pixels.

# Other Telescope Properties

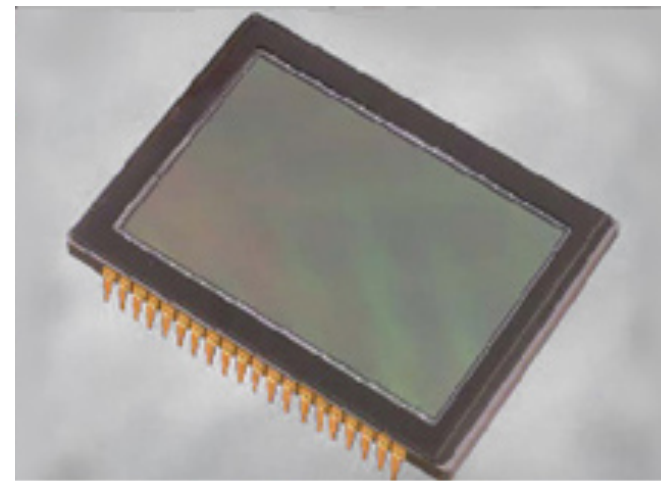
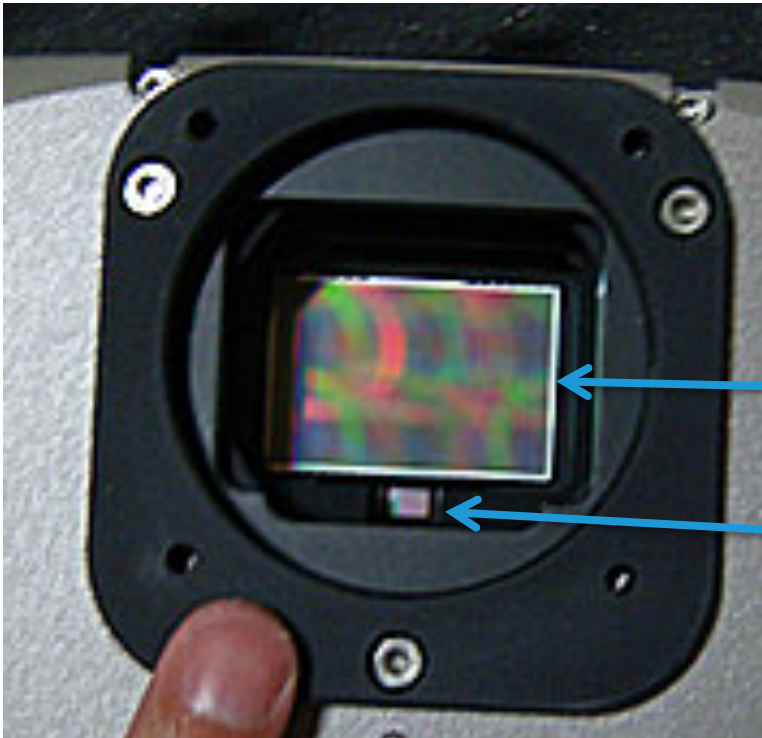
- Field of View: The size of the region in the focal plane that is (nearly) fully illuminated and has good image quality.
  - Usually determined by off-axis image aberrations.
    - 0.5 degrees for our telescope's Ritchey-Chretien optics
  - Other limits:
    - Baffles inserted to eliminate scattered light.
    - Size of the detector (the cameras on our telescope and on the Hubble Space Telescope).
  - With an eyepiece: (apparent eyepiece fov)/mag
    - For most of our eyepieces apparent fov = 70 degrees.

# CCD Imaging Detectors

- Charge Coupled Device: convert photons of light to electric charges.
  - Manipulation and detection of electric charges is well advanced (electronics).
  - Signals easily digitized for analysis by computers.
- Detector of choice in the near infrared, visible, and ultraviolet regions of the electromagnetic spectrum.
  - Have good quantum efficiency (50 – 80%), excellent linearity, and large dynamic range ( $\sim 20,000$ )

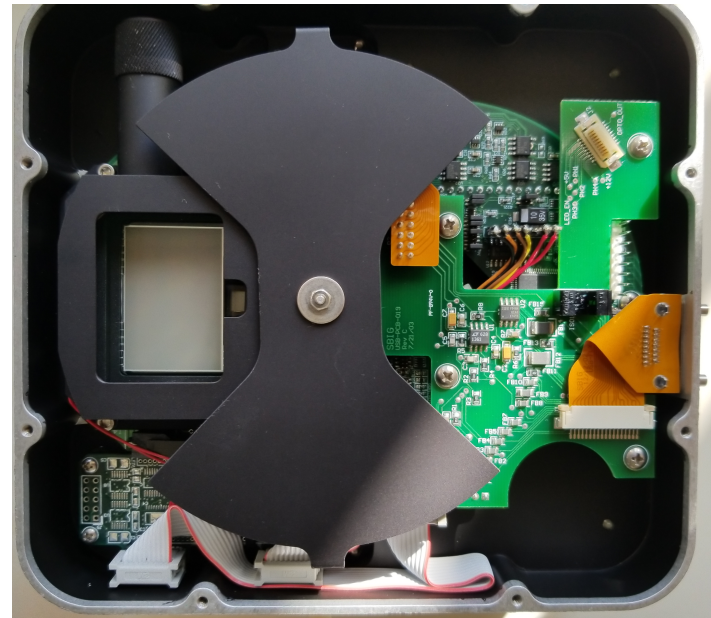
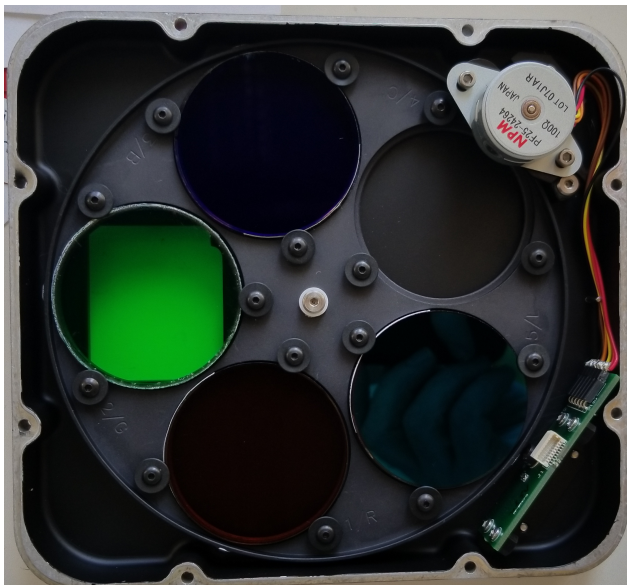
# SBIG STL1100m CCD Camera

- Contains two CCDs
  - 4008 x 2672 pixels main imager
  - 680 x 500 pixels guide imager

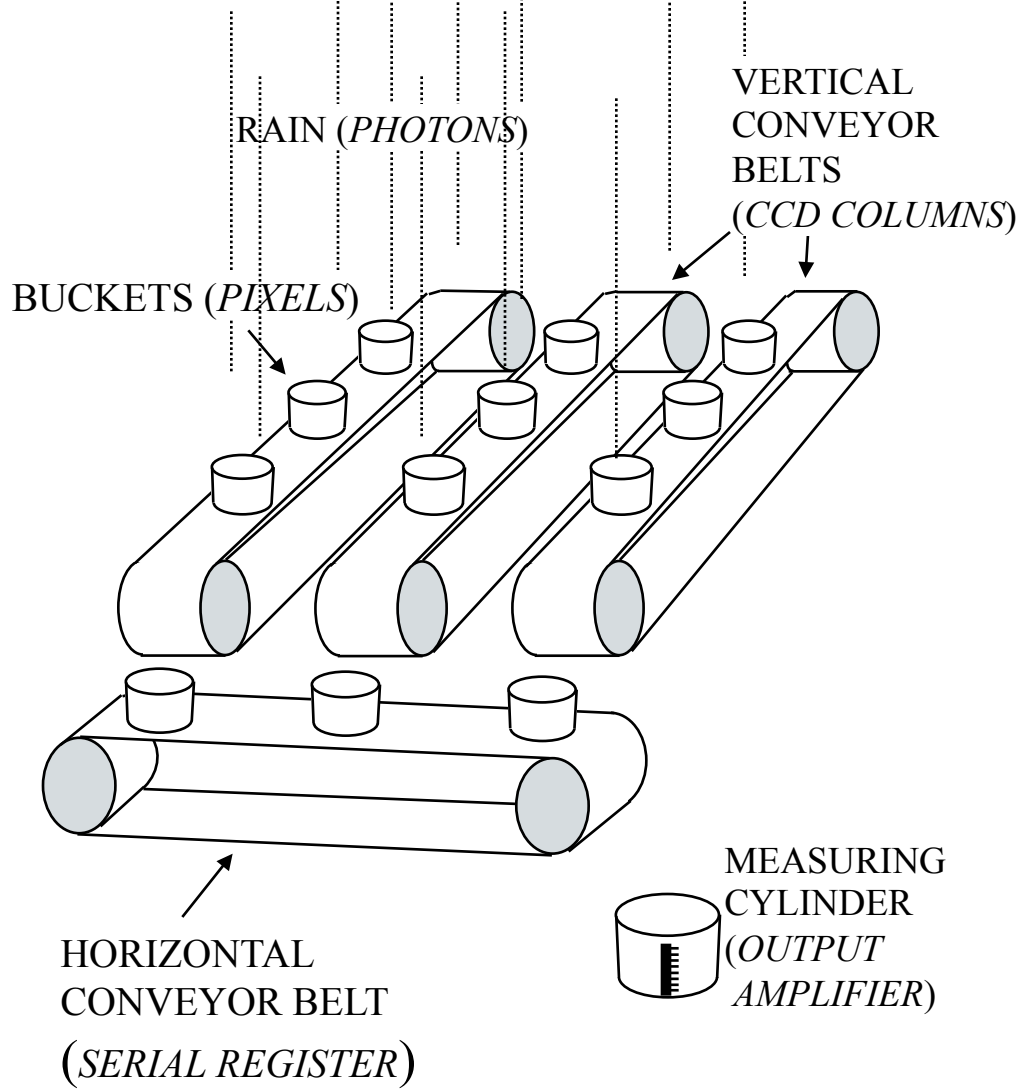


# SBIG STL1100m CCD Camera

- Filter wheel with 4 filters and an open position.
  - Blue (B), green (V), red (R), and infrared (I).
- Shutter
- Three-stage thermoelectric cooler, electronics, motors, *etc..*



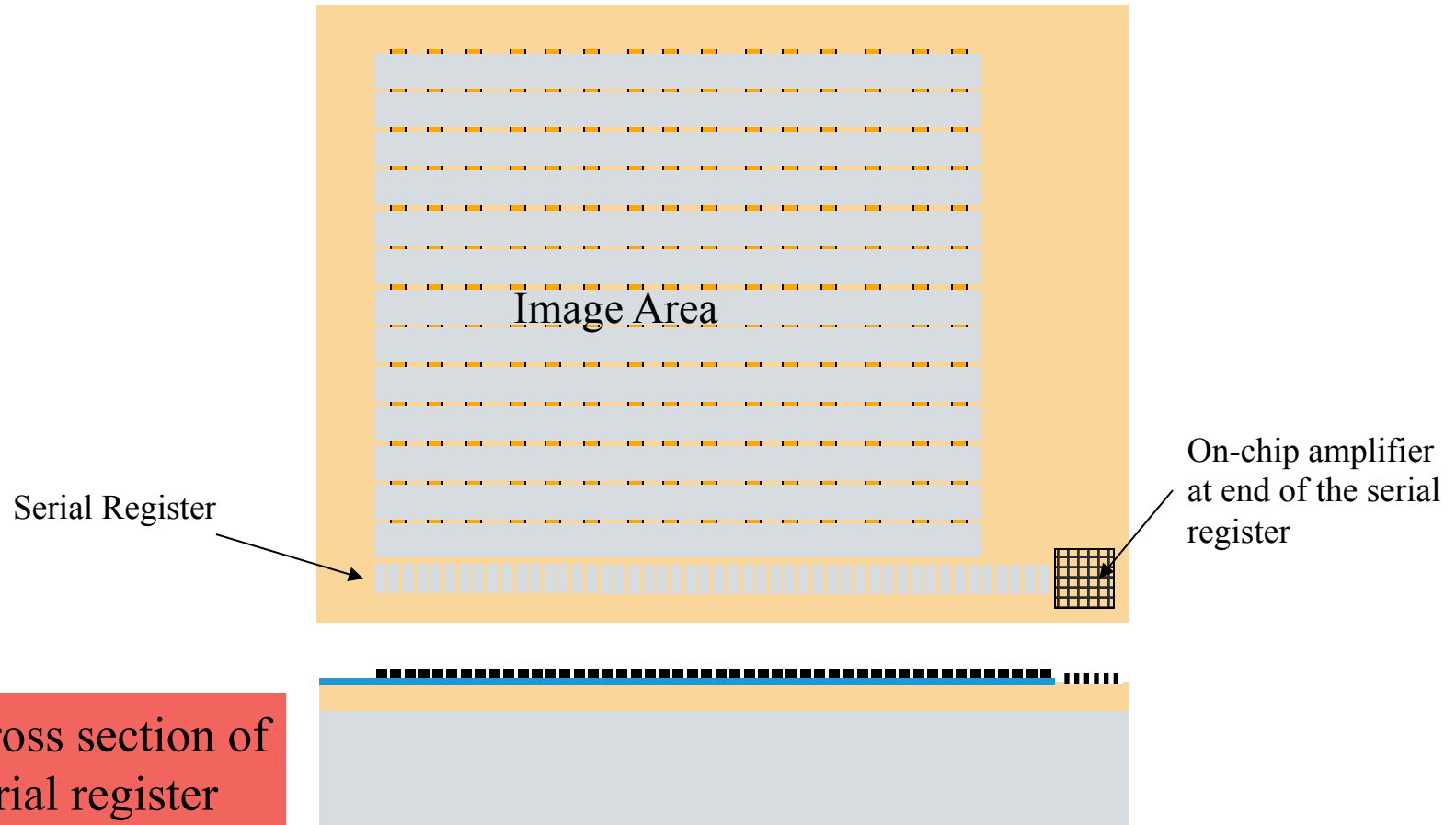
# CCD Analogy





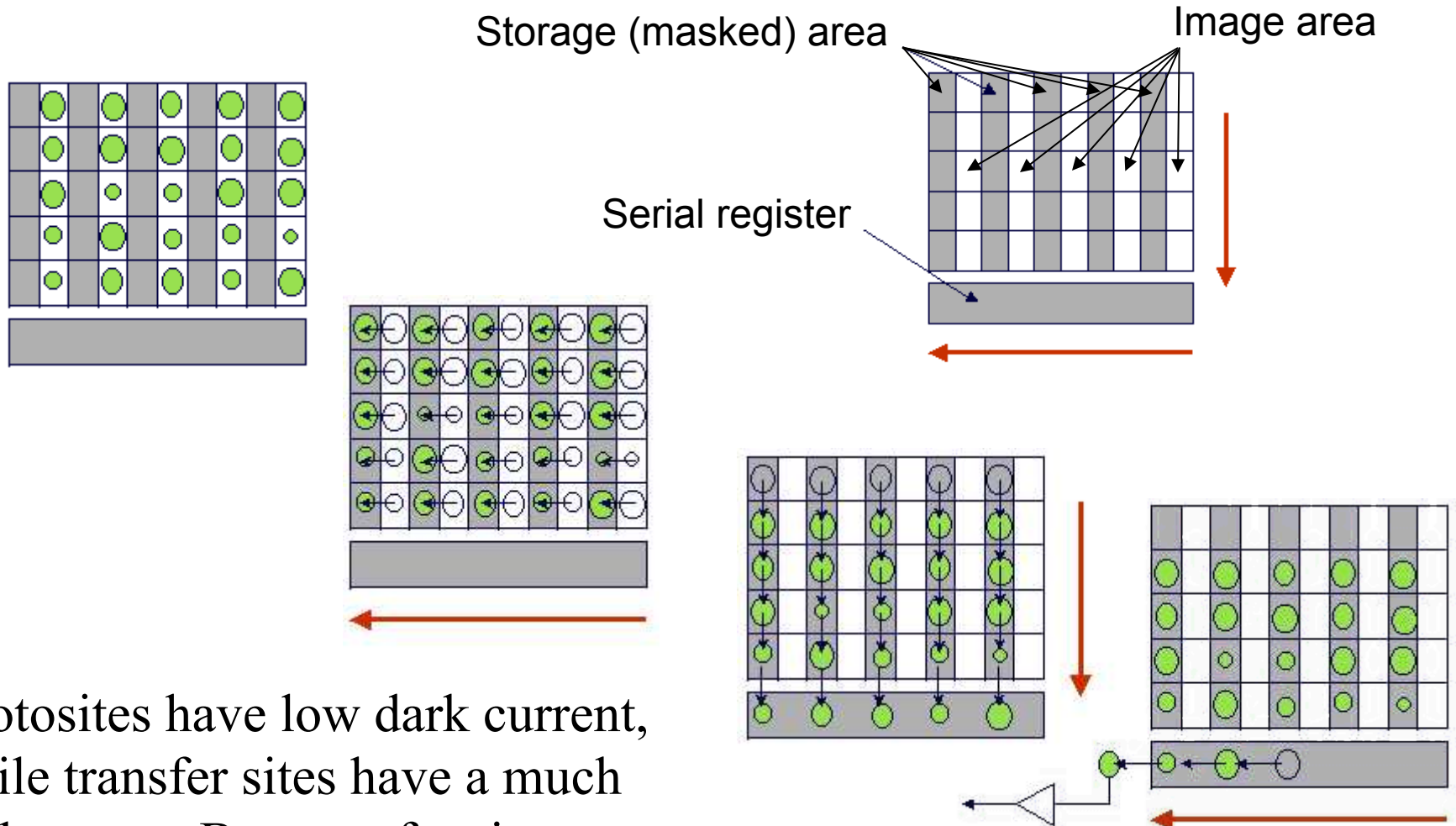
# Structure of a CCD

Below the image area (the area containing the horizontal electrodes) is the 'Serial register'. This also consists of a group of small surface electrodes. There are three electrodes for every column of the image area



Once again every third electrode in the serial register are connected together.

# Interline-Transfer CCD (ours)



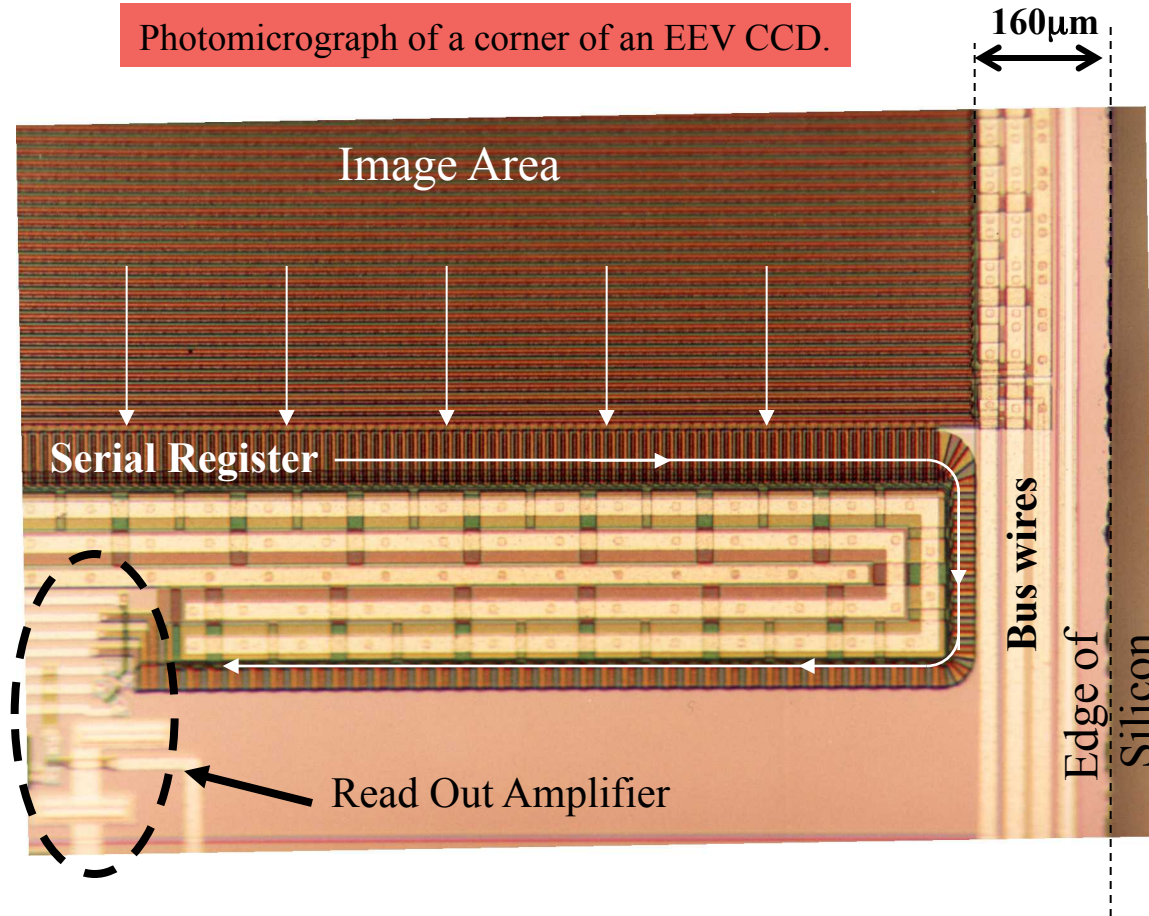
Photosites have low dark current, while transfer sites have a much higher one. But transfer sites are scrubbed during exposure.

# CCD's: Charge Detection

- The crucial step is the on-chip amplifier – it must add as little noise as possible to the small measured signals.
  - Serial register dumps the charge on a capacitor and the resulting voltage is amplified.
  - There is usually more amplification off of the chip.
- Voltage is then digitized (with 12 to 16 bits).
  - Must add an offset voltage (“the bias”)
    - The bias ensures that the input voltage to the analog-to-digital (A-to-D) converter never goes below the zero level.

# Structure of a CCD

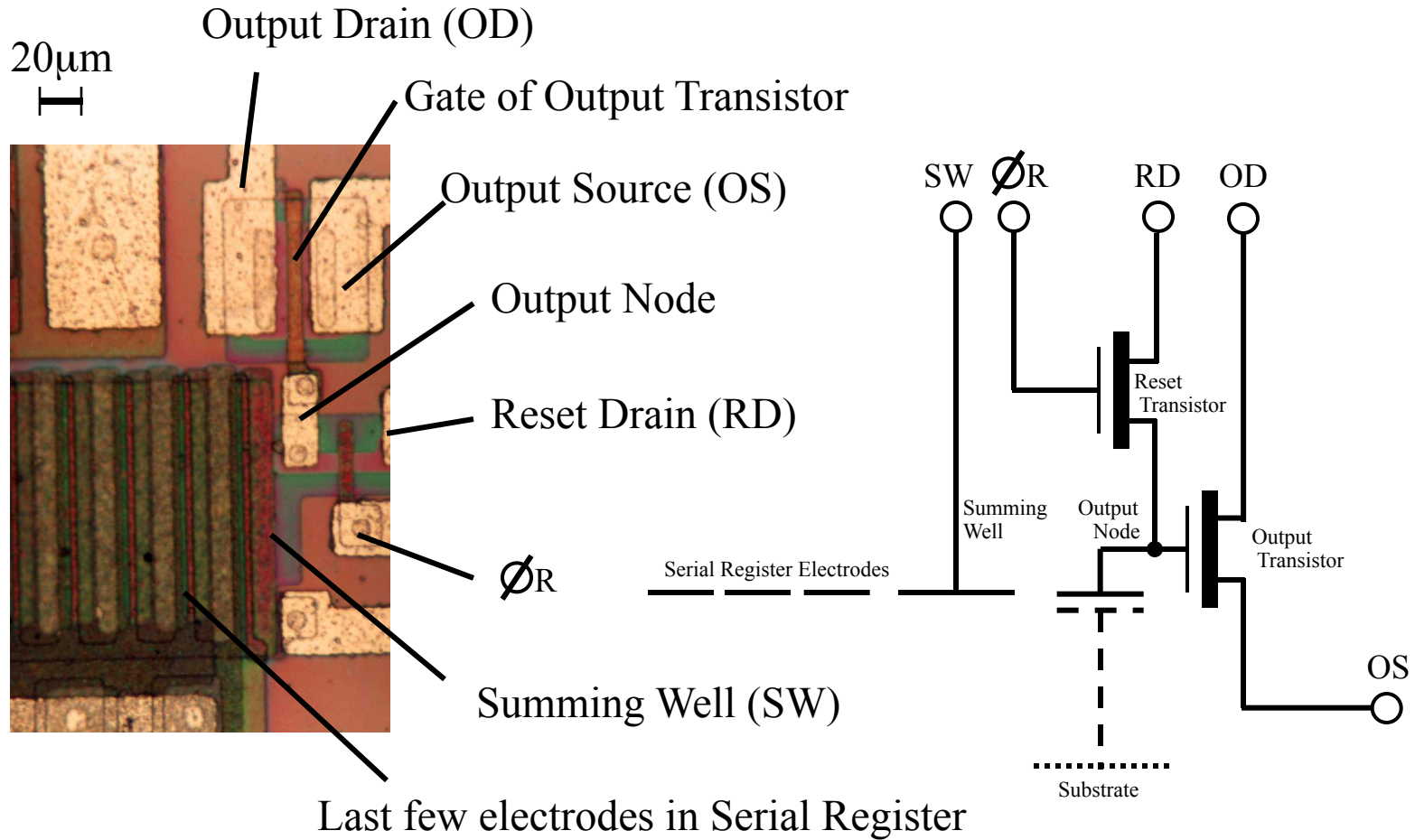
Photomicrograph of a corner of an EEV CCD.



The serial register is bent double to move the output amplifier away from the edge of the chip. This is useful if the CCD is to be used as part of a mosaic. The arrows indicate how charge is transferred through the device.

# Structure of a CCD

Photomicrograph of the on-chip amplifier of a Tektronix CCD and its circuit diagram.



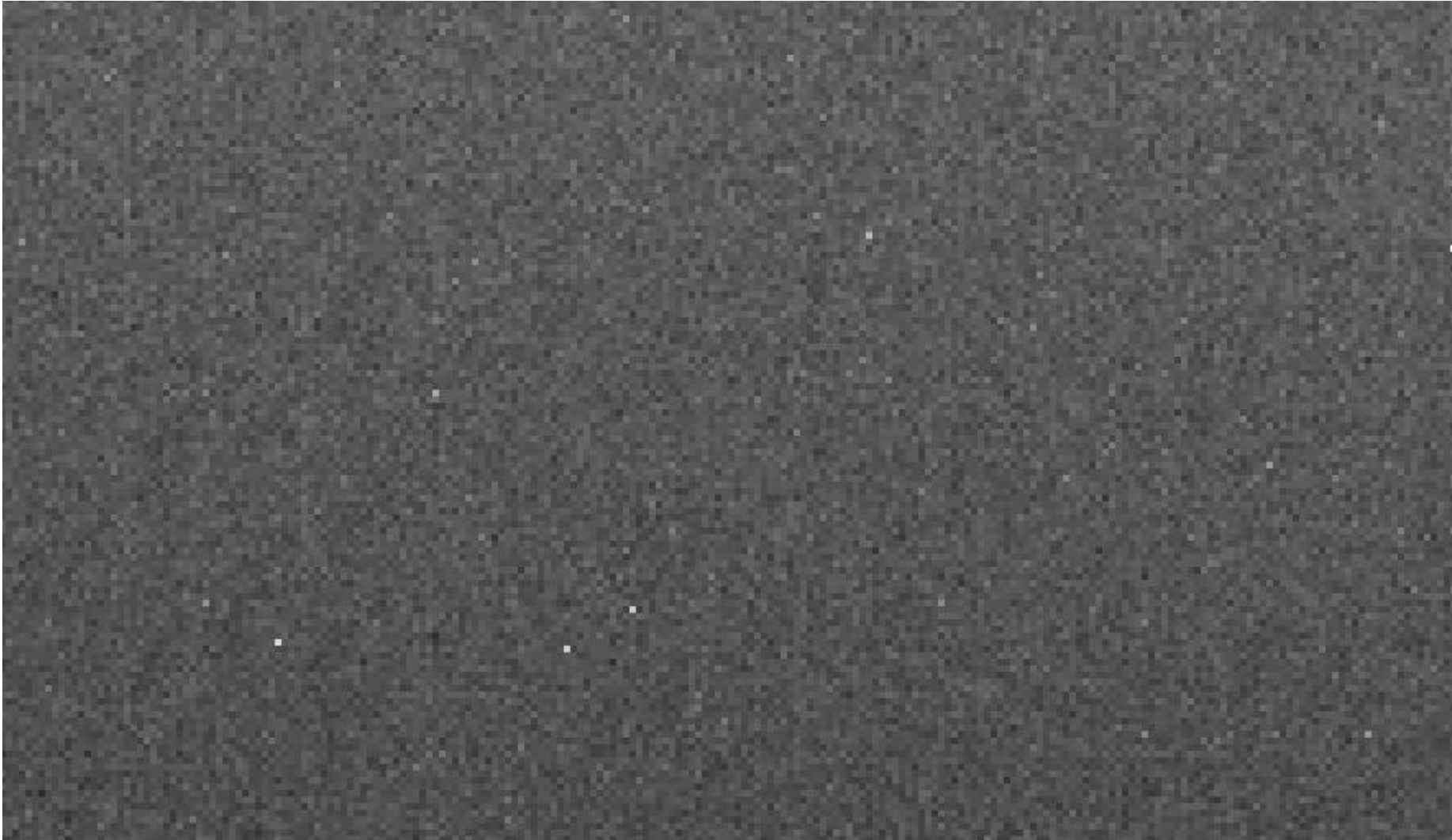
# Charge Detection Variants

- On-chip binning (e.g.,  $2 \times 2$ ) :
  - Combine two or more pixels from each column in the serial register.
  - Combine two or more pixels from the serial register in the summing well.
  - Combination occurs before measurement, so no noise is added. Increases signal relative to noise and reduces readout time.
- Partial readout (half frame, quarter frame):
  - Only measure some of the pixels. Reduces readout time.

# CCD Calibration

- Gain: the number of electrons per A-to-D digital unit (ADU or data number).
  - Really an inverse gain (is small if the amplifier gain is large).
- Read noise: the noise added by the amplification and measurement (usually given in electrons).

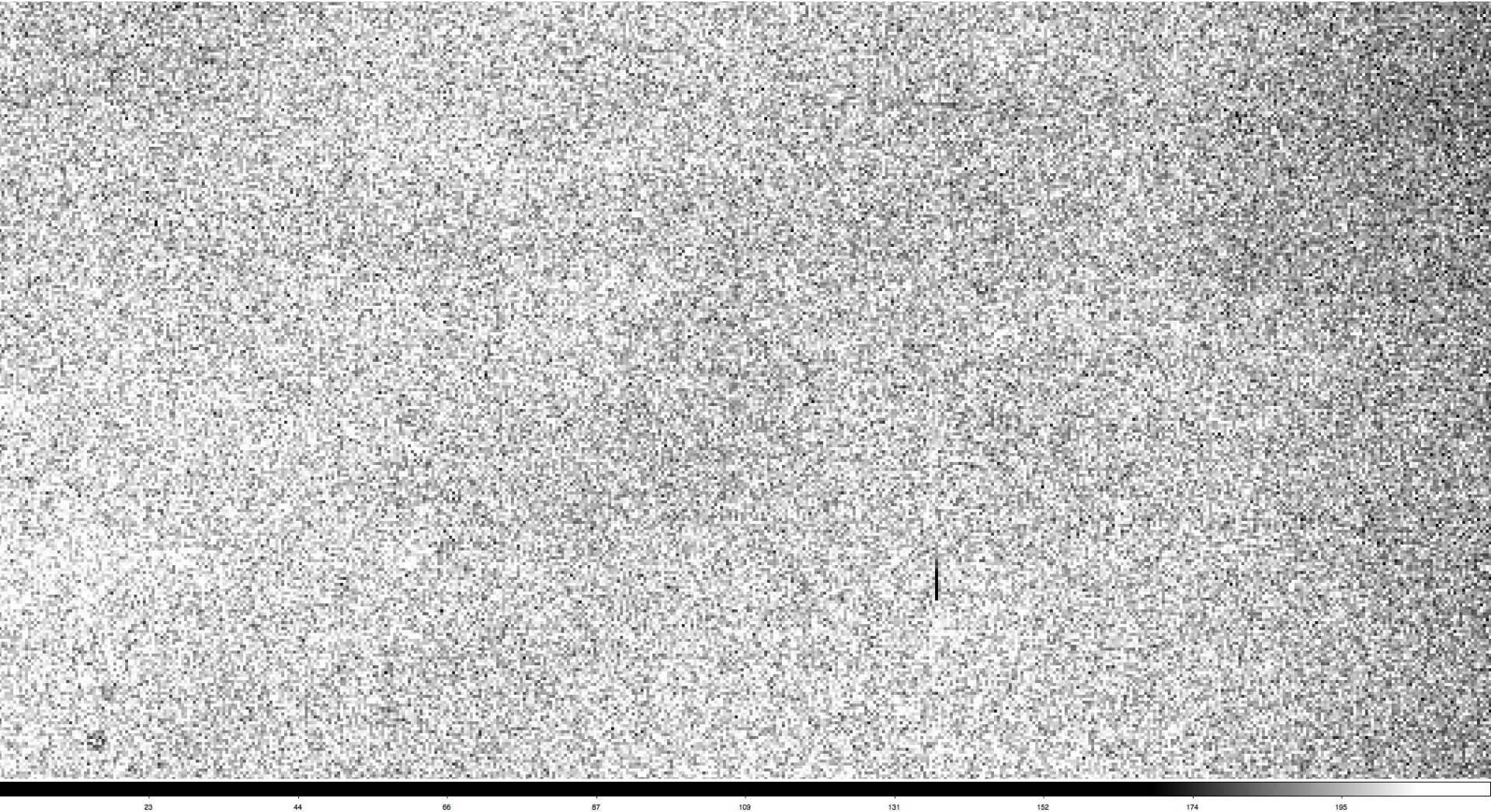
Zoomed bias frame from our camera.



Note “hot” pixels with high dark current. “Speckling” around the constant bias level is due to read noise.



# Zoomed flat-field (uniform illumination) image



23

44

66

87

109

131

152

174

195

The “speckling” is a combination of pixel-to-pixel sensitivity variations and the Poisson noise of the photon arrivals.

IDL - IDL

File Edit Source Project Run Window Help

Open New File New Project Save Cut Copy Paste Undo Back Forward Compile Run Stop In Over Out \$MAIN\$ Call Stack Reset

Proje... Outline = Varia... Default

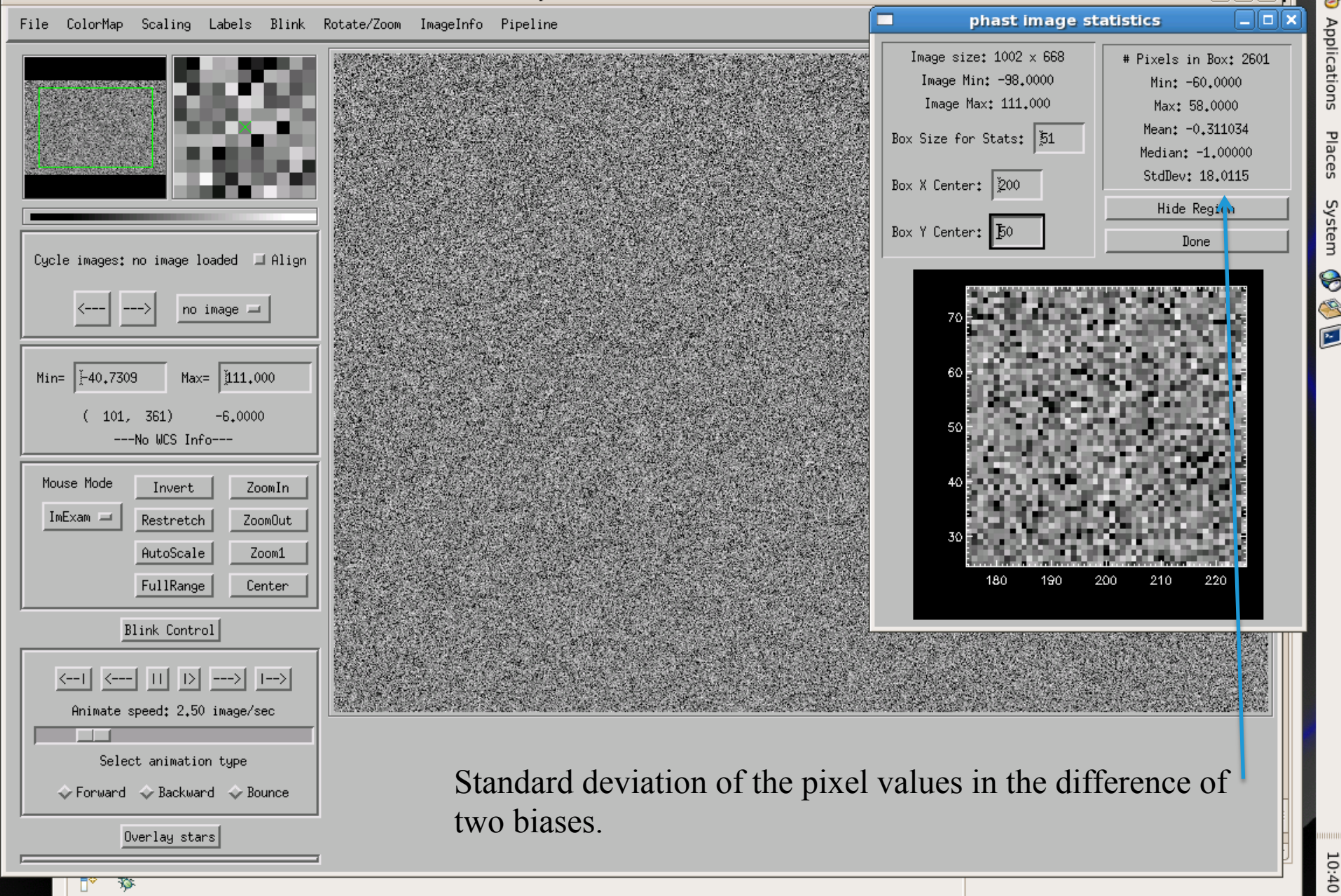
Differencing two images reduces the effect of signal variations (due to variations in brightness or pixel-to-pixel sensitivity variations) on the measured variance around the mean.

Use IDL to do image arithmetic and display the result with PhAst.

IDL Console Command History Problems Current Directory: /home/pryor/lab3/sep26cp

```
IDL> b2=readfits('biasquarterh1.00000006.BIAS.FIT',h) * 1.0
% READFITS: Now reading 1002 by 668 array
IDL> b1=readfits('biasquarterh1.00000005.BIAS.FIT',h) * 1.0
% READFITS: Now reading 1002 by 668 array
IDL> f2=readfits('flatquarterh1.00000008.FIT',h) * 1.0
% READFITS: Now reading 1002 by 668 array
IDL> db=b1-b2
IDL> df=f1-f2
IDL> phast, b1
IDL> phast, b2
IDL> phast, b1
IDL> phast, db
IDL> |
```

File ColorMap Scaling Labels Blink Rotate/Zoom ImageInfo Pipeline



phast image statistics

Image size: 1002 x 668  
 Image Min: -98.0000  
 Image Max: 111.0000

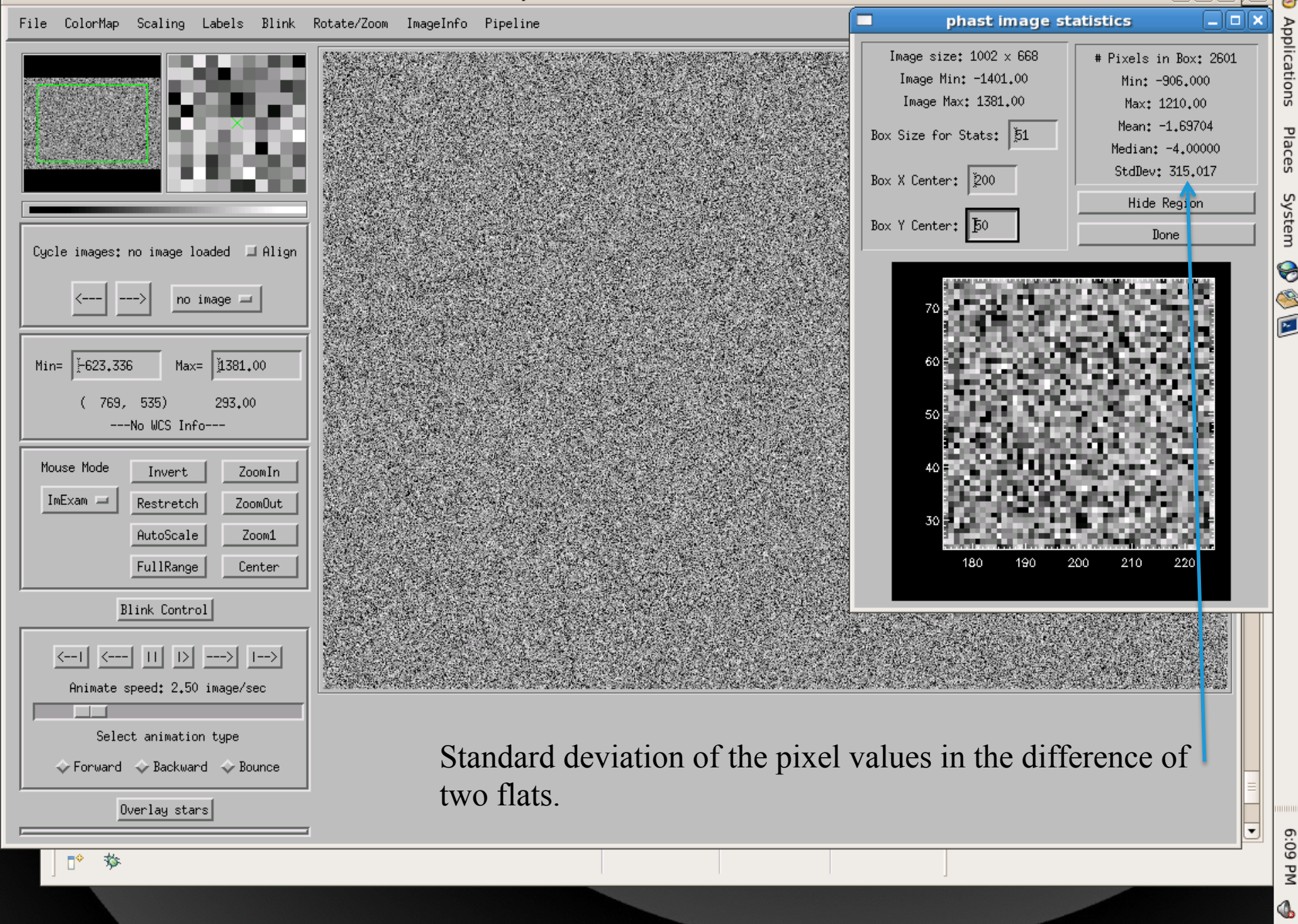
Box Size for Stats: 51  
 Box X Center: 200  
 Box Y Center: 50

# Pixels in Box: 2601  
 Min: -60.0000  
 Max: 58.0000  
 Mean: -0.311034  
 Median: -1.000000  
 StdDev: 18.0115

Hide Region  
 Done

Standard deviation of the pixel values in the difference of two biases.

File ColorMap Scaling Labels Blink Rotate/Zoom ImageInfo Pipeline



phast image statistics

Image size: 1002 x 668  
 Image Min: -1401.00  
 Image Max: 1381.00

Box Size for Stats: 51

Box X Center: 200  
 Box Y Center: 50

# Pixels in Box: 2601  
 Min: -906.000  
 Max: 1210.00  
 Mean: -1.69704  
 Median: -4.00000  
 StdDev: 315.017

Hide Region  
 Done

70  
60  
50  
40  
30  
180 190 200 210 220

Cycle images: no image loaded  Align

<--- <---> no image

Min= -623.336 Max= 1381.00  
 ( 769, 535) 293.00  
 ---No WCS Info---

Mouse Mode Invert ZoomIn  
 InExam Restretch ZoomOut  
 AutoScale Zoom1  
 FullRange Center

Blink Control

<--| <--- || |> ---> |-->

Animate speed: 2.50 image/sec

Select animation type  
 Forward  Backward  Bounce

Overlay stars

Standard deviation of the pixel values in the difference of two flats.

6:09 PM

[pryor@astrol... root@astrolab... pryor@astrola... IDL - /usr/local... IDL 0 phast: (1002x... phast image s...]

# CCD Calibration

- Read noise: the noise in electrons added by the amplification.
  - Difference two bias images:
    - $\Delta = s_2 - s_1$
    - $\rightarrow \sigma_{\Delta}^2 = ((d\Delta/ds_1)\sigma_{s_1})^2 + ((d\Delta/ds_2)\sigma_{s_2})^2 = \sigma_{s_1}^2 + \sigma_{s_2}^2$   
from propagation of errors
    - Since the noise in each pixel of a bias frame is the same read noise,  $\sigma_{s_1} = \sigma_{s_2} = rn$  and  $rn = \sigma_{\Delta}/\sqrt{2}$ .
    - So just need to find the variance of  $\Delta$  around mean for patches of the difference between two bias frames.
  - Produces the read noise in digital units (du or adu).

# CCD Calibration

- Read noise: the noise in electrons added by the amplification.
- Gain: the number of electrons per A-to-D digital unit (or data number).
  - Determined by the noise in an image with high signal: is dominated by Poisson noise (shot noise),  $\sigma_{N_e} = \text{sqrt}(N_e)$ .
  - Again difference two flat field images to remove variations due to illumination and sensitivity variations.

# CCD Calibration

- Gain: the number of electrons per A-to-D digital unit (or data number).
  - $\Delta = s_2 - s_1$  and  $s = (s_2 + s_1)/2$
  - $\rightarrow \sigma_{\Delta}^2 = \sigma_{s_1}^2 + \sigma_{s_2}^2 = 2\sigma_s^2$  (since  $s_1 \approx s_2$ )
  - Now  $N_e = g \times s \rightarrow \sigma_{N_e} = g \times \sigma_s$  from prop. of errors and  $\sigma_{N_e} = \text{sqrt}(N_e) = \text{sqrt}(g \times s)$ .
  - So  $\text{sqrt}(g \times s) = g \times \sigma_s \rightarrow g \times s = g^2 \times \sigma_s^2 = g^2 \times \sigma_{\Delta}^2 / 2$
  - Solving for  $g$ :  $g = 2s / \sigma_{\Delta}^2 = (s_1 + s_2) / \sigma_{\Delta}^2$