Lecture 4

September 27, 2018

CCD's and Observing

News

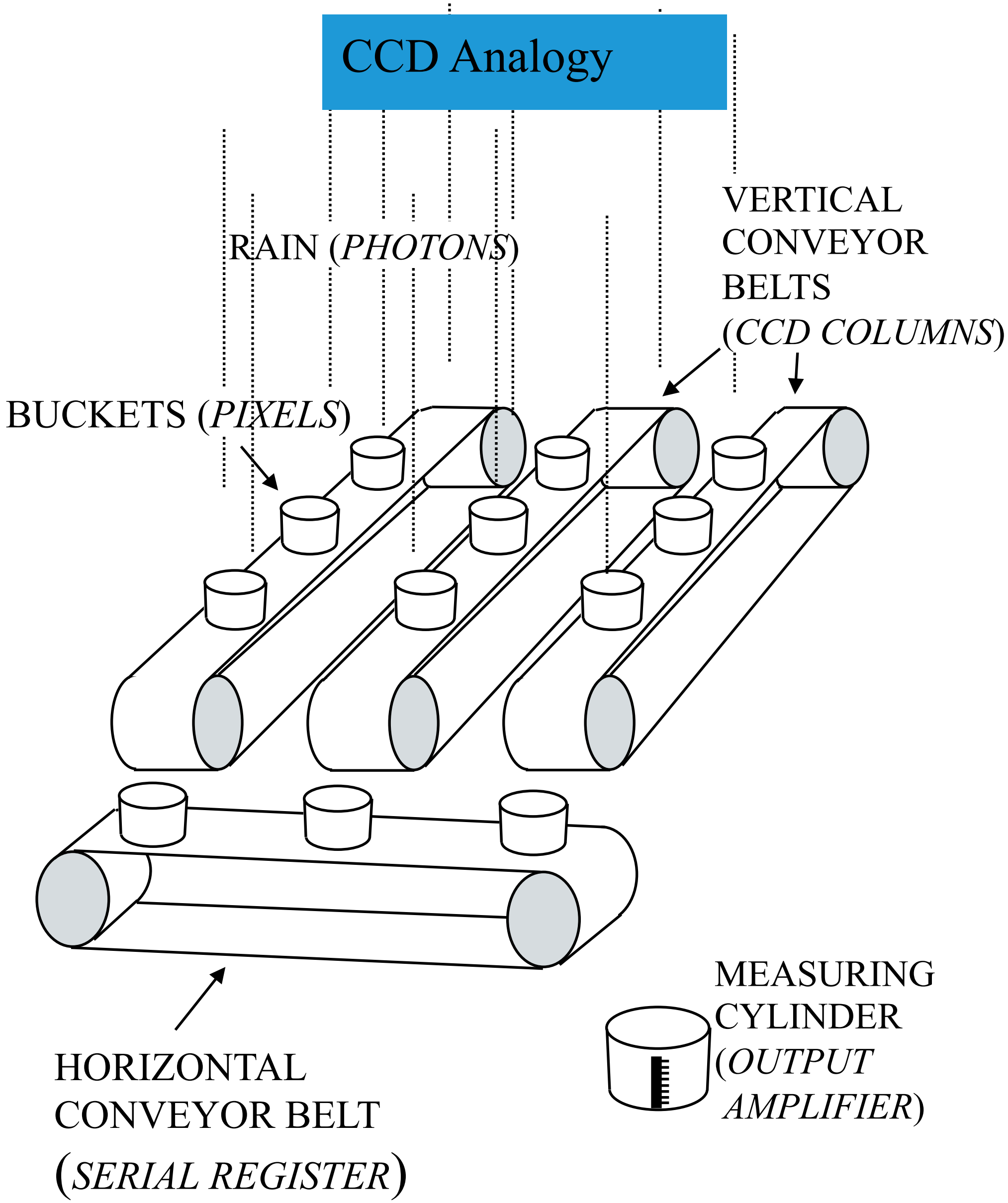
- I still want everyone to complete Lab 2, since that is where you learn how to operate the telescope.
  - Visual observing will continue this week for most groups – weather forecast more promising.
  - Lab periods: 7:00 – 9:00 and 9:00 – 11:00 PM
  - Lab 2 is now due October 11.

- Lab 3 handed out today. Due: October 11.
  - "Cloudy lab" data is part of this lab. Start working on these data, if you have them.
  - Most groups will get existing CCD data to analyze rather than taking their own.

News

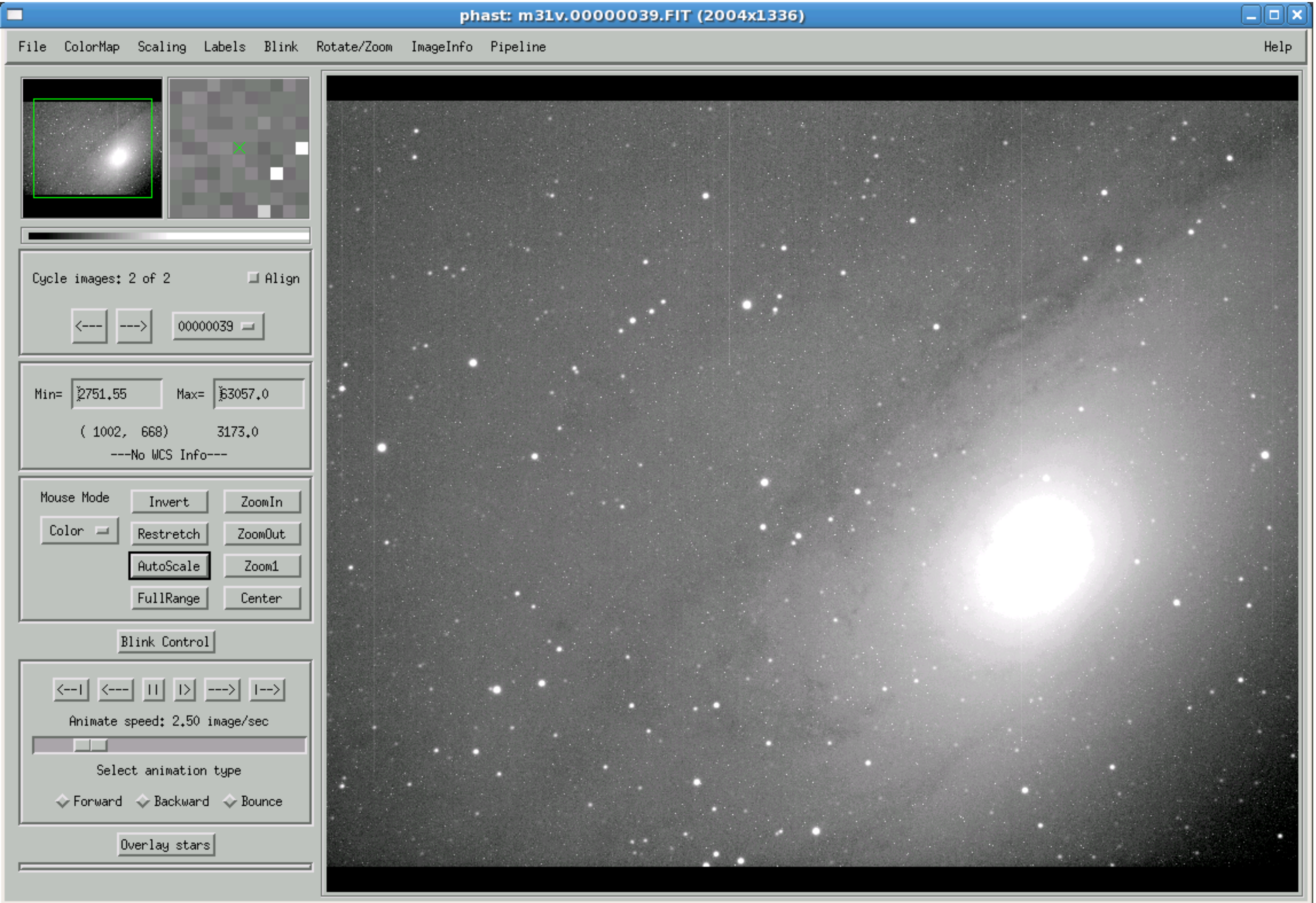
- Observing & analysis plans for the coming week:
  - Friday: clear – visual observing (lab 2); cloudy – analyze lab 3 data
  - Sunday: clear – finish visual observing (lab 2) & do some lab 3 observing if there is time; cloudy – analyze lab 3 data
  - Monday: clear – visual observing (lab 2); cloudy – analyze lab 3 data
  - Tuesday: clear – lab 3 observing; cloudy – write up lab 2 and analyze lab 3 data
  - Wednesday: clear – visual observing (lab 2); cloudy – analyze lab 3 data

CCD Analogy



Slides from Simon Tulloch

A 300 s exposure of M31. How do we convert this array of numbers into quantitative measurements of the brightnesses of stars and the galaxy?



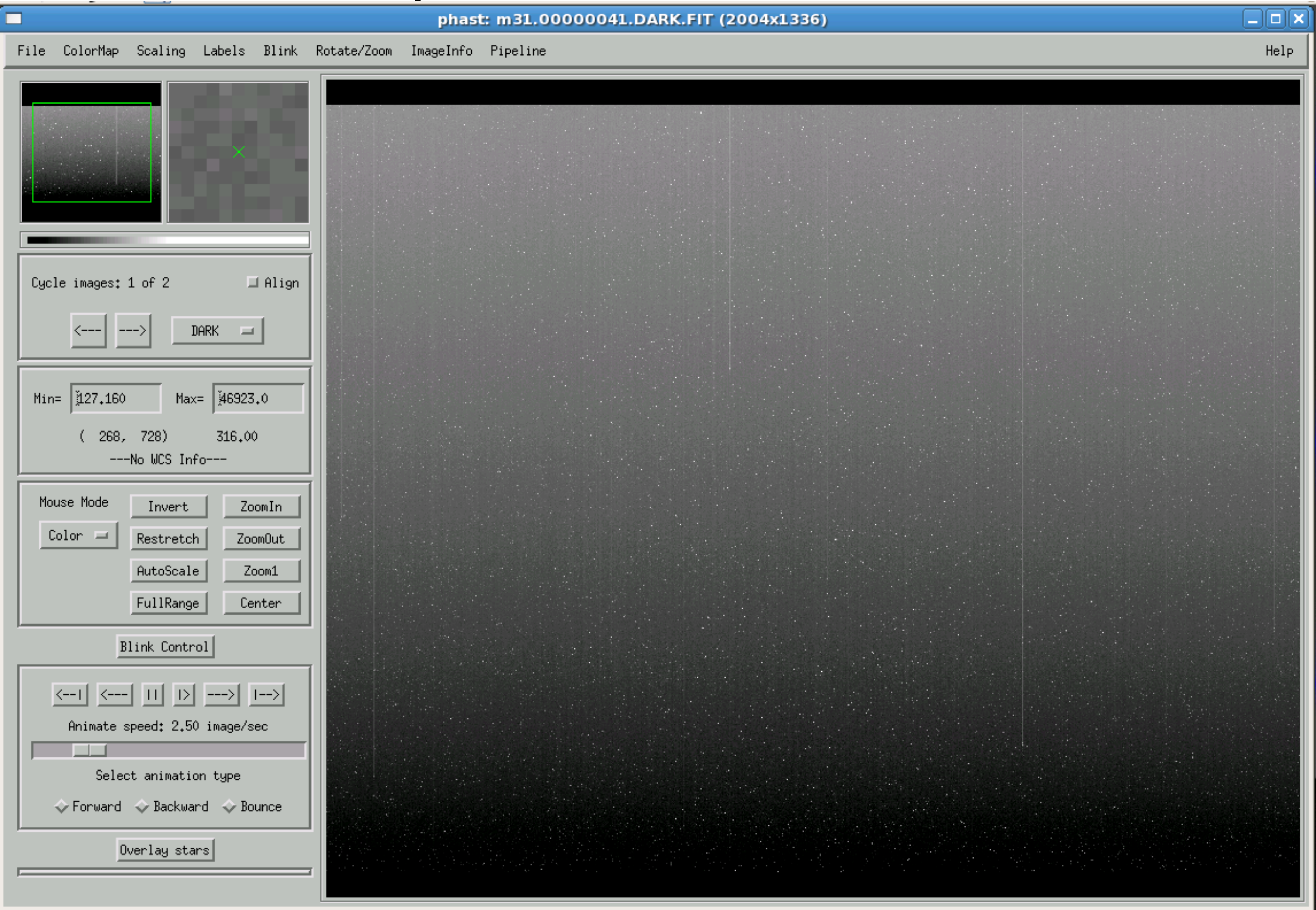
CCD (+camera + telescope) Calibration

- Additive corrections: ensure that zero CCD signal corresponds to zero detected light.
  - Measure and remove electronic bias signal.
  - Measure and remove “dark current” signal from thermally-generated electrons.
- Multiplicative corrections: What is the proportionality constant between corrected CCD signal and photons/cm^2/sec (also per wavelength interval) coming from a star or piece of a galaxy.
- Sources of noise.

CCD (+camera + telescope) Calibration

- Bias frame: a zero-length exposure with the shutter closed.
  - Contains only electronic bias (and noise from the electronics).
  - Subtract from science image.
- Dark frame: a non-zero-length exposure with the *shutter closed*.
  - Contains only thermal emission ("dark current") and the bias. Typically same length exposure as science image.
  - Subtract from science image (our CCDSOFT system has an auto-dark subtraction mode).

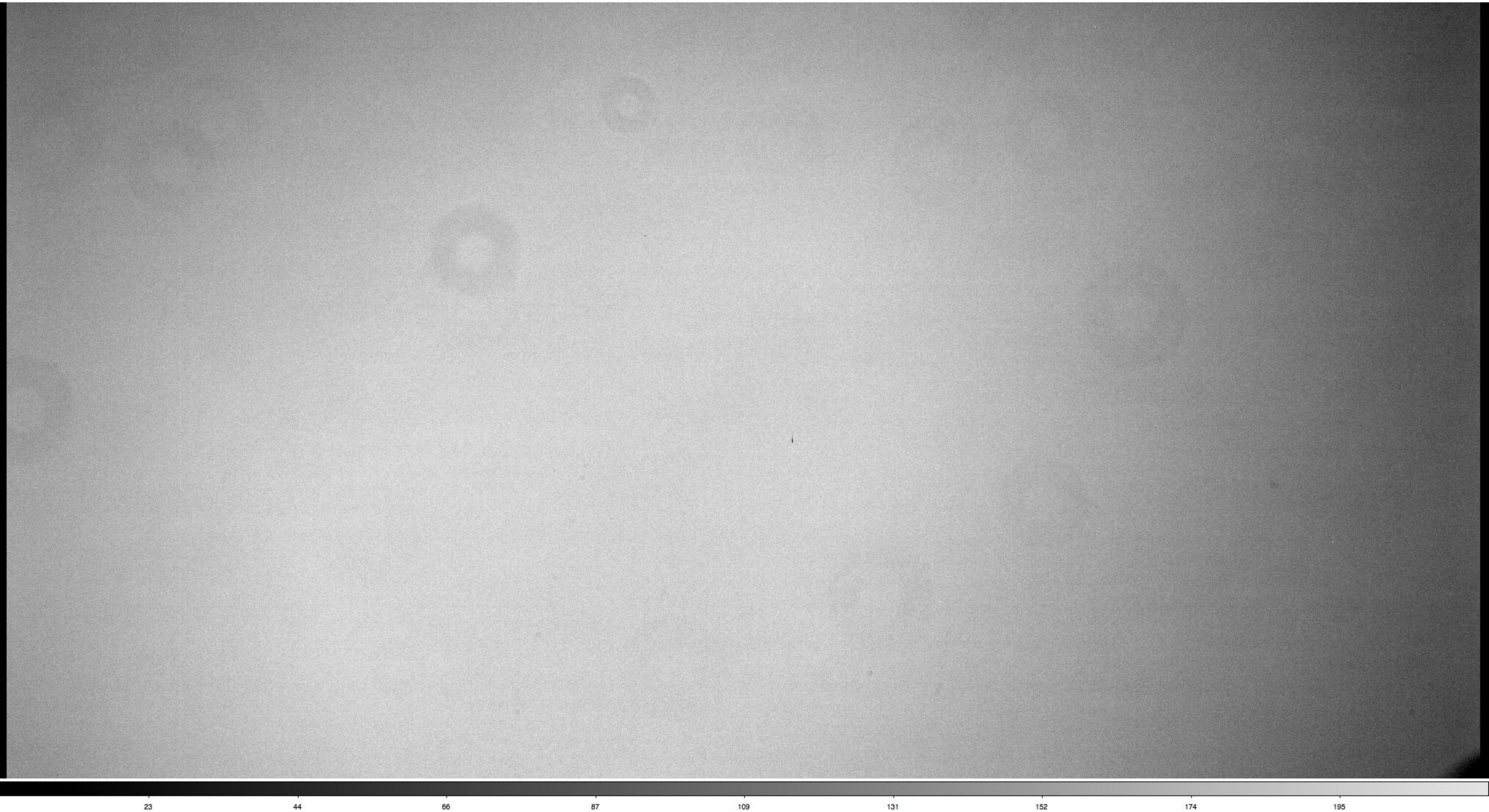
A 300 s dark exposure.



CCD (+camera + telescope) Calibration

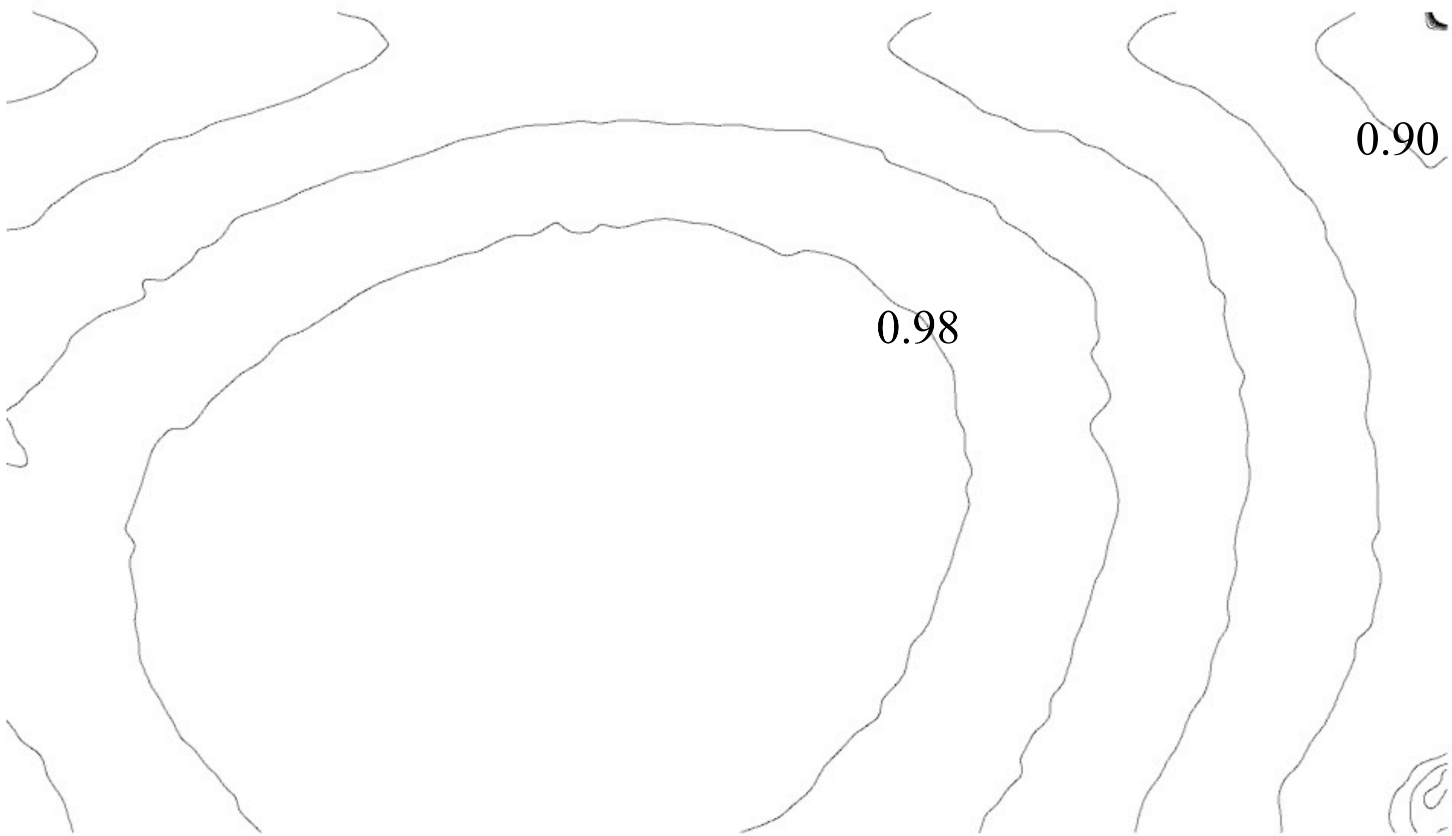
- Additive corrections: ensure that zero CCD signal corresponds to zero detected light.
- Multiplicative corrections:
  - Proportionality constant (gain) relating corrected CCD signal to # of electrons (# of detected photons).
  - Proportionality constant relating # of detected photons to the # of arriving photons.
    - Correcting variations in the constant across the image (pixel-to-pixel sensitivity variations; vignetting) − a “flat-field correction”.
    - Correcting the average sensitivity of the CCD + telescope (CCD quantum efficiency; absorption in filters, windows, and atmosphere; reflectivity of mirrors) − absolute calibration.

Flat field image

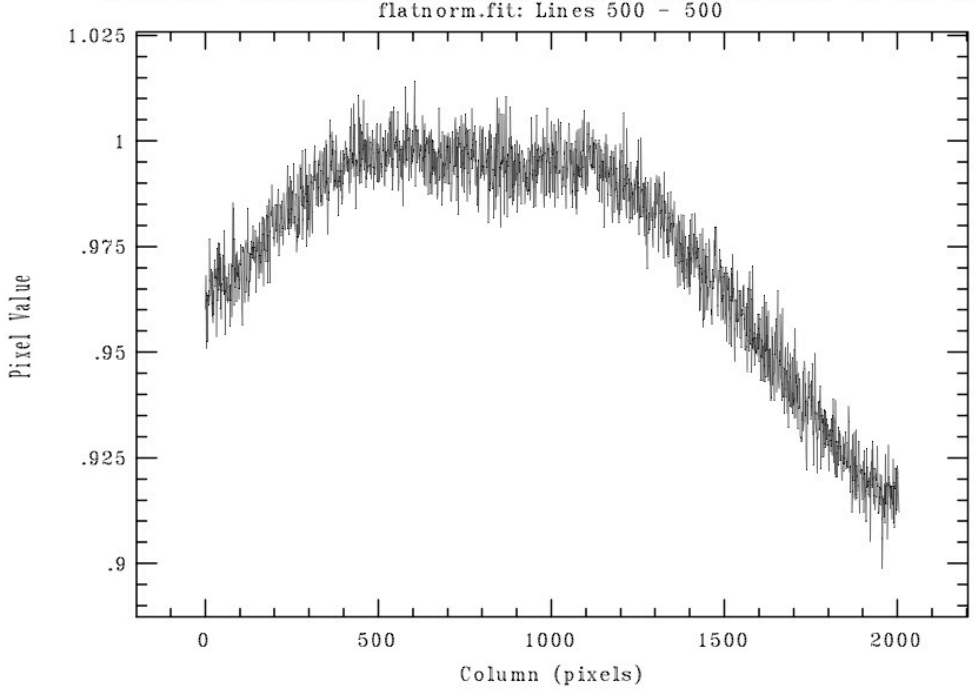


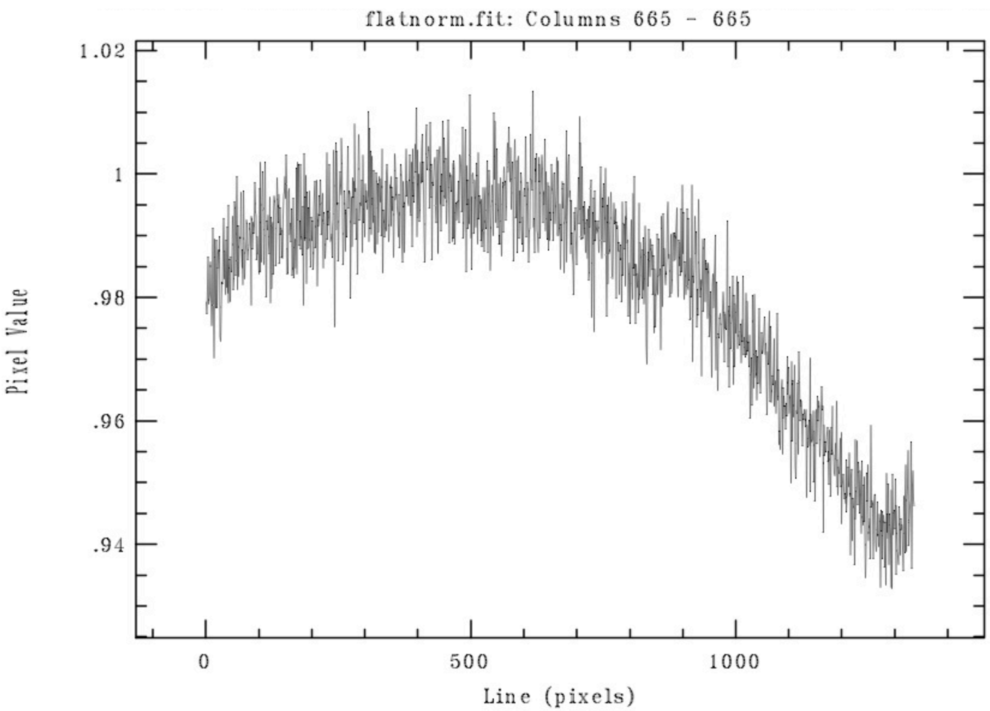
The “doughnuts” are the out-of-focus shadows of dust on the filter or CCD window. The corners are darker because of incomplete illumination (vignetting).

Contours of a flat-field image divided by maximum.



So only in the right-hand corners is the illumination less than 90% of maximum.



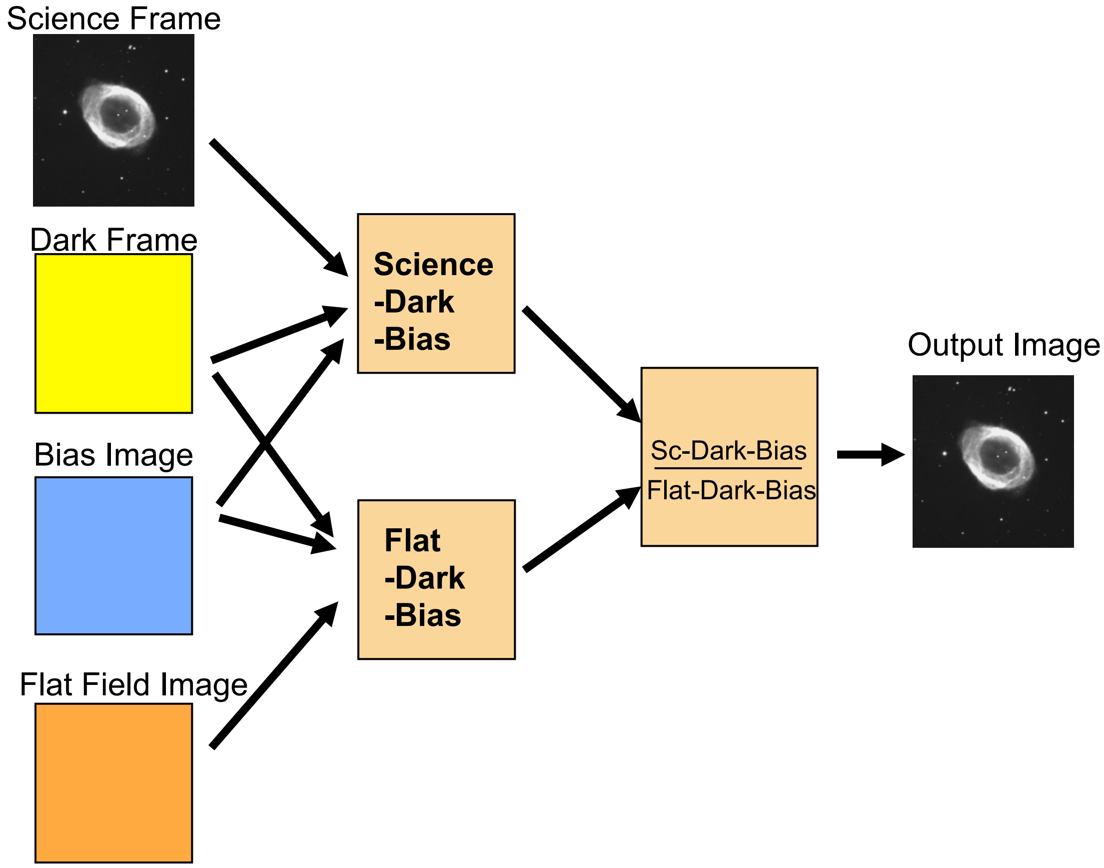


Horizontal and vertical cuts through a normalized flat.

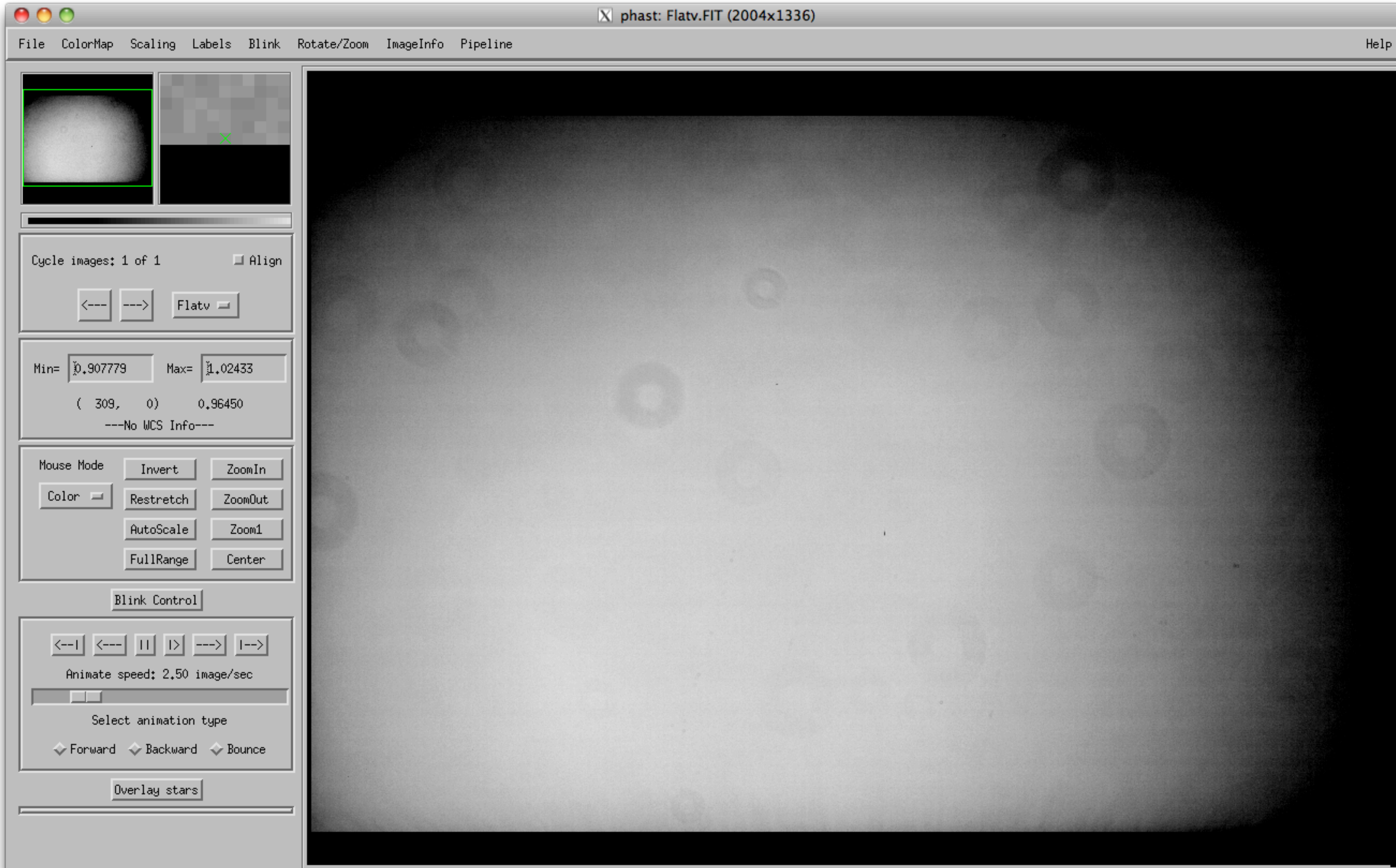
Note that pixel-to-pixel sensitivity variations are less than 1.5%.

CCD calibration

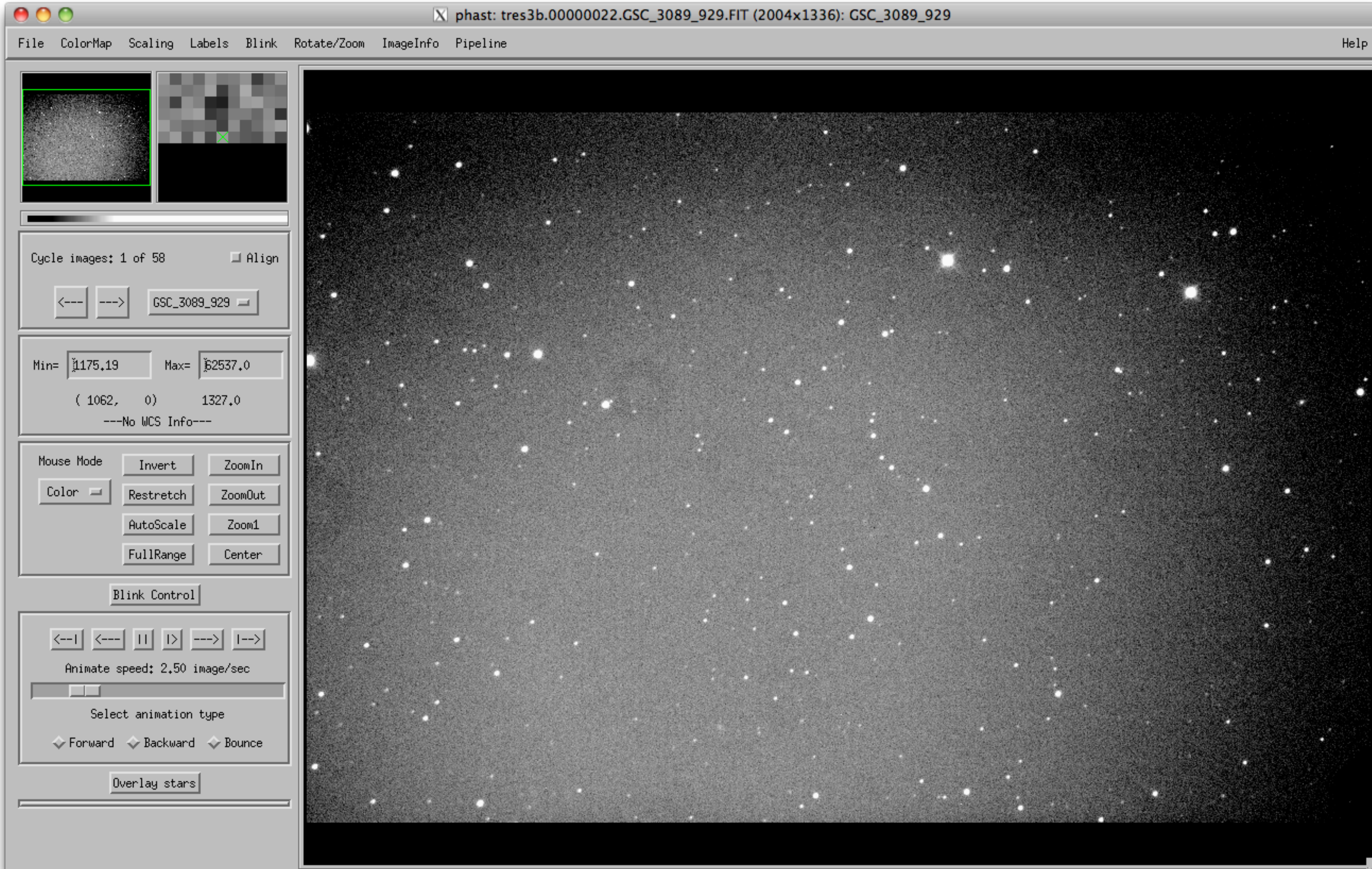
If there is significant dark current present:



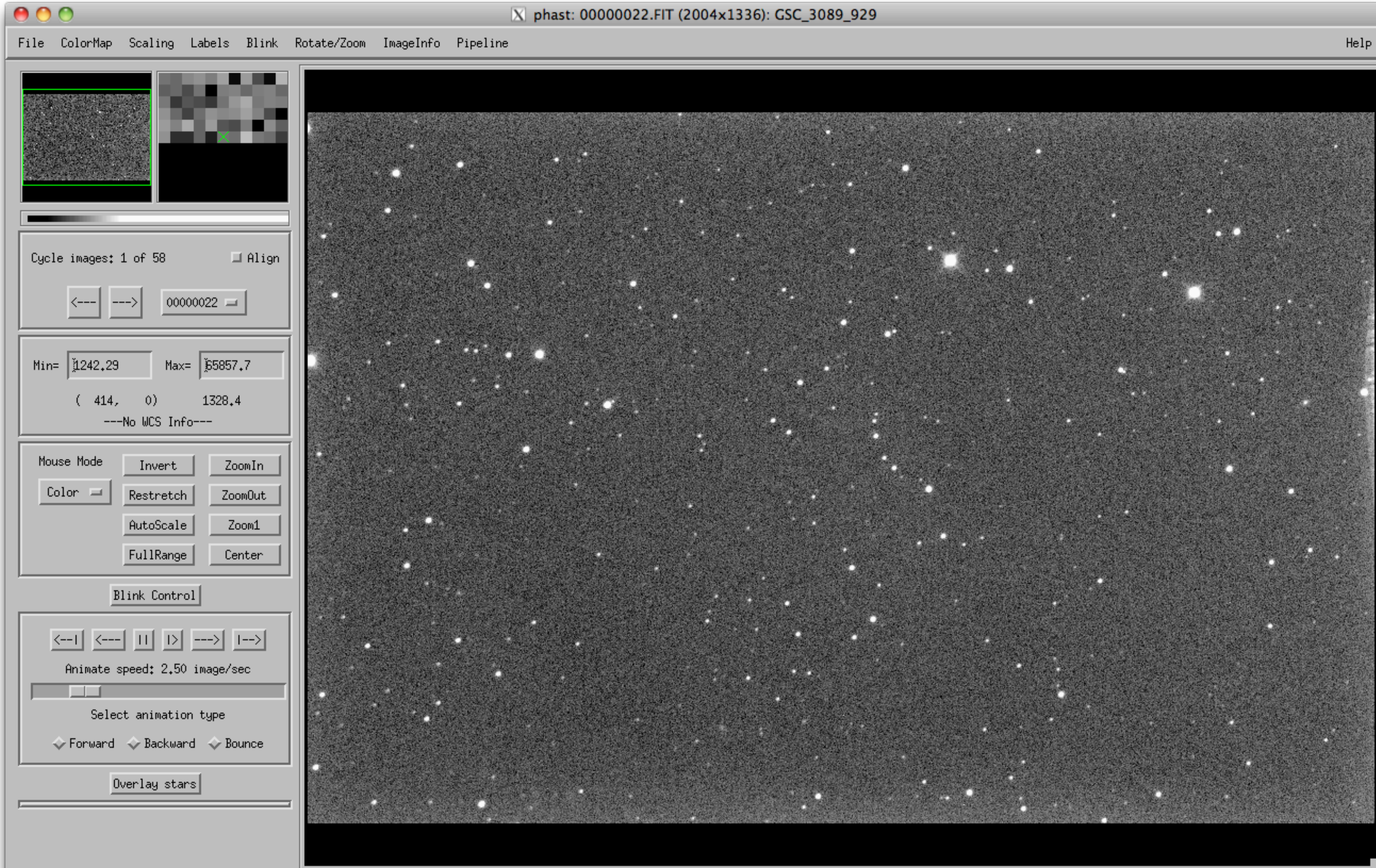
A flatfield image produced by the median of dome exposures (auto-dark subtracted).



Raw image (autodark subtracted); can see the flatfield pattern in the sky level.



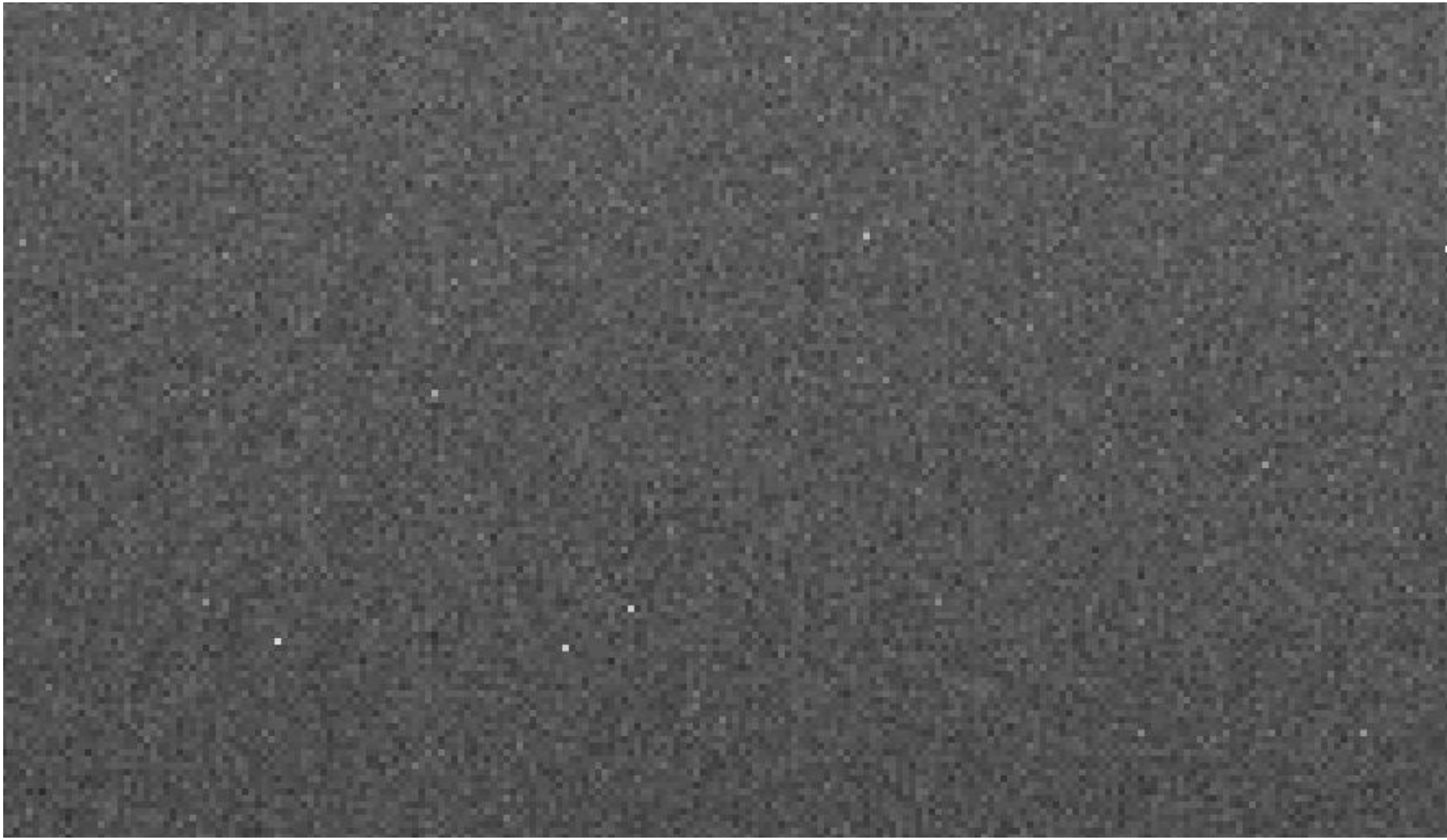
Flattened image = (science − dark)/flat
Good, though not perfect correction.



CCD Calibration

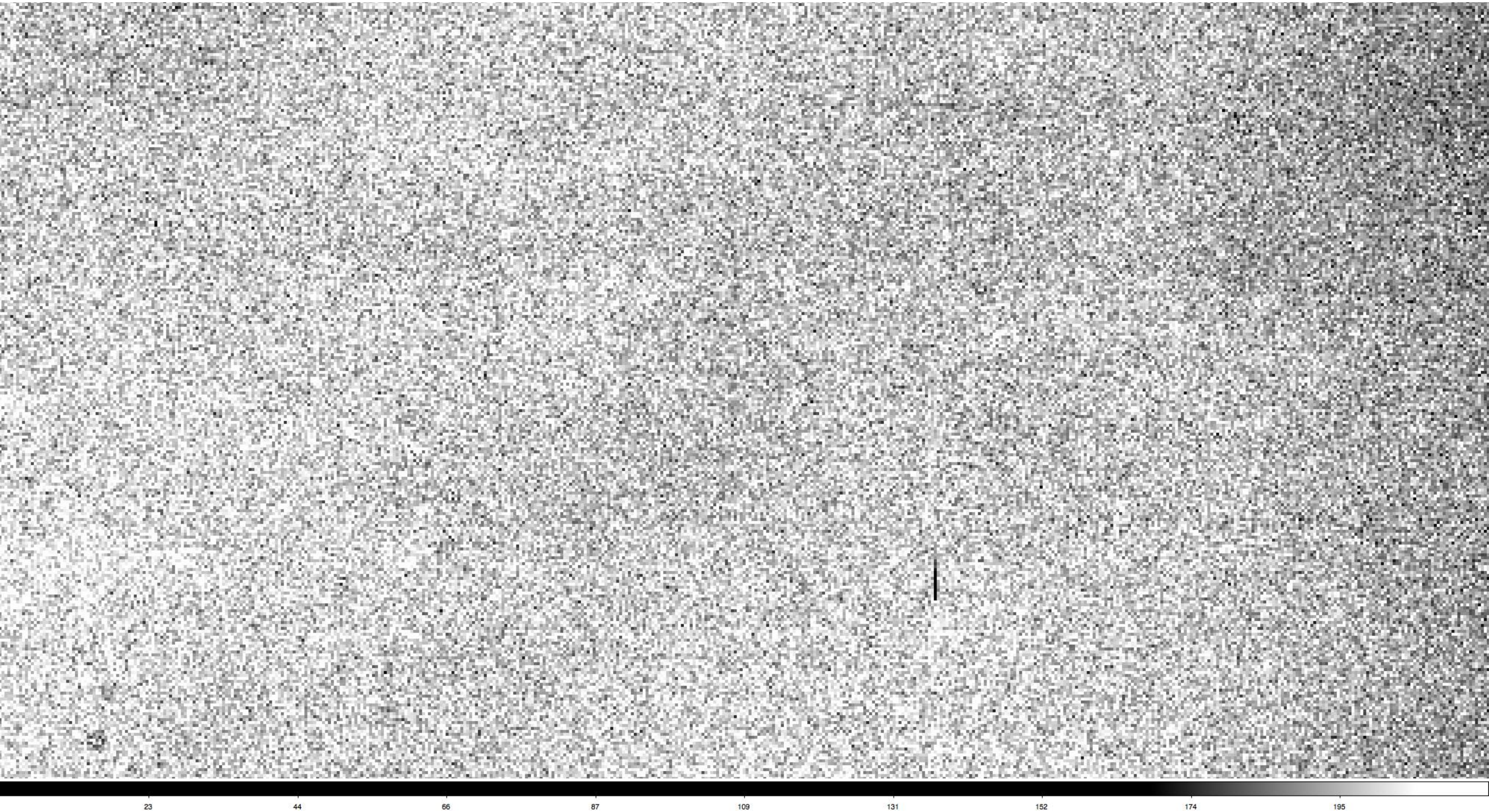
- Gain: the number of electrons per A-to-D digital unit (ADU or data number).
  - Really an inverse gain (is small if the amplifier gain is large).
- Read noise: the noise added by the amplification and measurement (usually given in electrons).

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

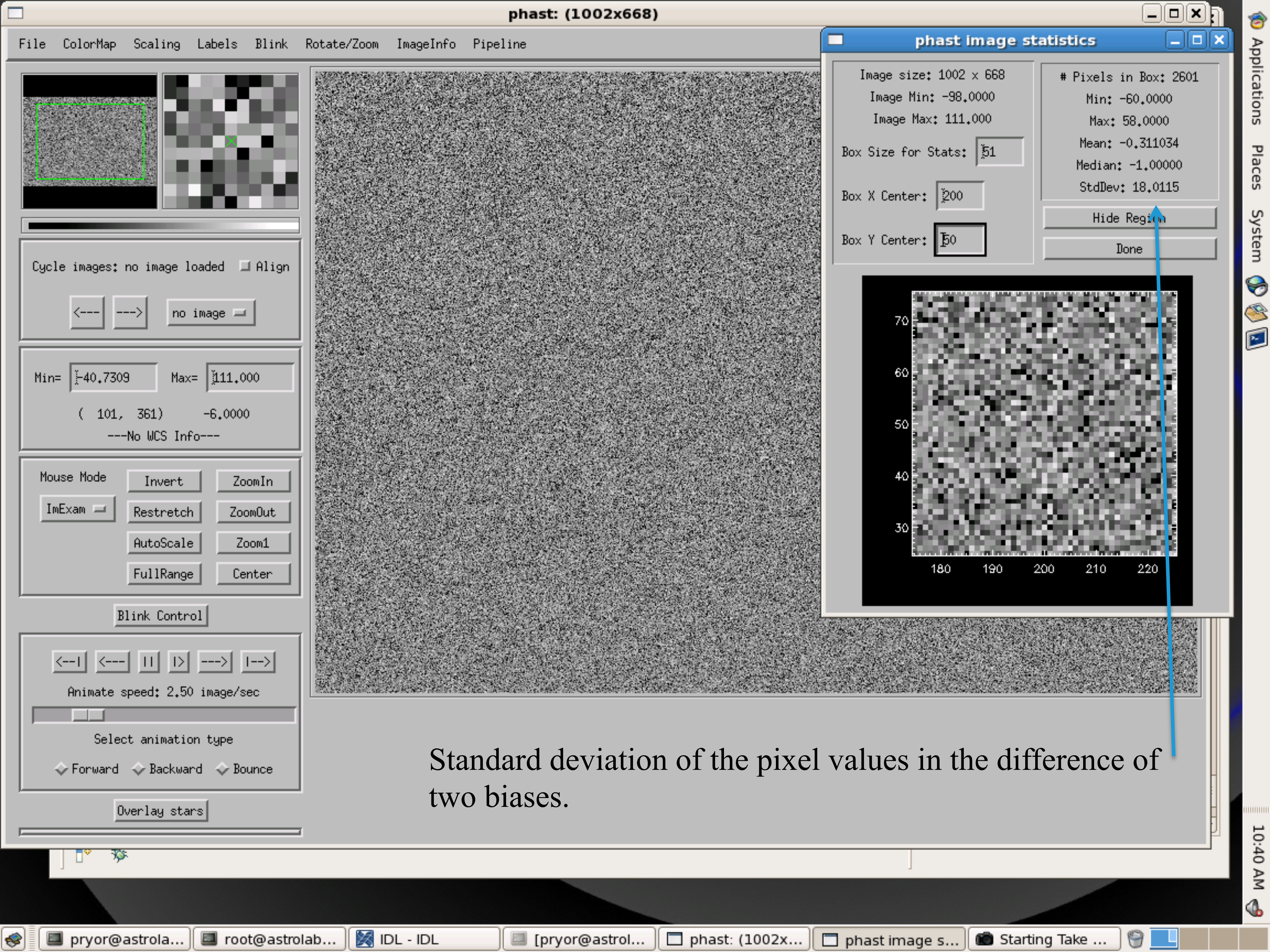


The "speckling" is a combination of pixel-to-pixel sensitivity variations and the Poisson noise of the photon arrivals.

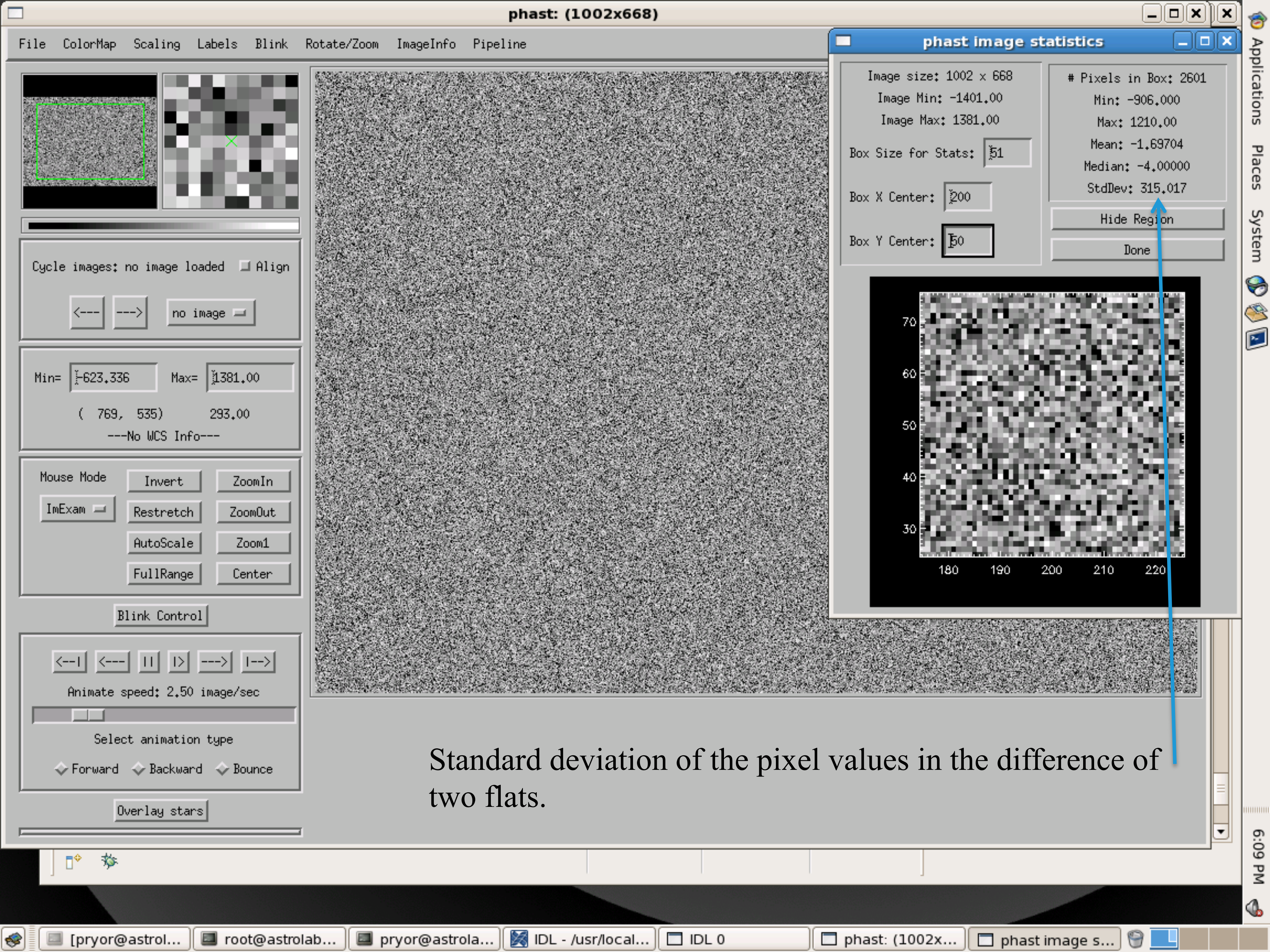
Differencing two images reduces the effect of signal variations (due to variations in brightness or pixel-to-pixel sensitivity variations) on the measured variance around the mean.

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

```
IDL> b2=readfits('biasquarterhi.00000006.BIAS.FIT',h) * 1.0
% READFITS: Now reading 1002 by 668 array
IDL> b1=readfits('biasquarterhi.00000005.BIAS.FIT',h) * 1.0
% READFITS: Now reading 1002 by 668 array
IDL> f2=readfits('flatquarterhi.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>
```



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



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

CCD Calibration

- Read noise: the noise in electrons added by the amplification.
  - Difference two bias images:
    - $\Delta = s_2 - s_1$
    - ➔ $\sigma_\Delta^2 = ((d\Delta/ds_1)\sigma_{s1})^2 + ((d\Delta/ds_2)\sigma_{s2})^2 = \sigma_{s1}^2 + \sigma_{s2}^2$ from propagation of errors
    - Since the noise in each pixel of a bias frame is the same read noise, $\sigma_{s1} = \sigma_{s2} = rn$ and $rn = \sigma_\Delta/\sqrt{2}$.
    - So just need to find the variance of Δ around mean for patches of the difference between two bias frames.
  - Produces the read noise in digital units (du or adu).

CCD Calibration

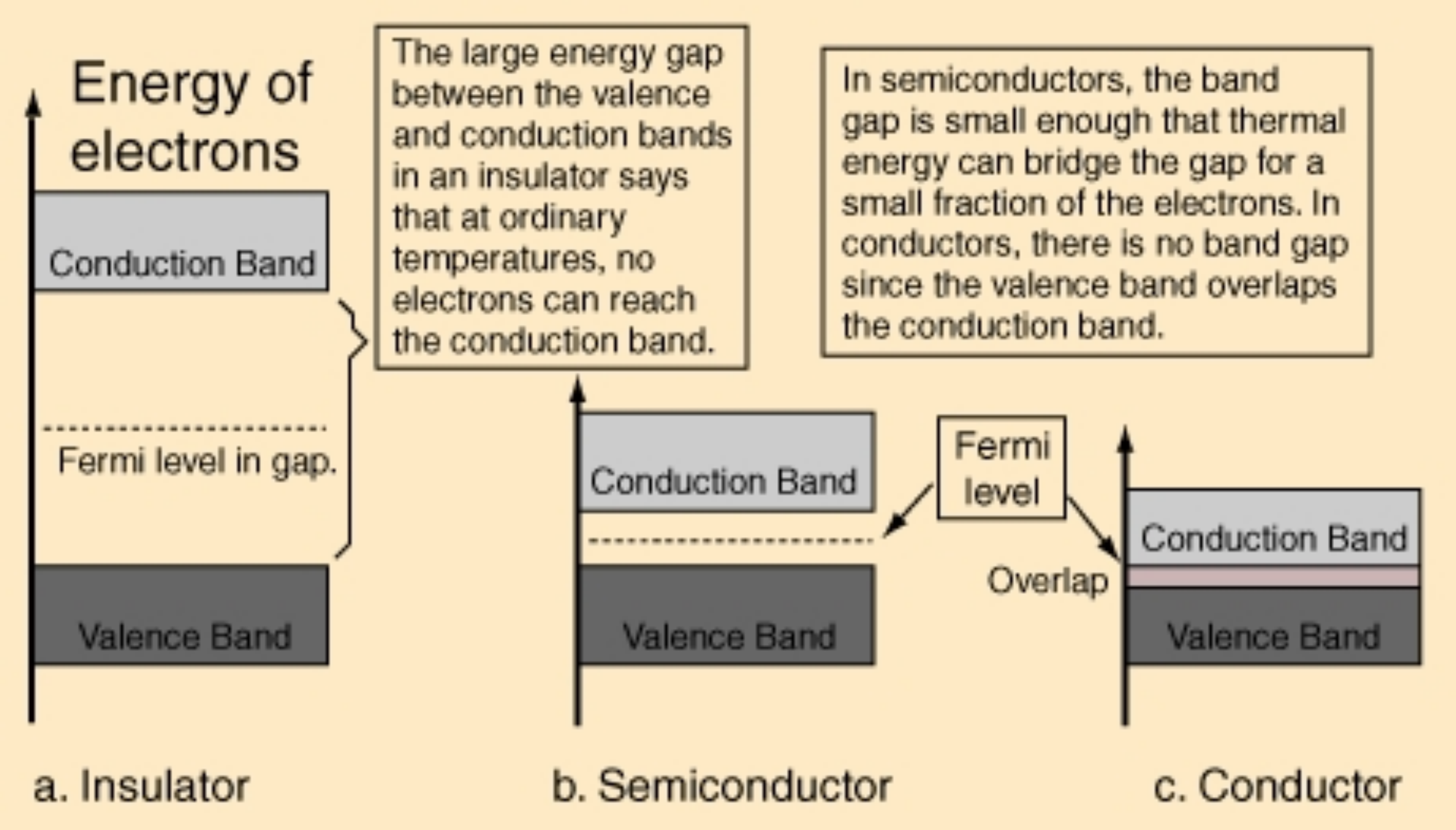
- Read noise: the noise in electrons added by the amplification.
- Gain: the number of electrons per A-to-D digital unit (or data number).
  - Determined by the noise in an image with high signal: is dominated by Poisson noise (shot noise), $\sigma_{Ne} = sqrt(N_e)$.
  - Again difference two flat field 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 $s = (s_2 + s_1)/2$
  - ➔ $\sigma_\Delta^2 = \sigma_{s1}^2 + \sigma_{s2}^2 = 2\sigma_s^2$ (since $s_1 \approx s_2$)
  - Now $N_e = g \times s$ ➔ $\sigma_{Ne} = g \times \sigma_s$ from prop. of errors and $\sigma_{Ne} = \text{sqrt}(N_e) = \text{sqrt}(g \times s)$.
  - So $\text{sqrt}(g \times s) = g \times \sigma_s$ ➔ $g \times s = g^2 \times \sigma_s^2 = g^2 \times \sigma_\Delta^2/2$
  - Solving for g: $g = 2s/\sigma_\Delta^2 = (s_1 + s_2)/\sigma_\Delta^2$

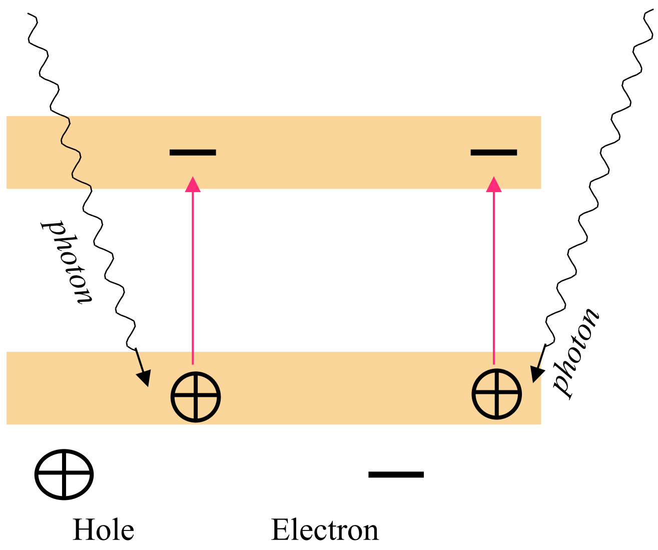
CCD's: Creation of Charge

- A brief review of electronic states in solids



CCD's: Creation of Charge

- Photoelectric effect
  - Silicon bandgap is $E_g = 1.11$ eV. Corresponds to
    - $\lambda = hc/E_g = 1.12\ \mu m$
    - $T = E_g/k = 1.29 \times 10^4$ K
  - The rate of thermal creation of hole/electron pairs is
    $$\propto \exp(-E_g / kT)$$
    - The exponential is small at room temperature, but there are many electrons in a solid. So cooling is usually needed to suppress the thermal creation ("dark current").
  - Without an electric field to separate the electron-hole pairs, they recombine in ~100 microseconds.



CCD's: Creation of Charge

- Photoelectric effect in silicon
  - Probability that a photon is absorbed when traversing an interval dx of Si is dx/a(λ), where a(λ) is the *absorption length*.
  - $dFlux = -Flux\ dx/a(\lambda)$
    ➔ $dF/F = -dx/a(\lambda)$
    ➔ $F(x) = F_0 \exp(-x/a(\lambda))$
  - Prob a photon absorbed in x is $(1-R)(1-\exp(-x/a(\lambda)))$ where R is the reflection coeff

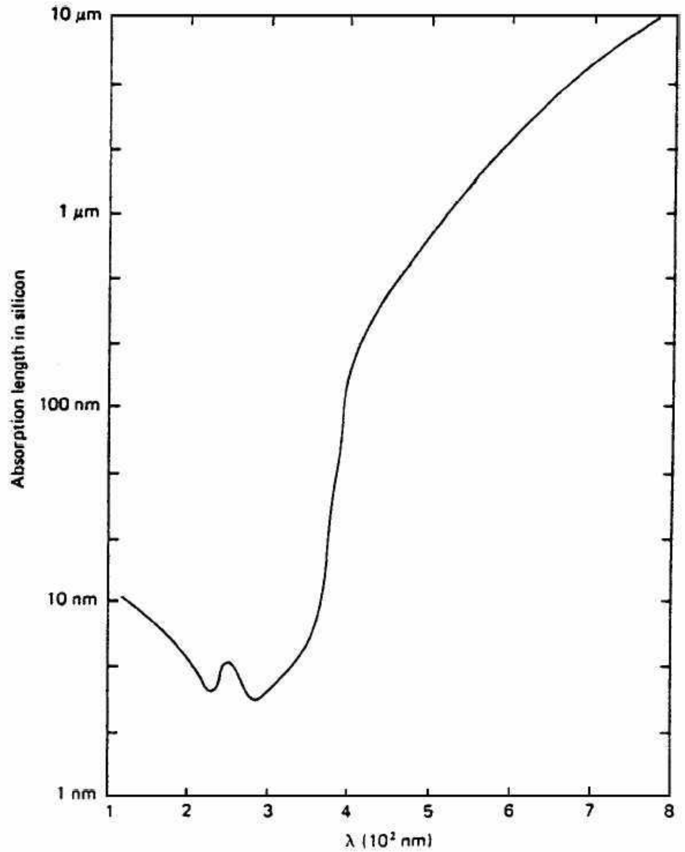
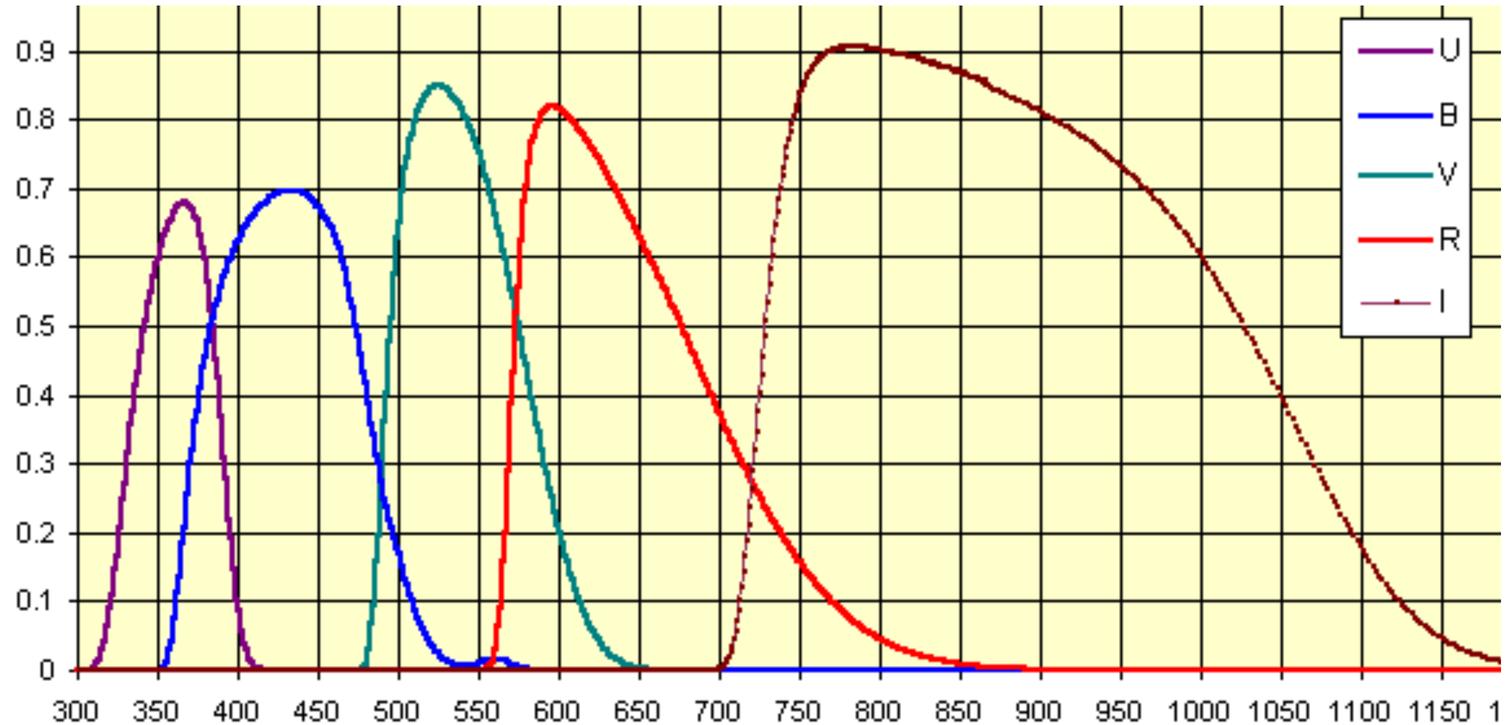
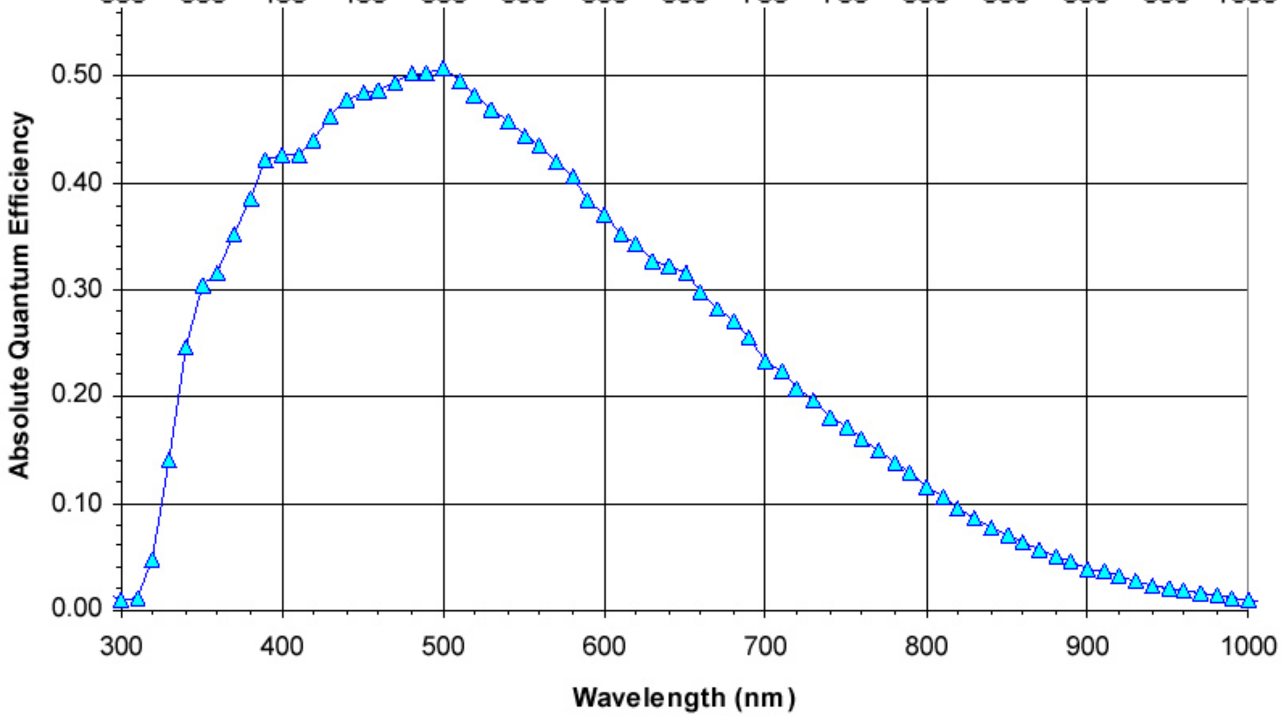


Fig. 3.1. The photon absorption length in silicon is shown as a function of wavelength in nanometers. From Reicke (1994).





The quantum efficiency of the CCD is varying significantly across the V and B bands.

CCD’s: Charge Storage (pixel)

- The basic CCD element (pixel) is the metal-oxide-semiconductor (MOS) capacitor.
  - Applying positive voltage to the metal electrode (gate) repels holes, producing a depletion region with an E field in it.
  - Photoelectrons collect in the depletion region.

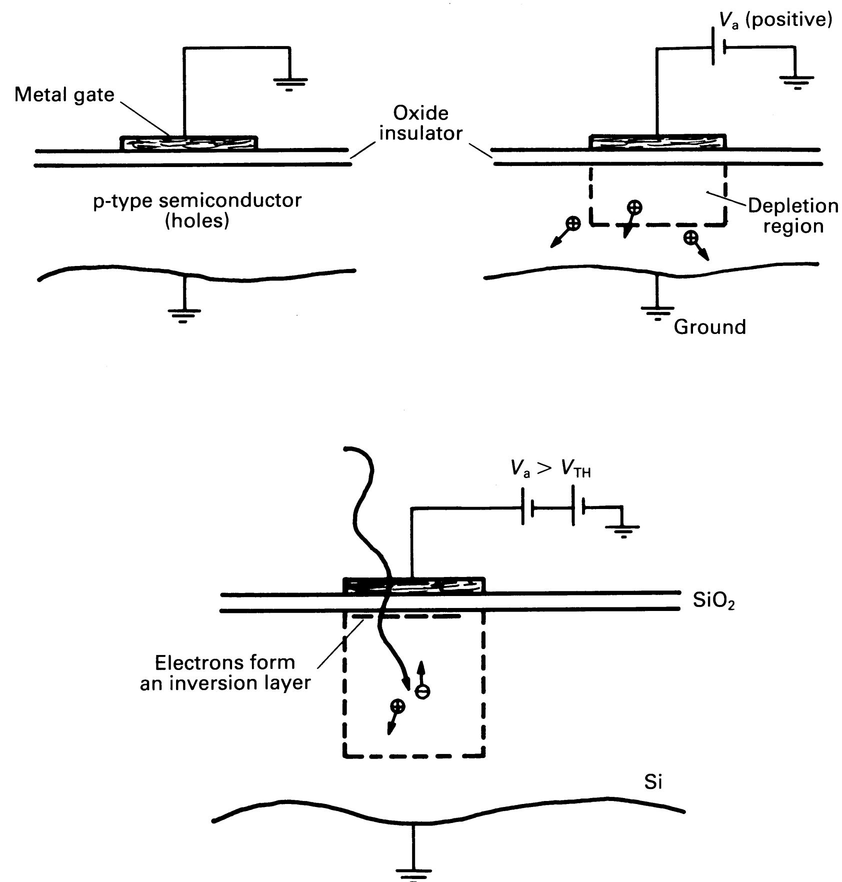
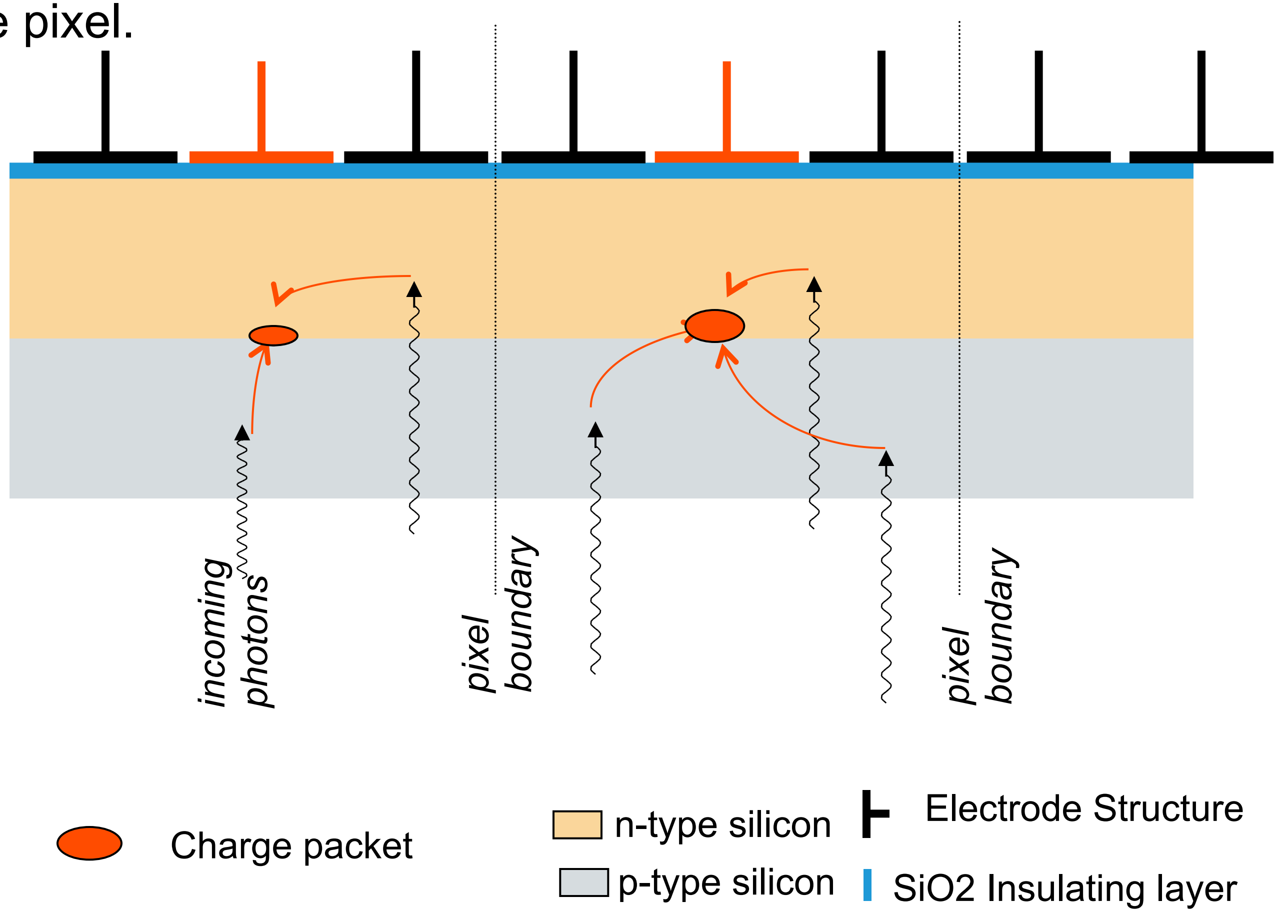


Fig. 6.7. A single metal-oxide-semiconductor (MOS) storage well, the basic element in a CCD.

Charge collection in a CCD

Photons entering the CCD create electron-hole pairs. The electrons are then attracted towards the most positive potential in the device where they create 'charge packets'. Each packet corresponds to one pixel.



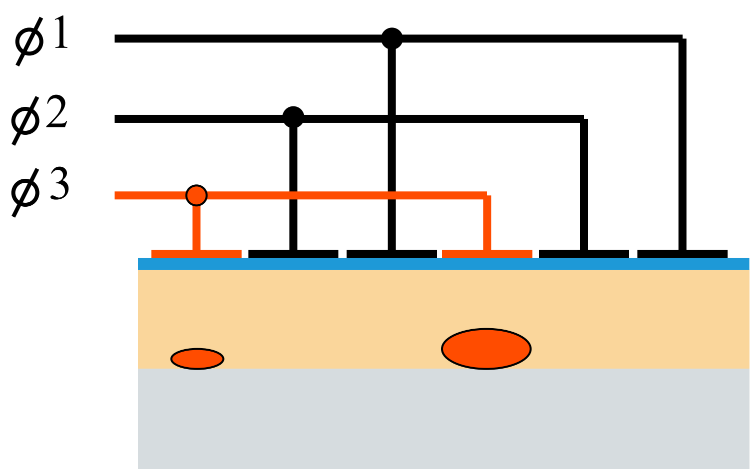
Charge Collection: Full Well

- As charge packets become larger, the electrons repel each other and the charge leaks into adjacent pixels.
  - Usually along a column; channel stops prevent diffusion between columns.
  - Bigger pixels (area and depth) have larger full wells.
  - Values: 30,000 – 500,000 electrons. Our camera has a full well of ~60,000 electrons.
- Signal also limited by the 16 bits of the signal digitizer; $2^{16} - 1 = 65535$.

Charge Transfer in a CCD 1.

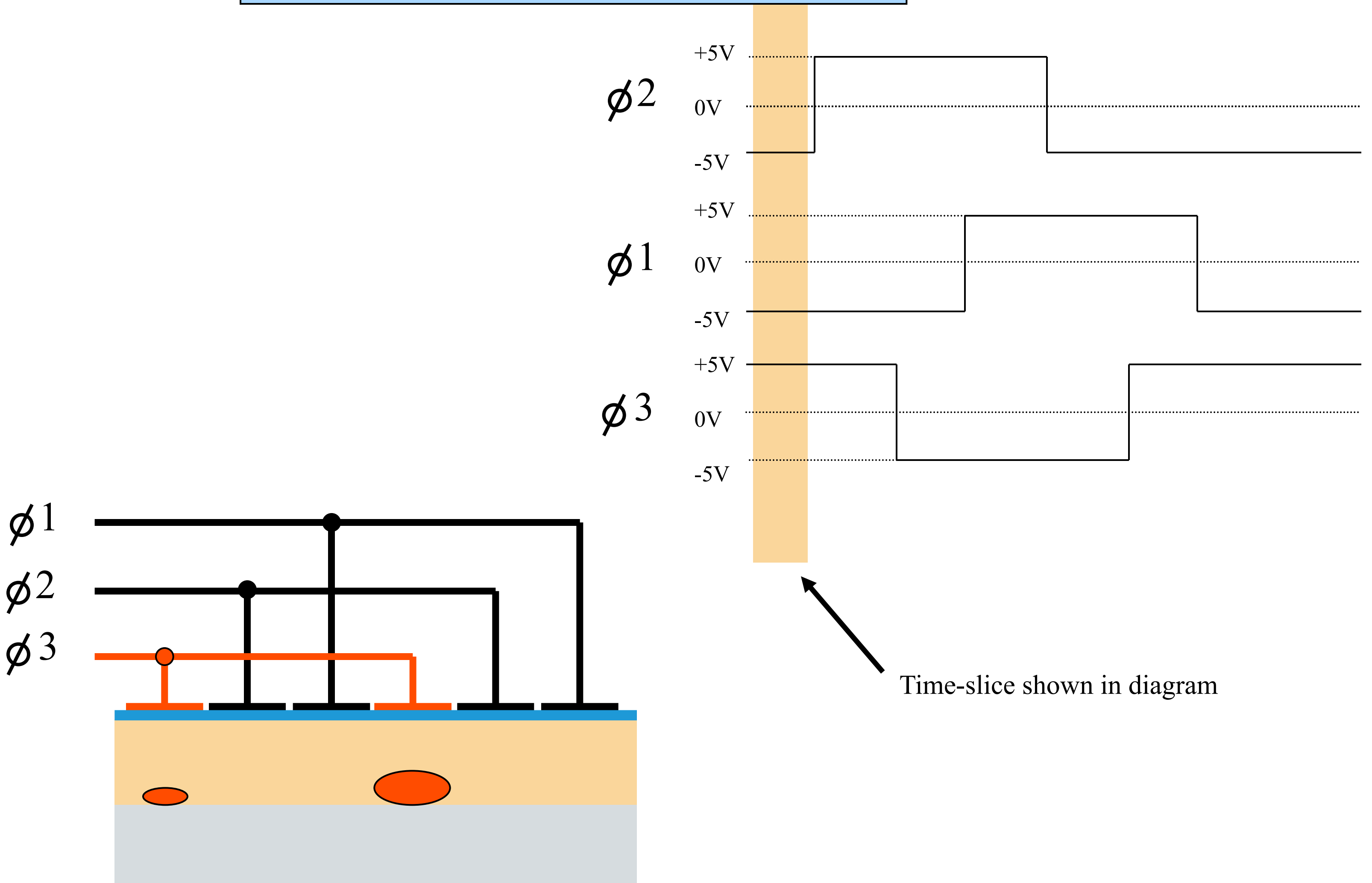
In the following few slides, the implementation of the 'conveyor belts' as actual electronic structures is explained.

The charge is moved along these conveyor belts by modulating the voltages on the electrodes positioned on the surface of the CCD. In the following illustrations, electrodes color coded red are held at a positive potential, those colored black are held at a negative potential.

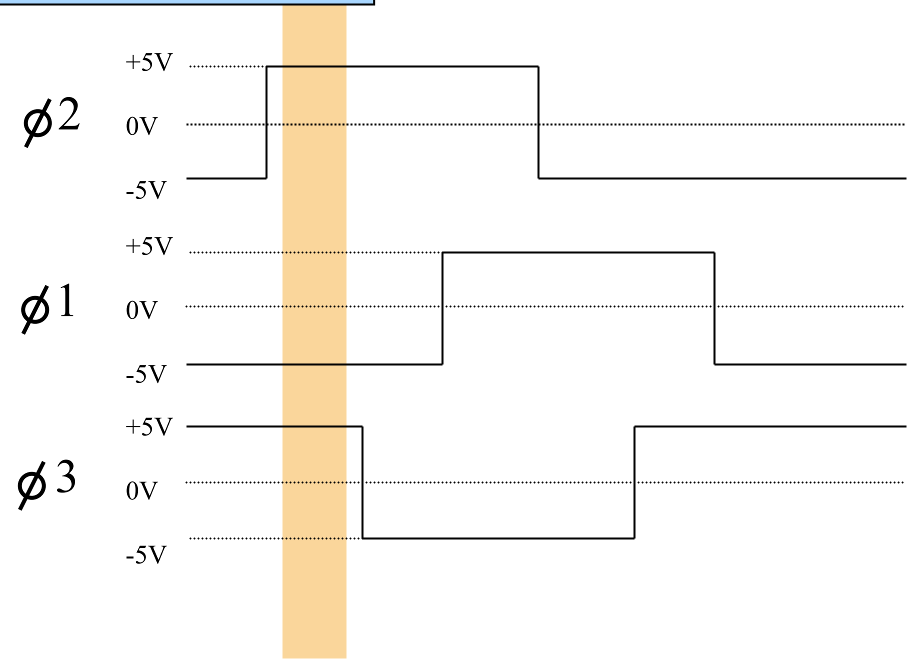


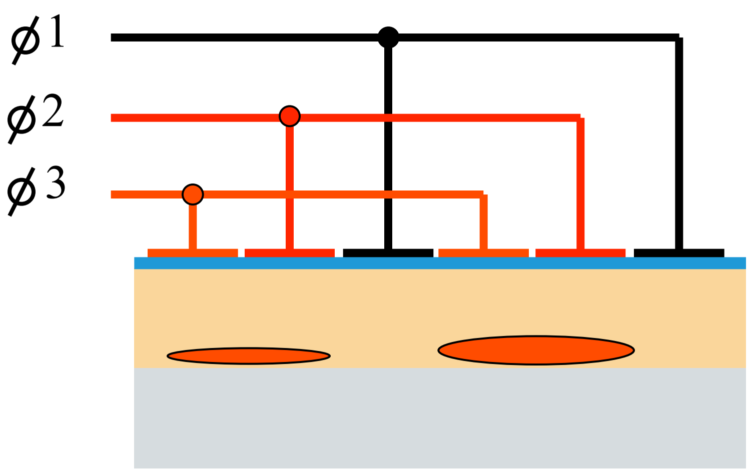
Slides from Simon Tulloch

Charge Transfer in a CCD 2.

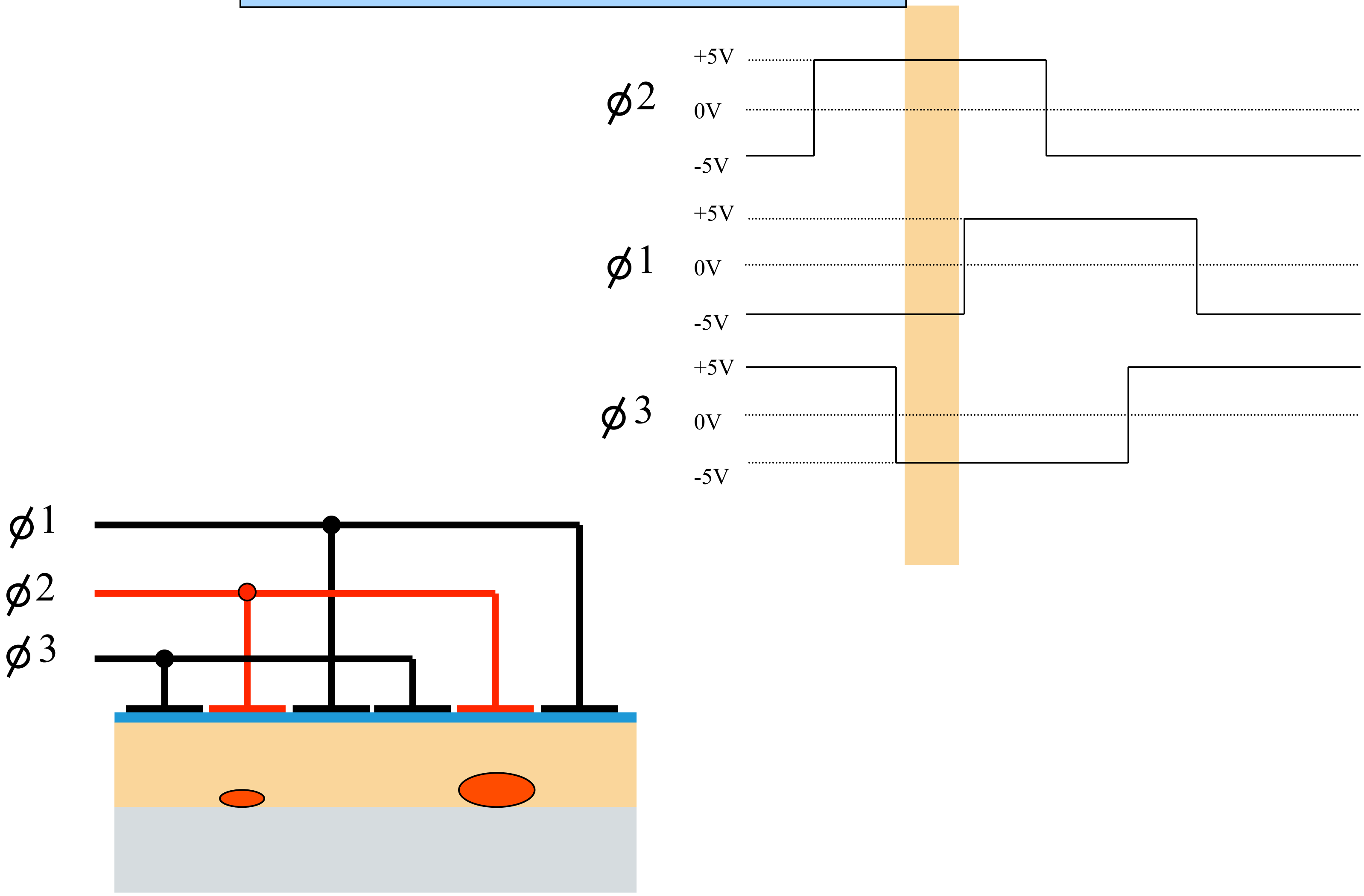


Charge Transfer in a CCD 3.

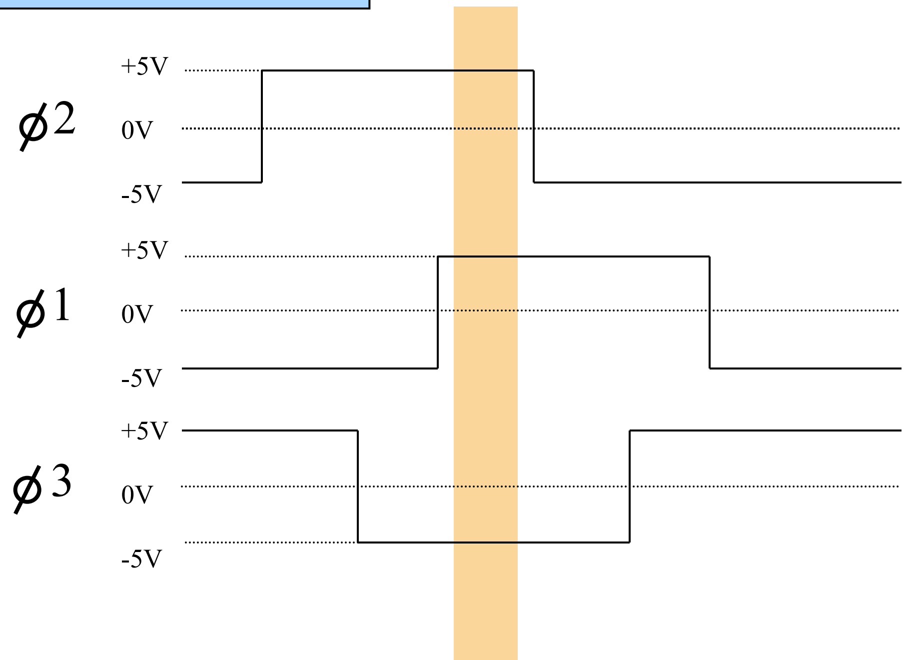


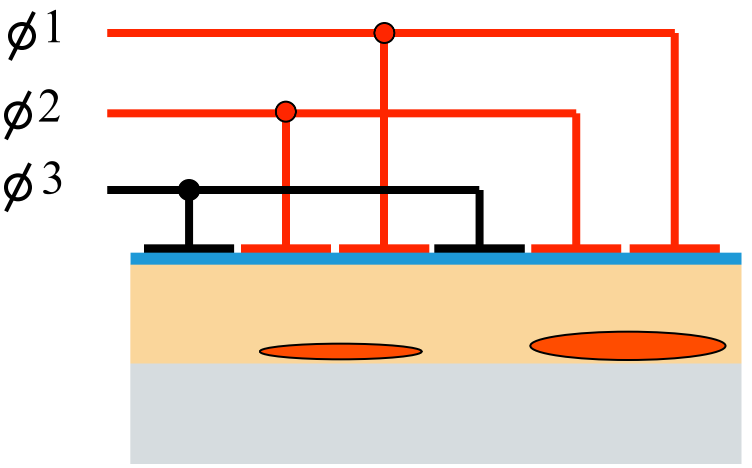


Charge Transfer in a CCD 4.

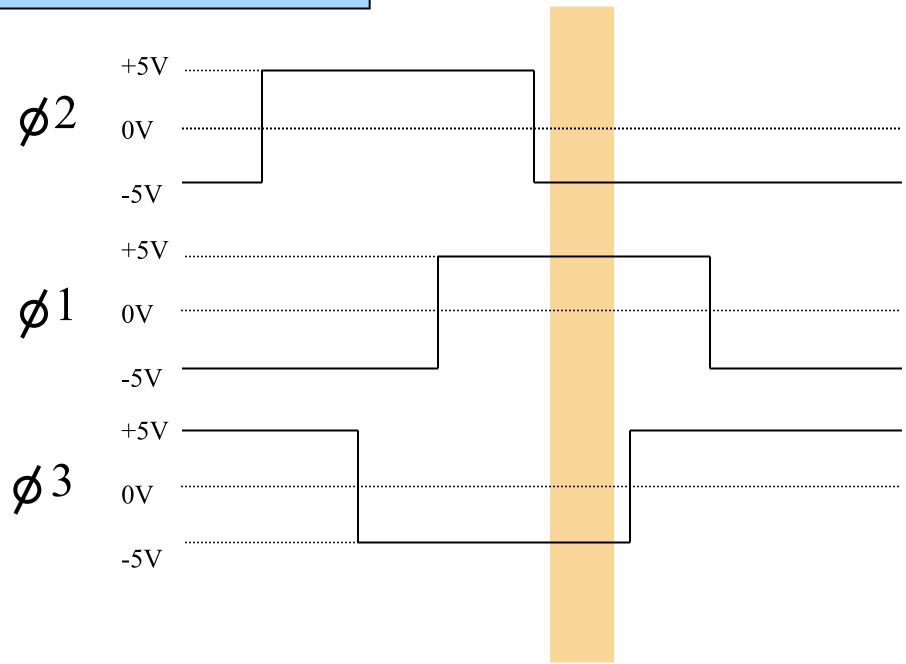


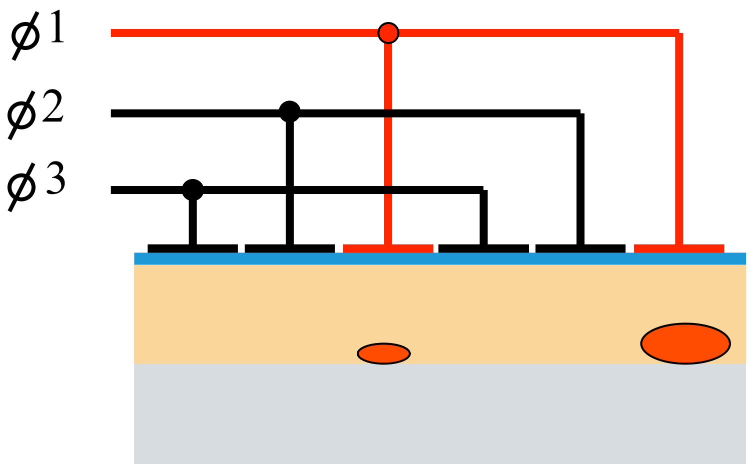
Charge Transfer in a CCD 5.





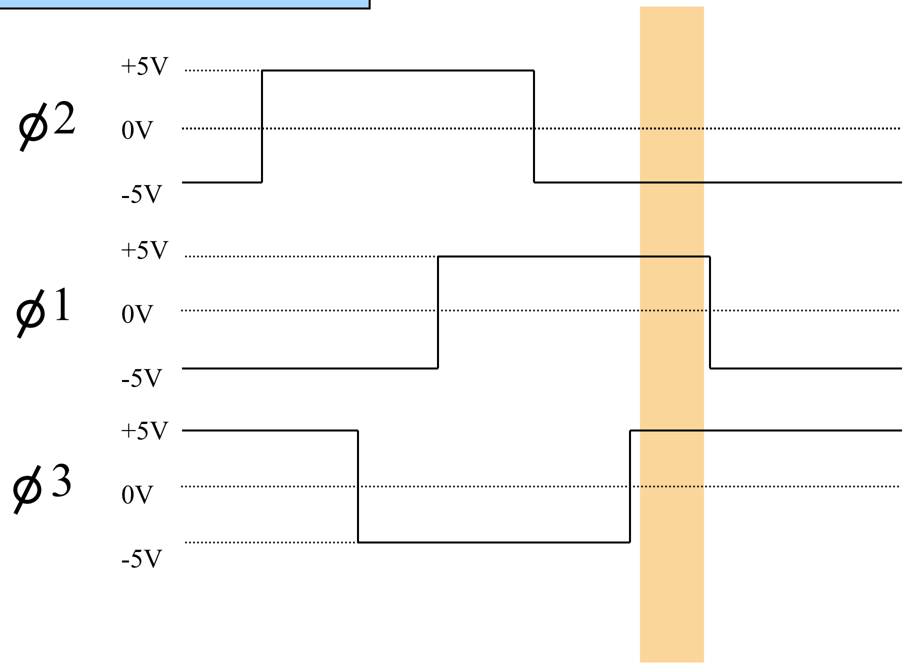
Charge Transfer in a CCD 6.

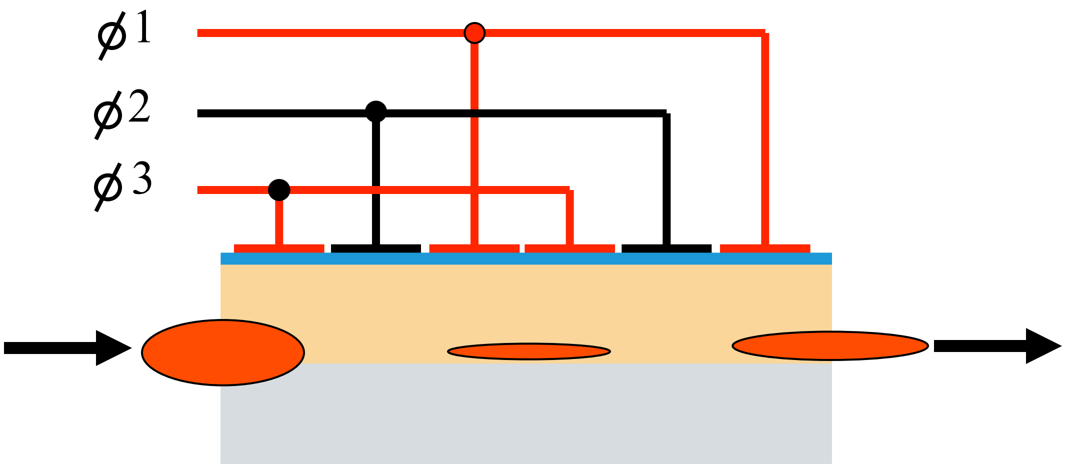




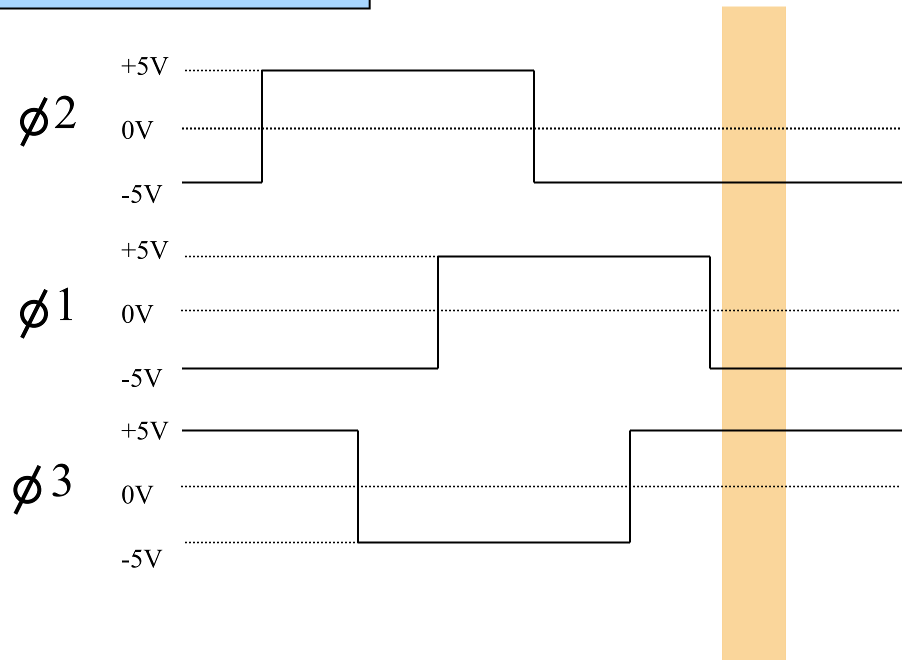
Charge Transfer in a CCD 7.

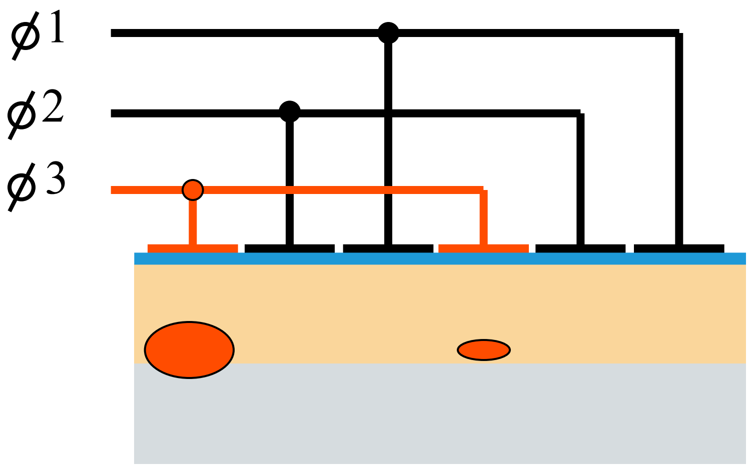
Charge packet from subsequent pixel enters from left as first pixel exits to the right.





Charge Transfer in a CCD 8.



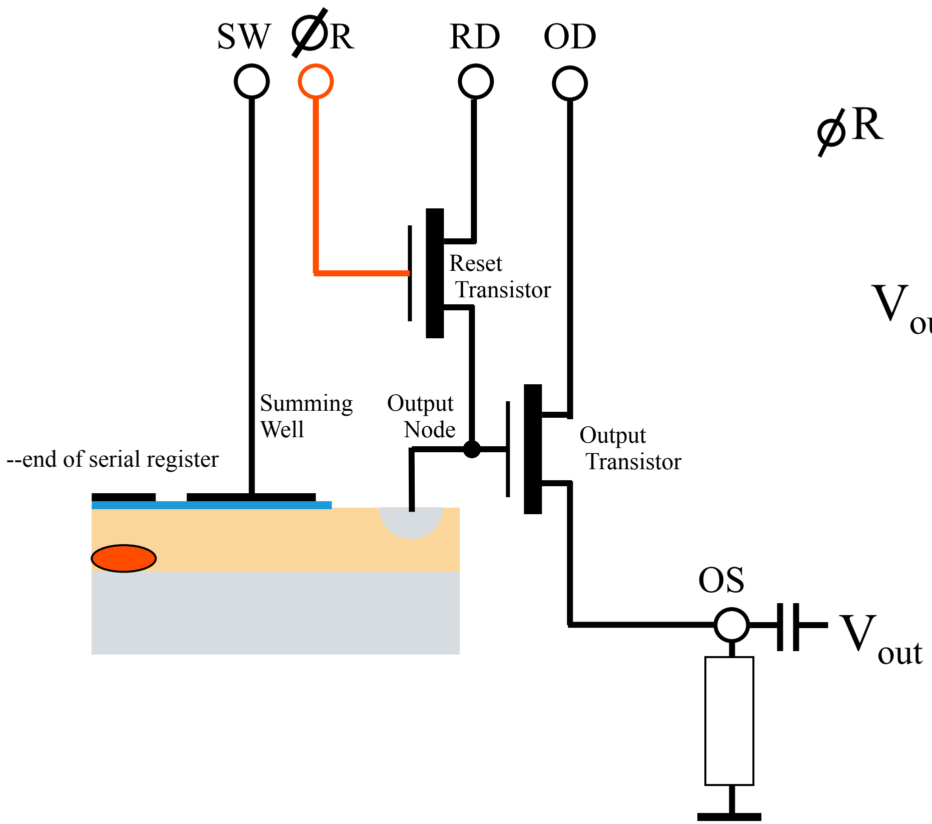


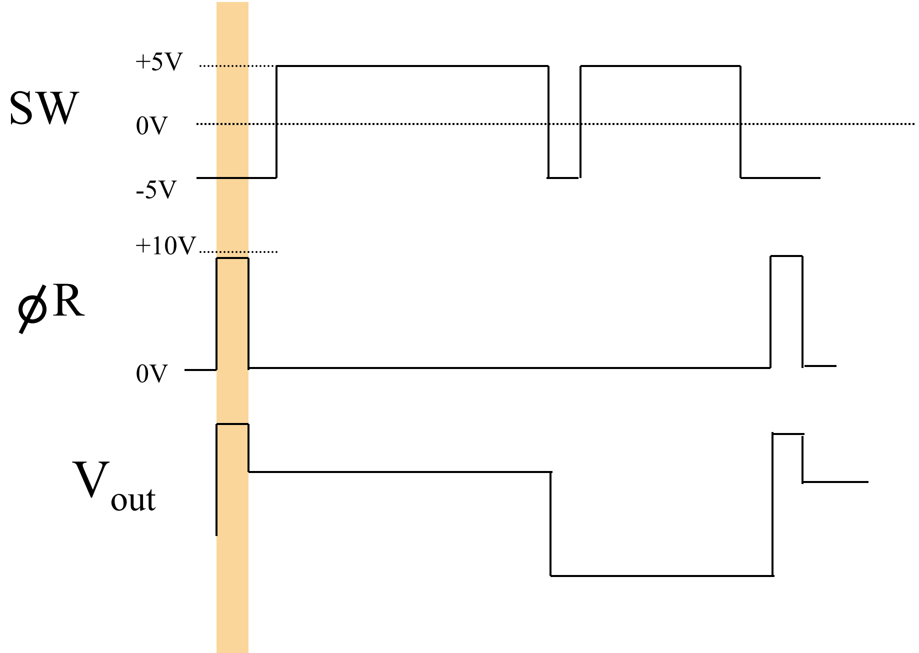
Charge transfer efficiency needs to be very high (~0.99999) because the charge is transferred 1000's of times.

On-Chip Amplifier 1.

The on-chip amplifier measures each charge packet as it pops out the end of the serial register.

RD and OD are held at constant voltages



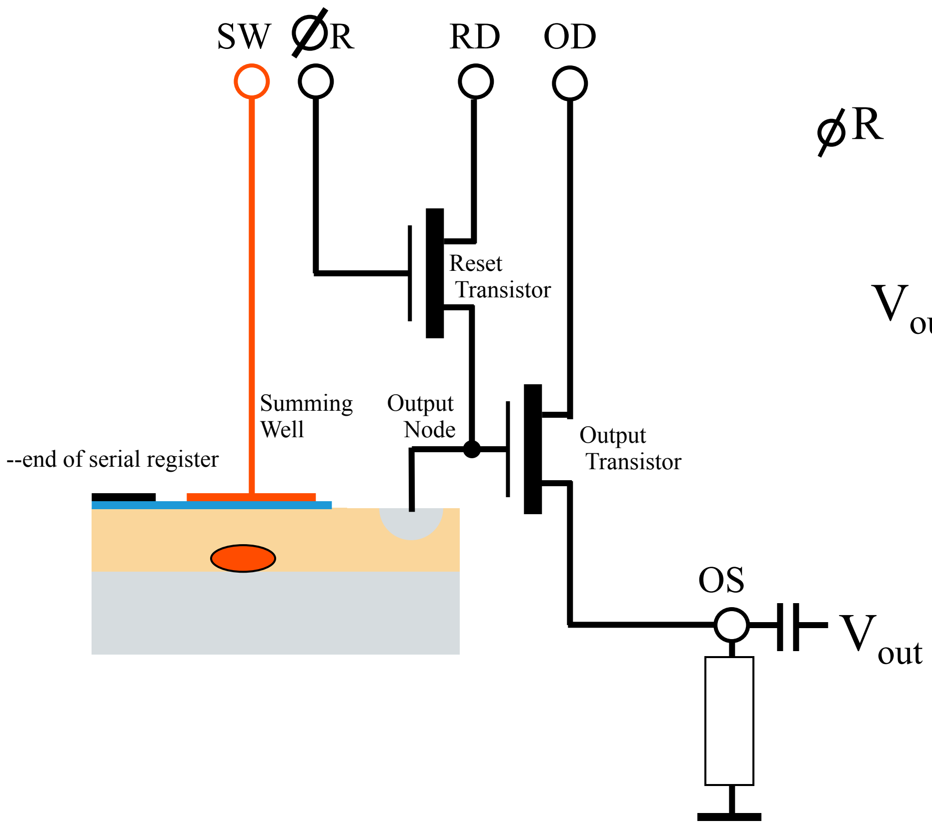


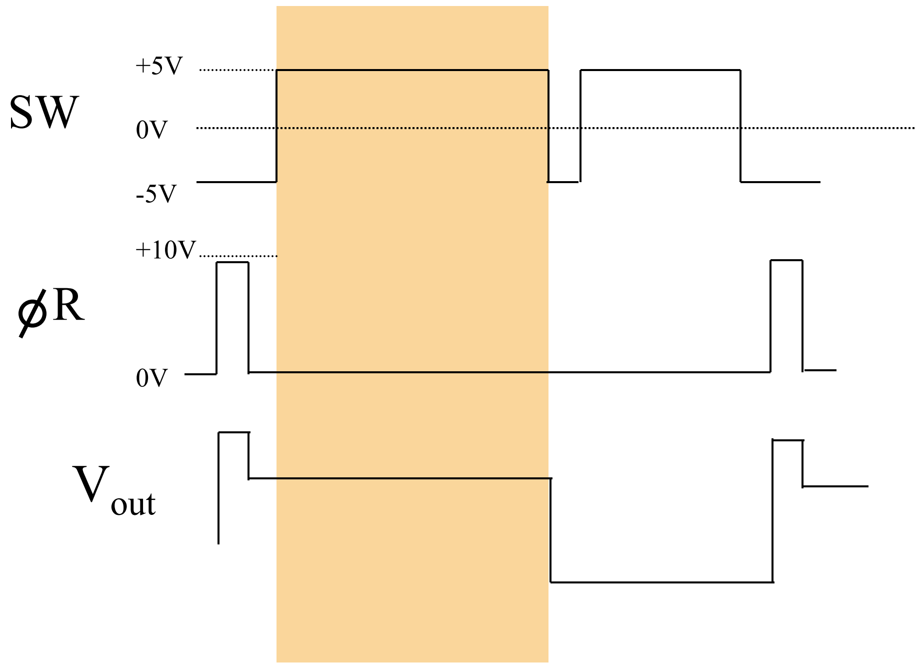
(The graphs above show the signal waveforms)

The measurement process begins with a reset of the 'output node'. This removes the charge remaining from the previous pixel. The output node is in fact a tiny capacitor (< 0.1pF).

On-Chip Amplifier 2.

The charge is then transferred onto the Summing Well. V_{out} is now at the ‘Reference level’

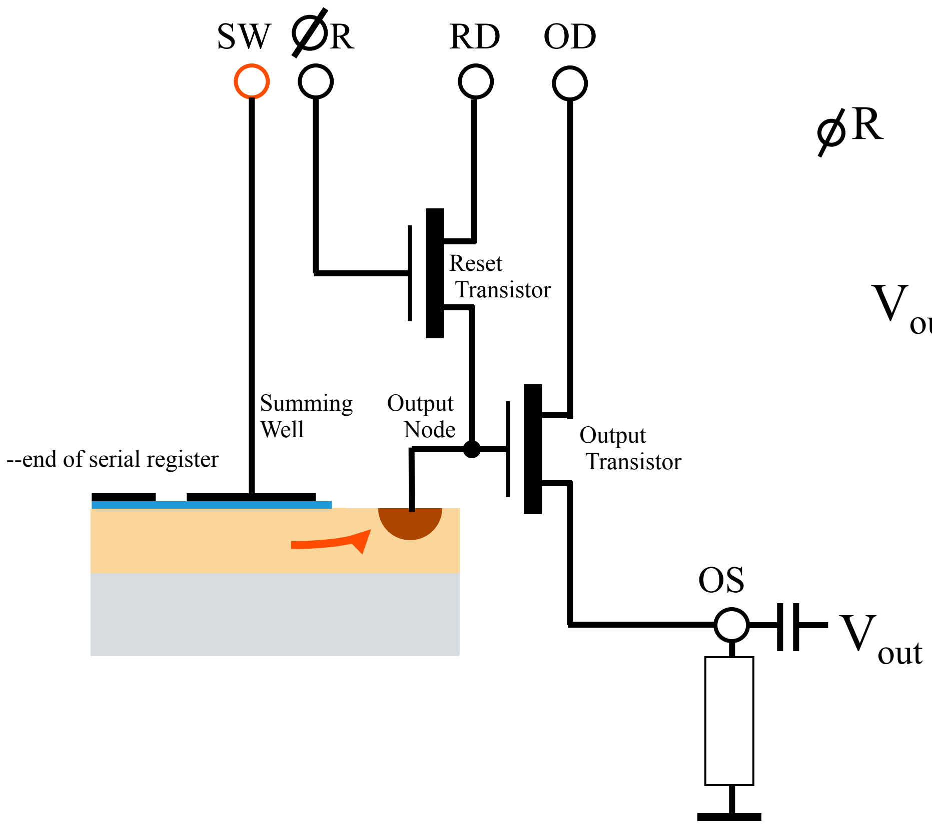


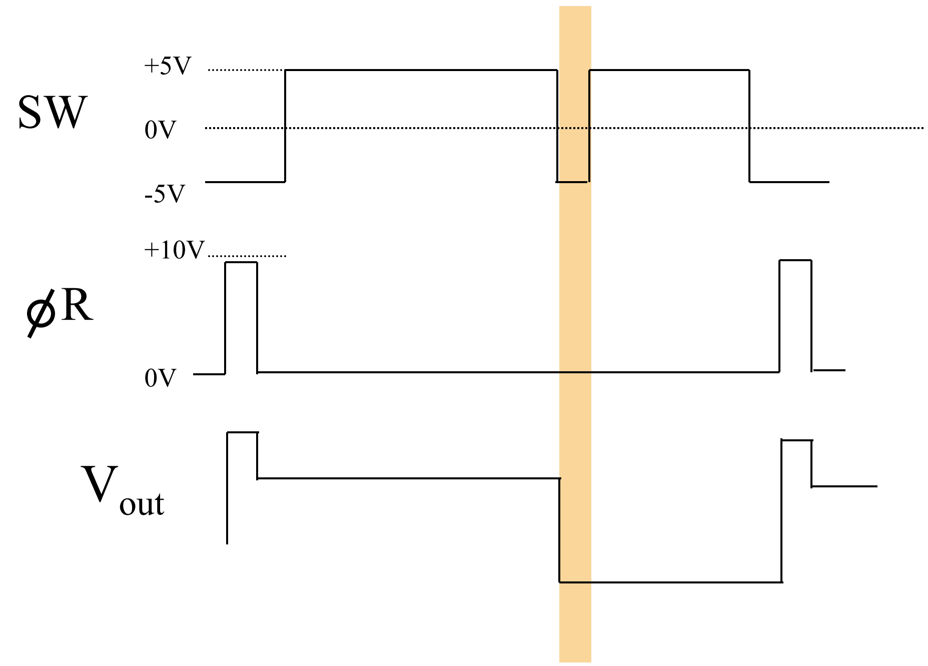


There is now a wait of up to a few tens of microseconds while external circuitry measures this ‘reference’ level.

On-Chip Amplifier 3.

The charge is then transferred onto the output node. V_{out} now steps down to the 'Signal level'

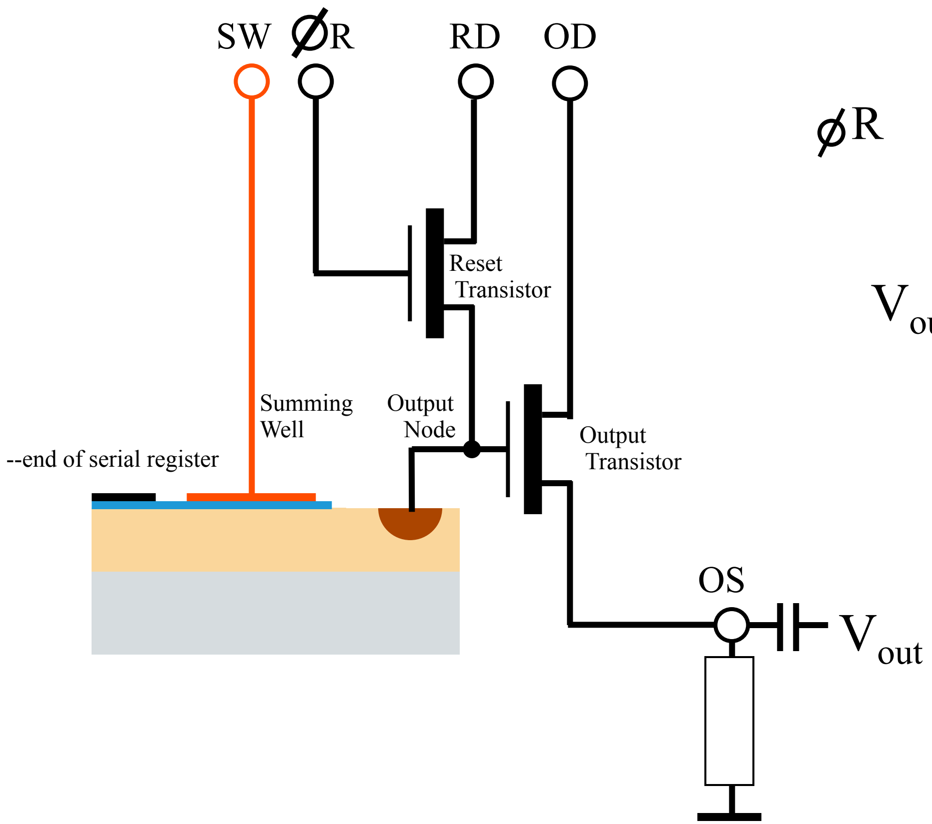


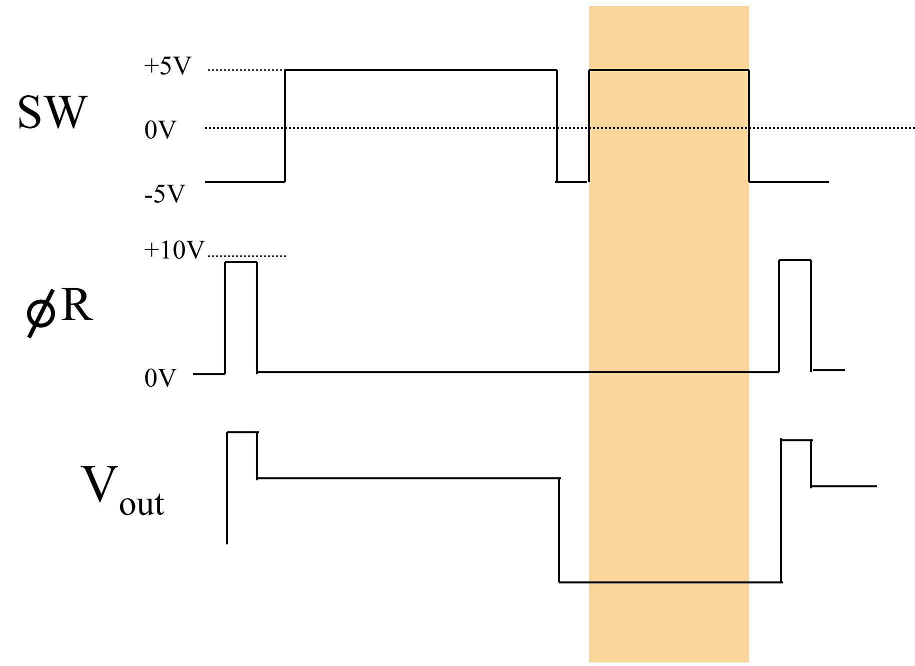


This action is known as the 'charge dump'. The voltage step in V_{out} is as much as several μV for each electron contained in the charge packet.

On-Chip Amplifier 4.

V_{out} is now sampled by external circuitry for up to a few tens of microseconds.



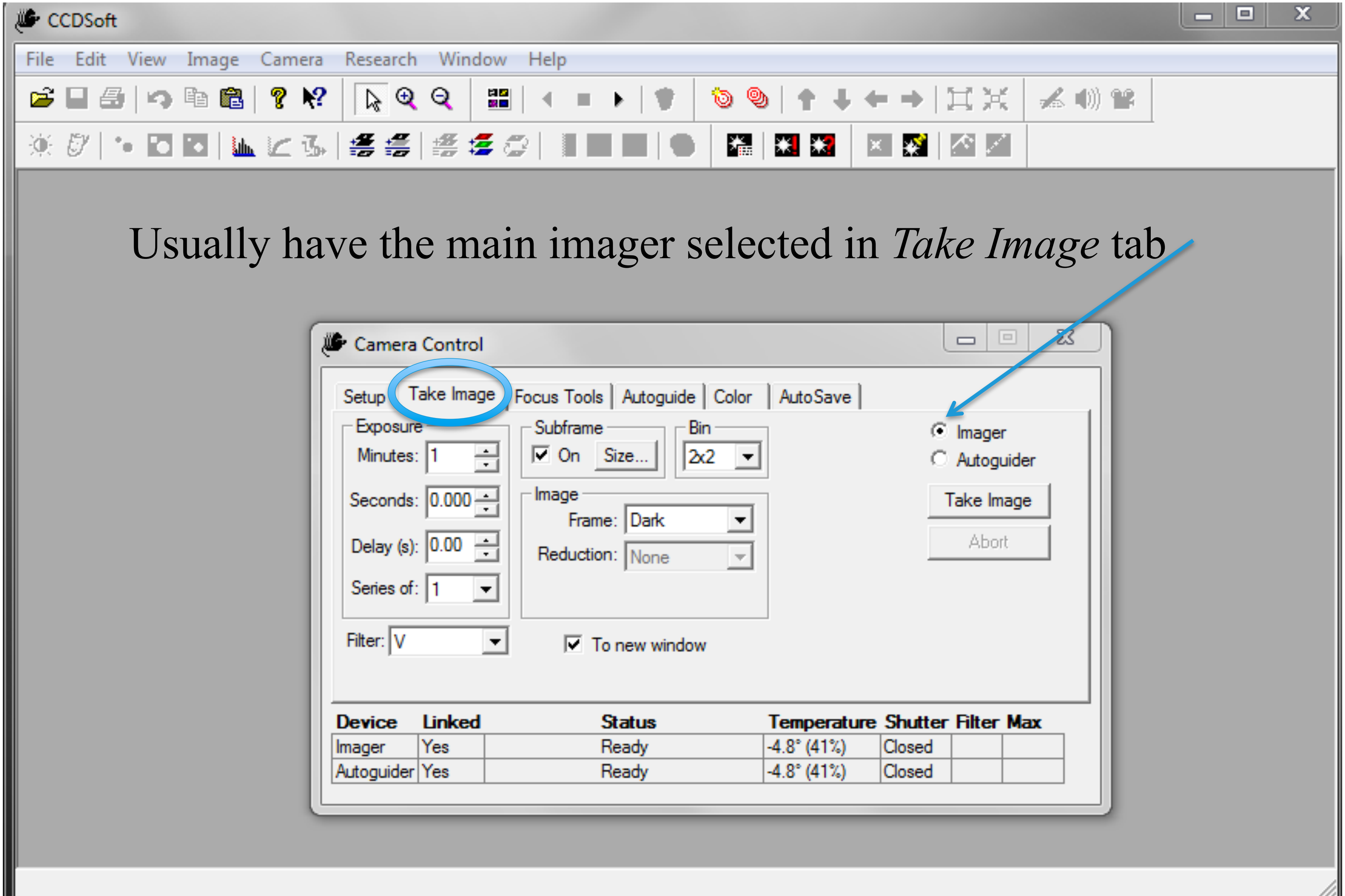


The value of (sample level - reference level) will be proportional to the size of the input charge packet.

Low-noise readout is SLOW. A full-frame readout of our CCD takes about 26 seconds.

CCD Camera Control

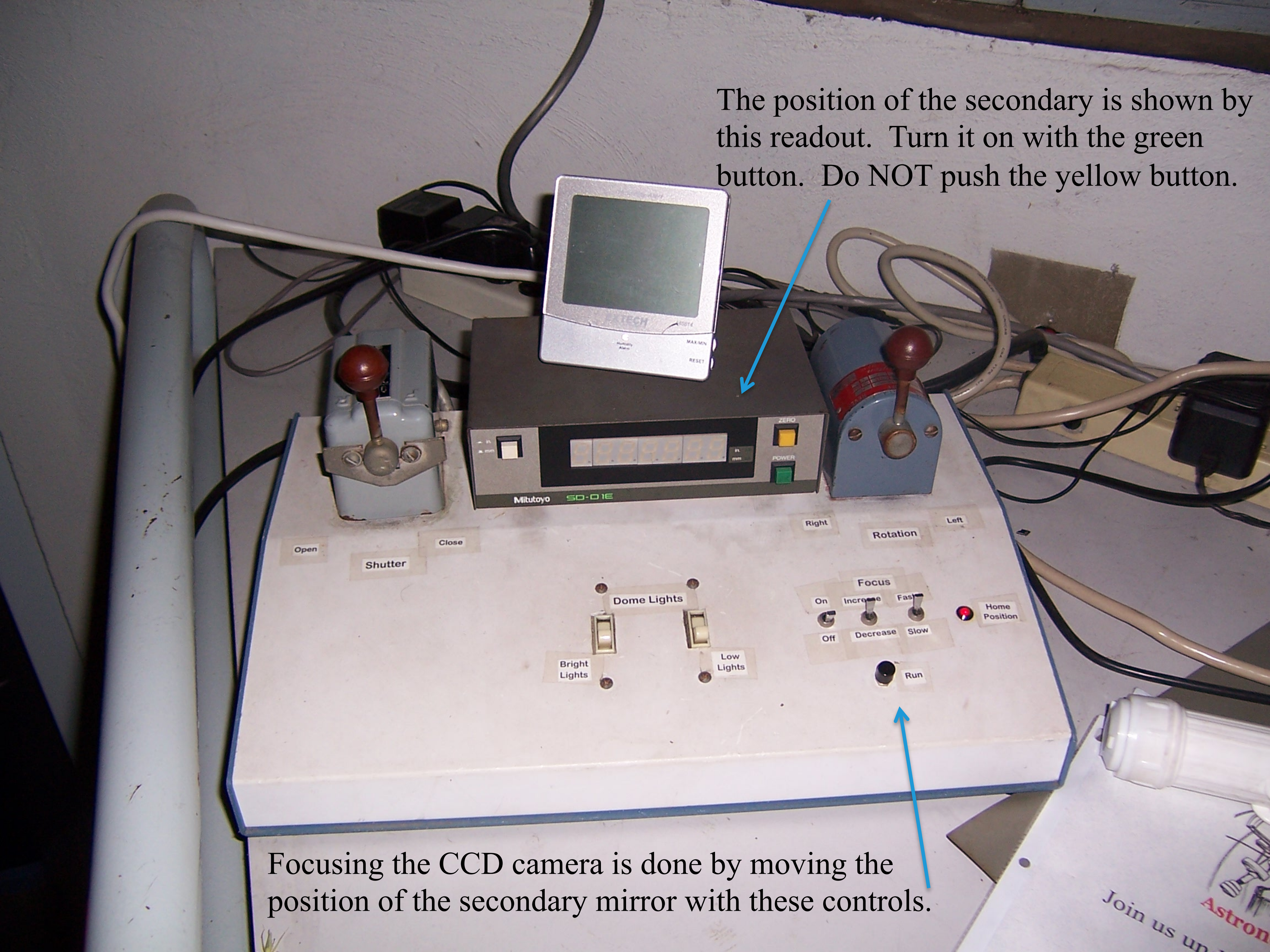
Usually have the main imager selected in *Take Image* tab



Focusing the CCD

- We focus the telescope on the CCD by moving the secondary mirror.
  - Controls are on the observing panel.
  - Mirror position is shown on the display above the panel (turn on with the green power button).
    - Don’t push the yellow “zero” button.

The position of the secondary is shown by this readout. Turn it on with the green button. Do NOT push the yellow button.



Focusing the CCD camera is done by moving the position of the secondary mirror with these controls.

Focusing the CCD

- We focus the telescope on the CCD by moving the secondary mirror.
  - Controls are on the observing panel.
  - Mirror position is shown on the display above the panel (turn on with the green power button).
    - Don't push the yellow "zero" button.
  - Be careful not to use saturated images to determine the focus.
  - Best focus will be around 0.000 mm, value increases by about 0.100 mm for every 5 C *decrease* in temperature.

Sequence of 7 images spaced by 0.05 mm in mirror position.

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Sequence of 7 images spaced by 0.05 mm in mirror position.

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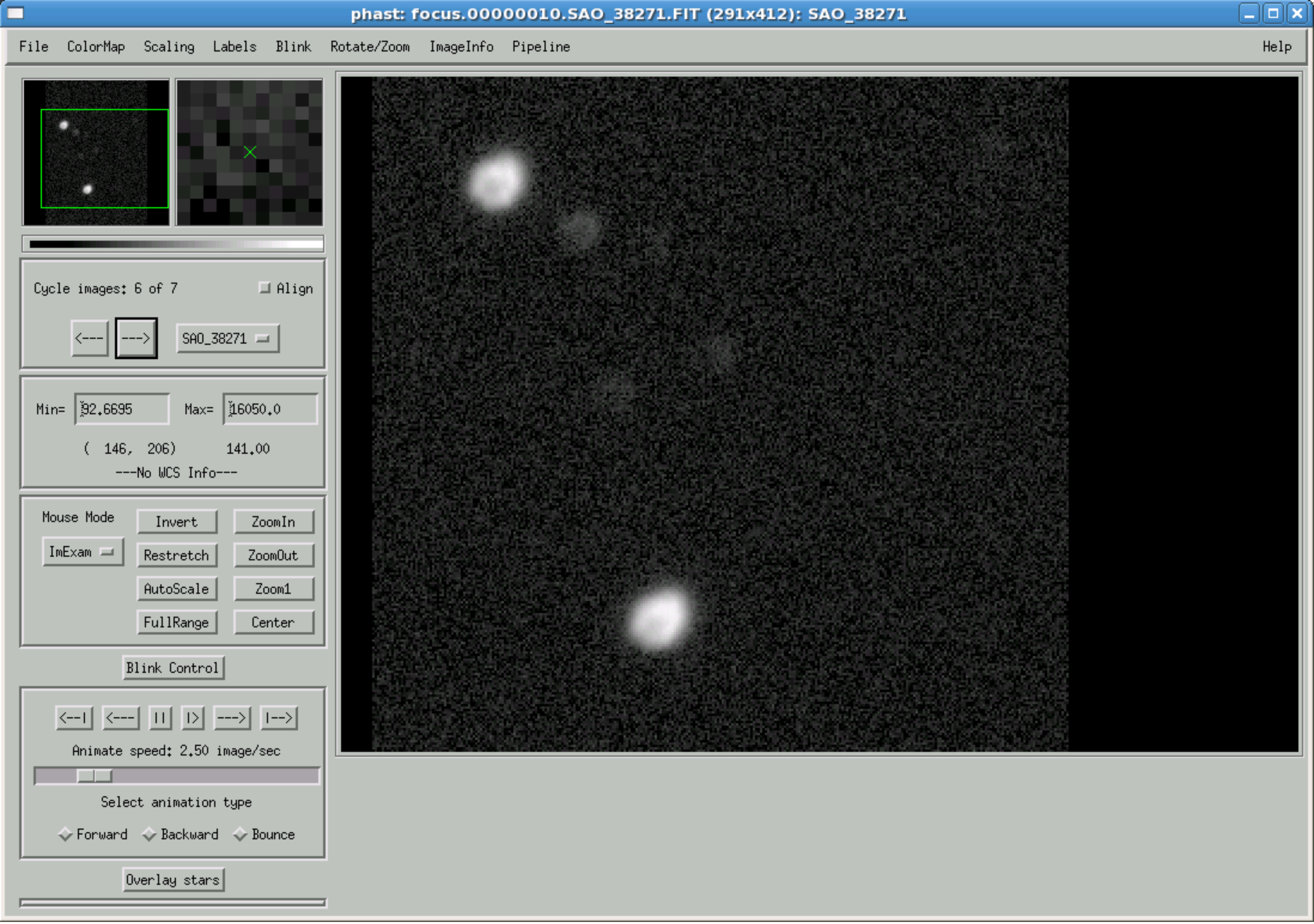
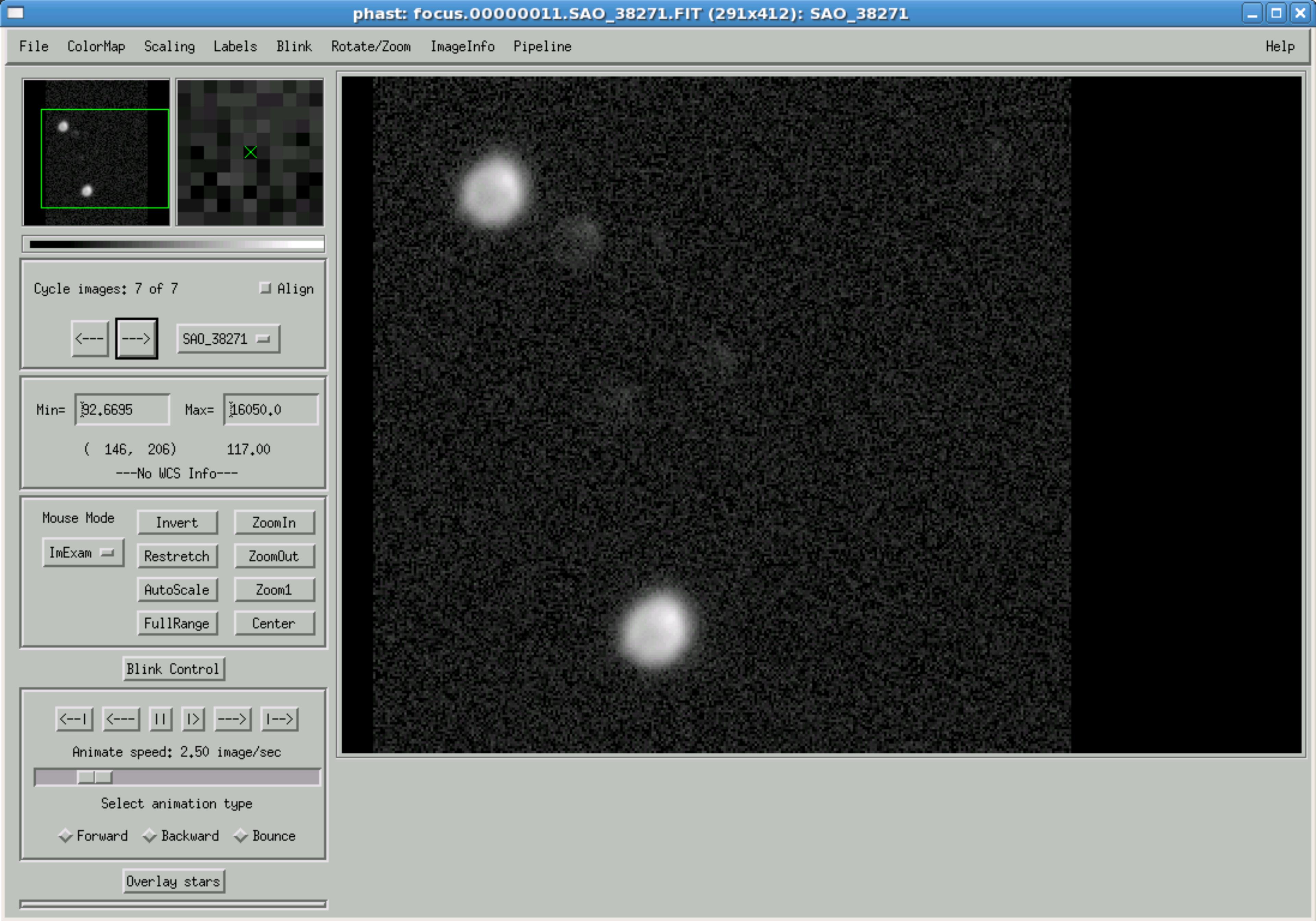


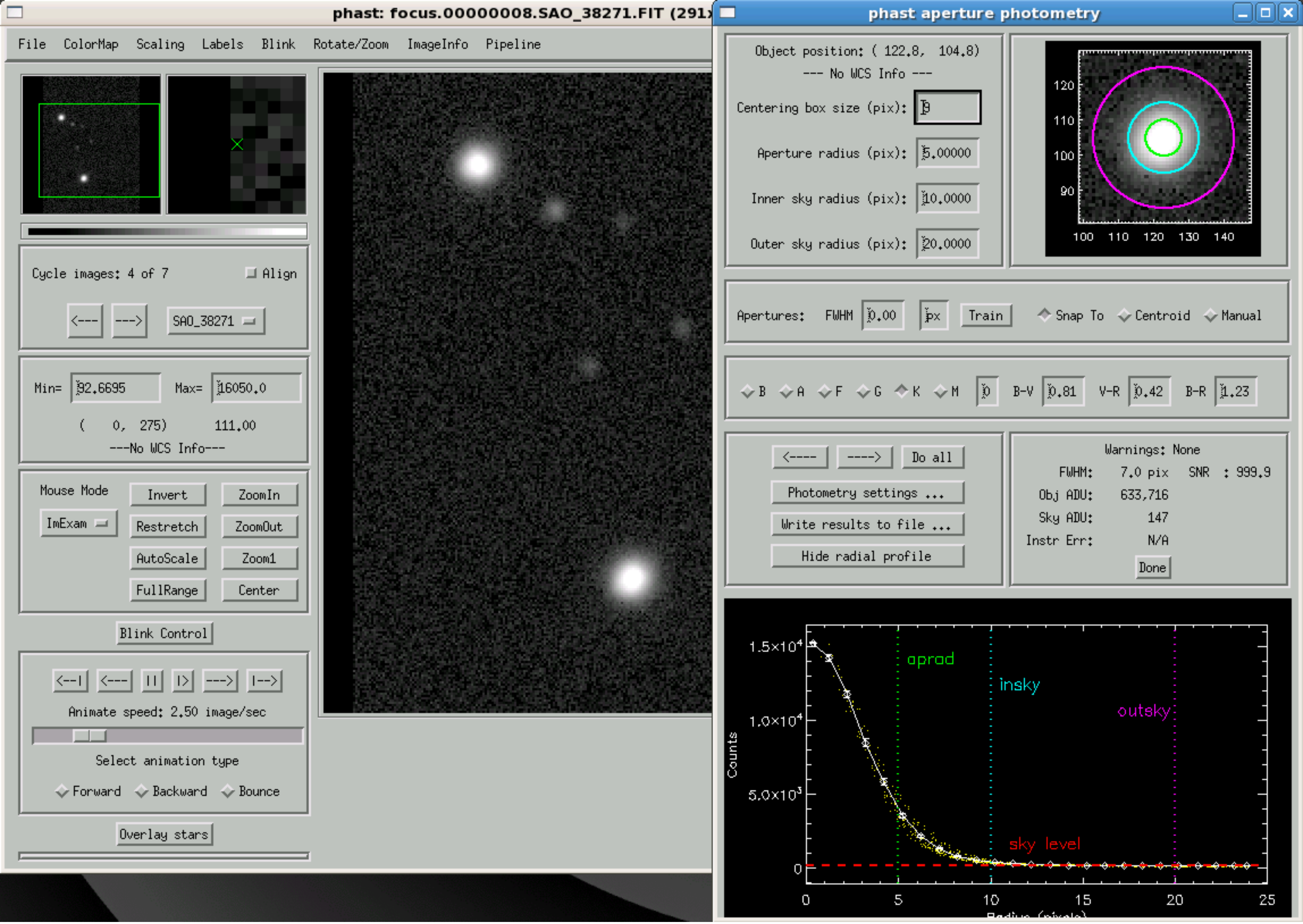
Sequence of 7 images spaced by 0.05 mm in mirror position.



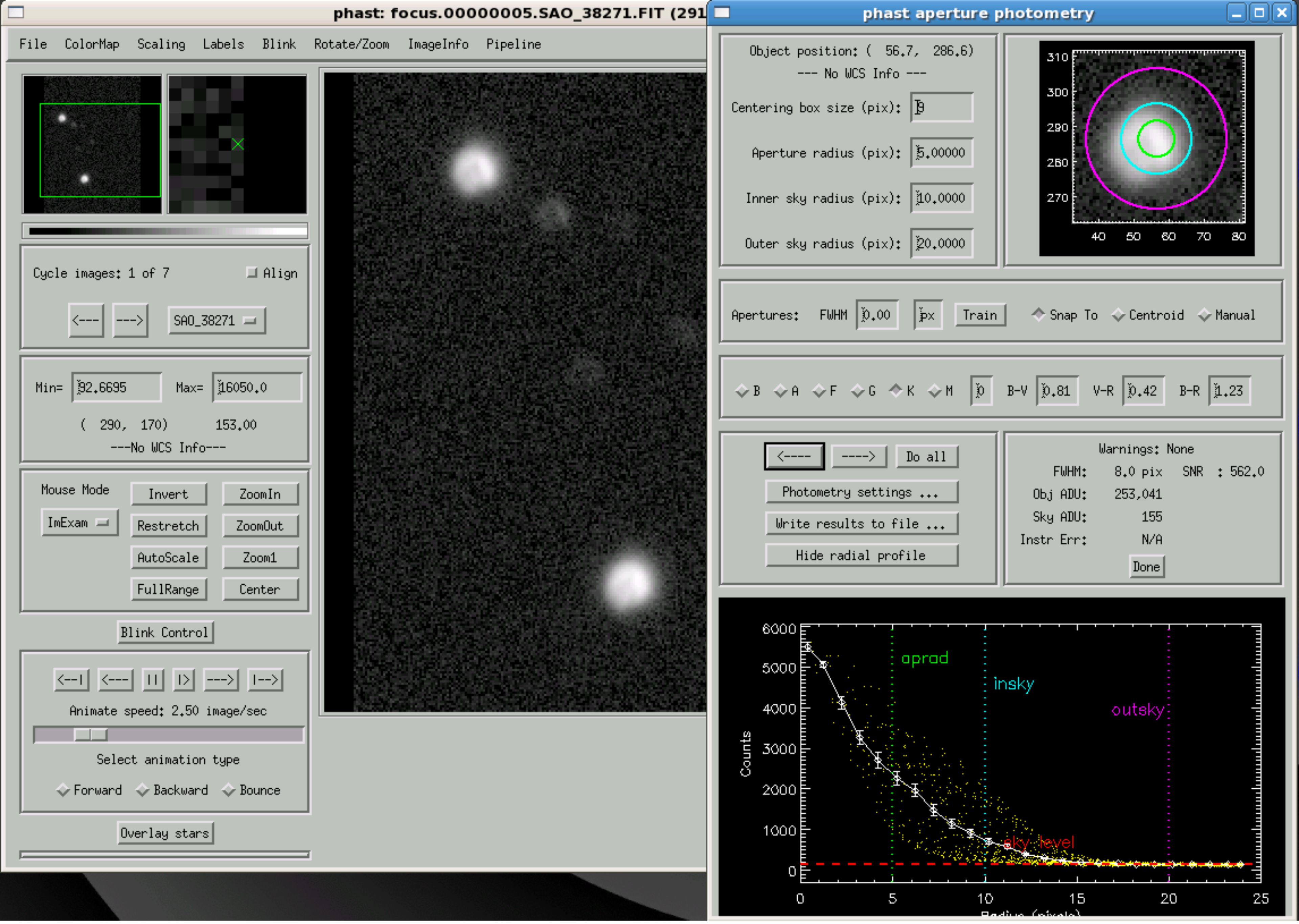
Sequence of 7 images spaced by 0.05 mm in mirror position.

Focusing the CCD

- Use RUPhAst and its aperture photometry tool (p key or left-mouse-button) to measure the full-width at half-maximum (FWHM) of stellar images.
  - RUPhAst fits a gaussian to the profile of the star to determine the FWHM.
  - Smallest FWHM is the best focus.
    - But should also visually assess the quality of the fit to the profile.
    - Subsequent slides show a good and a bad focus that had similar derived FWHM's.

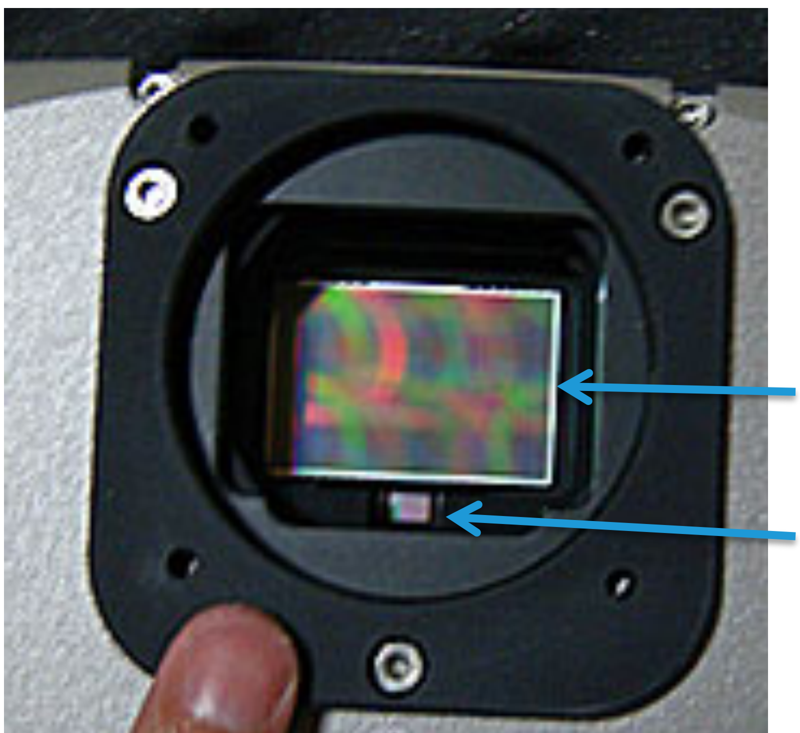


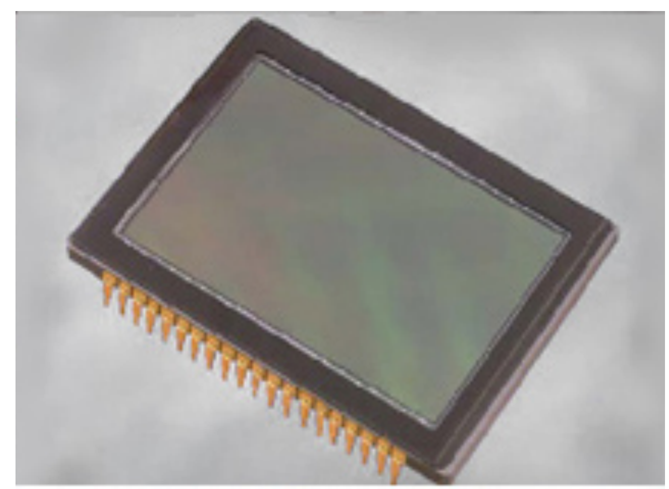
phast: focus.00000008.SAO_38271.FIT (291x
File ColorMap Scaling Labels Blink Rotate/Zoom ImageInfo Pipeline
Cycle images: 4 of 7
Align
<--- ---> SAO_38271
Min= 92.6695 Max= 16050.0
(0, 275) 111.00
---No WCS Info---
Mouse Mode
ImExam
Invert ZoomIn
Restretch ZoomOut
AutoScale Zoom1
FullRange Center
Blink Control
Animate speed: 2.50 image/sec
Select animation type
Forward Backward Bounce
Overlay stars
phast aperture photometry
Object position: (122.8, 104.8)
--- No WCS Info ---
Centering box size (pix): 9
Aperture radius (pix): 5.00000
Inner sky radius (pix): 10.0000
Outer sky radius (pix): 20.0000
Apertures: FWHM 0.00 px Train
Snap To Centroid Manual
B A F G K M 0 B-V 0.81 V-R 0.42 B-R 1.23
<---- ----> Do all
Photometry settings ...
Write results to file ...
Hide radial profile
Warnings: None
FWHM: 7.0 pix SNR : 999.9
Obj ADU: 633,716
Sky ADU: 147
Instr Err: N/A
Done
aprad
insky
outsky
sky level
Counts
Radius (pixels)

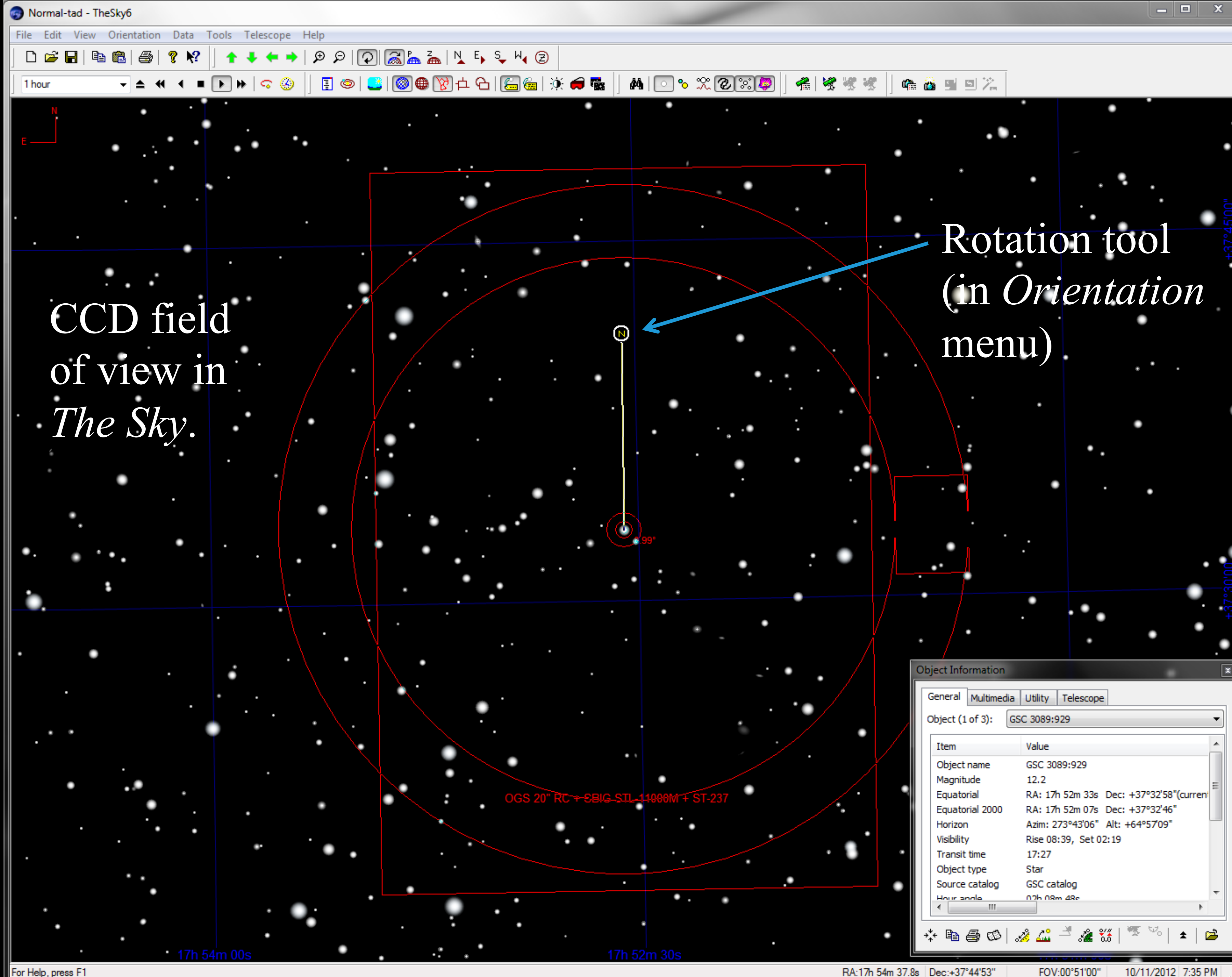

phast: focus.00000005.SAO_38271.FIT (291
File ColorMap Scaling Labels Blink Rotate/Zoom ImageInfo Pipeline
Cycle images: 1 of 7
Align
<--- ---> SAO_38271
Min= 92.6695 Max= 16050.0
(290, 170) 153.00
---No WCS Info---
Mouse Mode
ImExam
Invert ZoomIn
Restretch ZoomOut
AutoScale Zoom1
FullRange Center
Blink Control
Animate speed: 2.50 image/sec
Select animation type
Forward Backward Bounce
Overlay stars
phast aperture photometry
Object position: (56.7, 286.6)
--- No WCS Info ---
Centering box size (pix): 9
Aperture radius (pix): 5.00000
Inner sky radius (pix): 10.0000
Outer sky radius (pix): 20.0000
Apertures: FWHM 0.00 px Train Snap To Centroid Manual
B A F G K M 0 B-V 0.81 V-R 0.42 B-R 1.23
<---- ----> Do all
Photometry settings ...
Write results to file ...
Hide radial profile
Warnings: None
FWHM: 8.0 pix SNR : 562.0
Obj ADU: 253,041
Sky ADU: 155
Instr Err: N/A
Done
aprad
insky
outsky
sky level
Counts
Radius (pixels)

CCD Camera Guiding

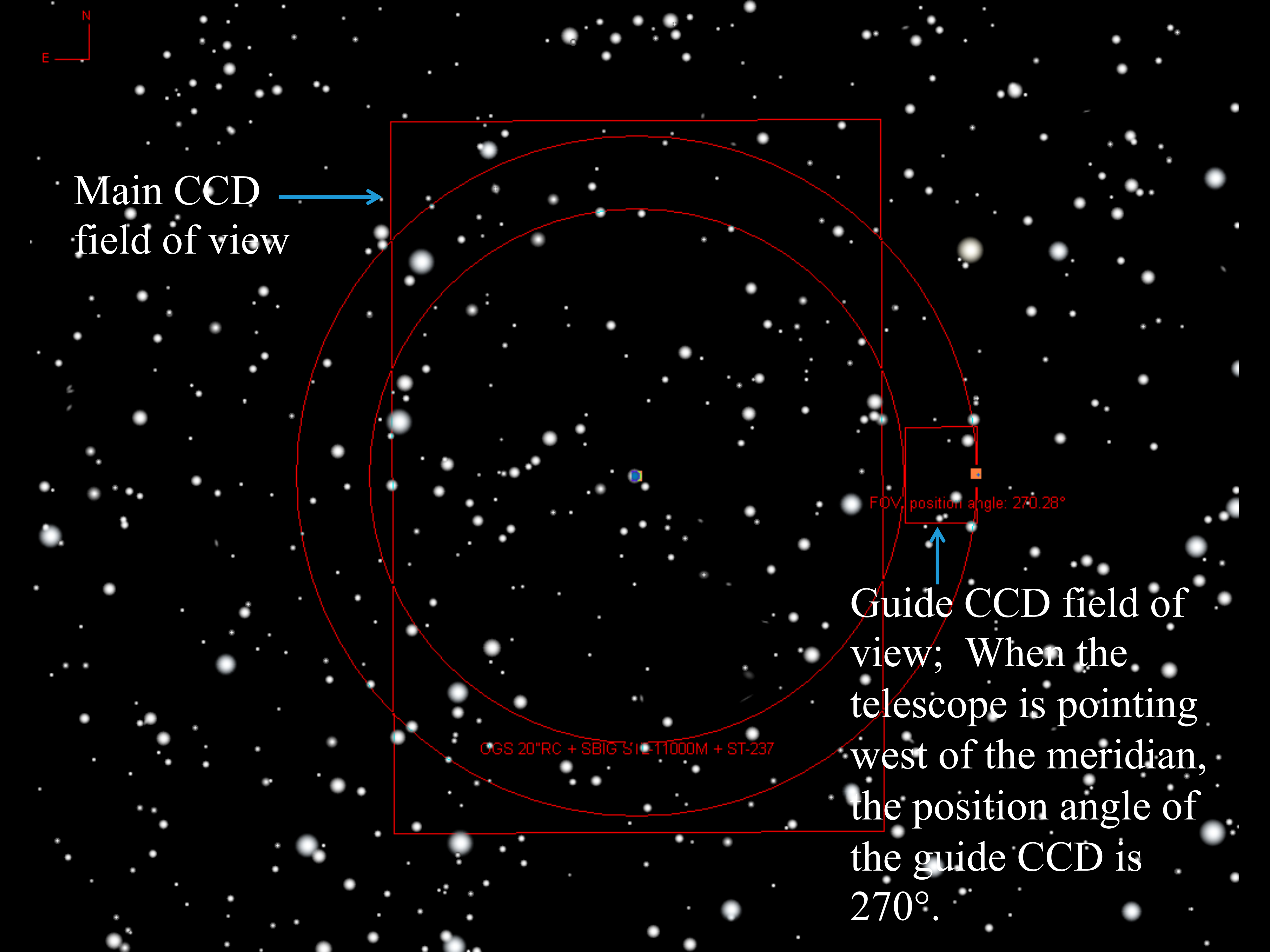
- Contains two CCDs
  - 4008 x 2672 pixels main imager
  - 680 x 500 pixels guide imager



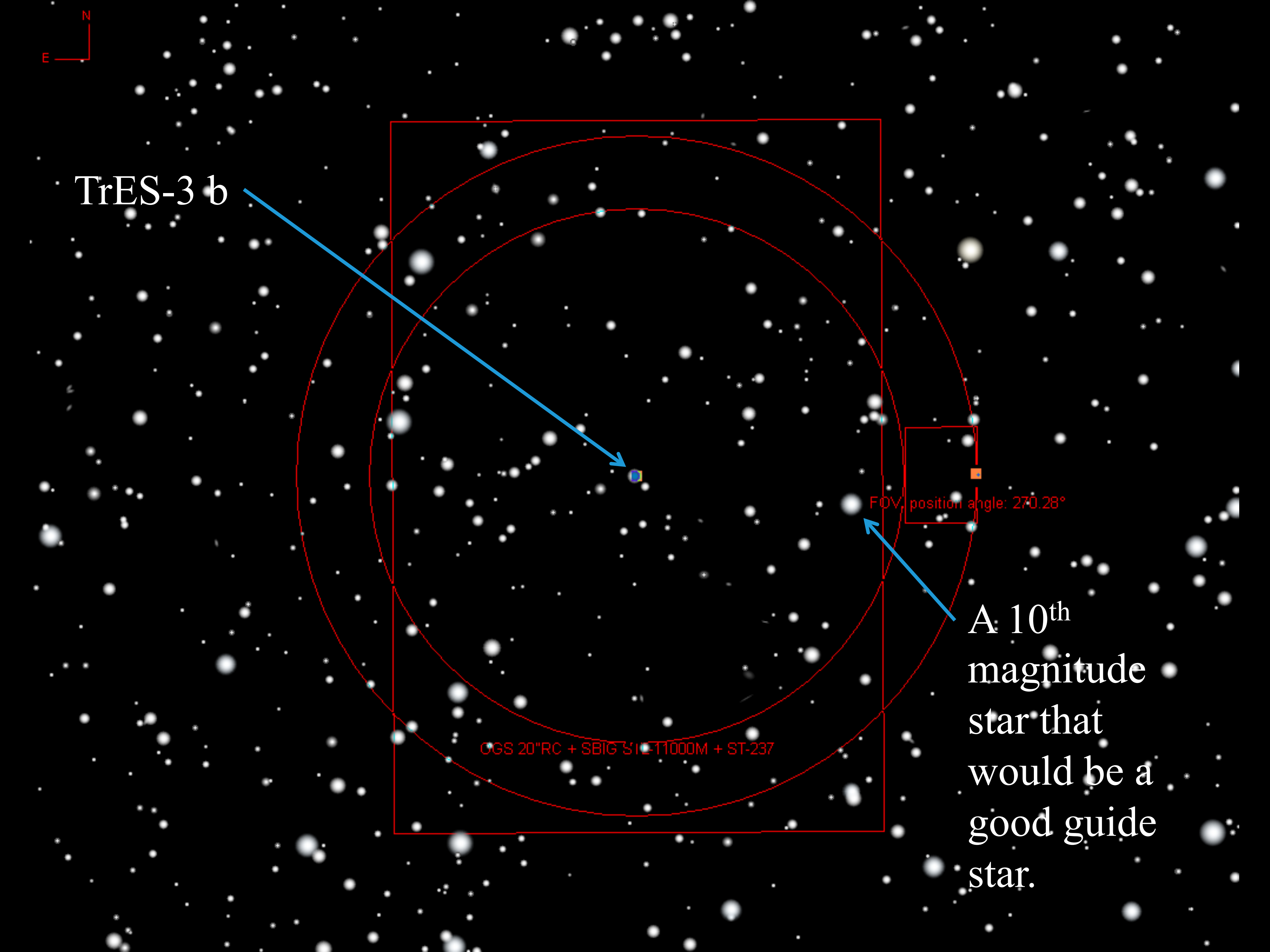


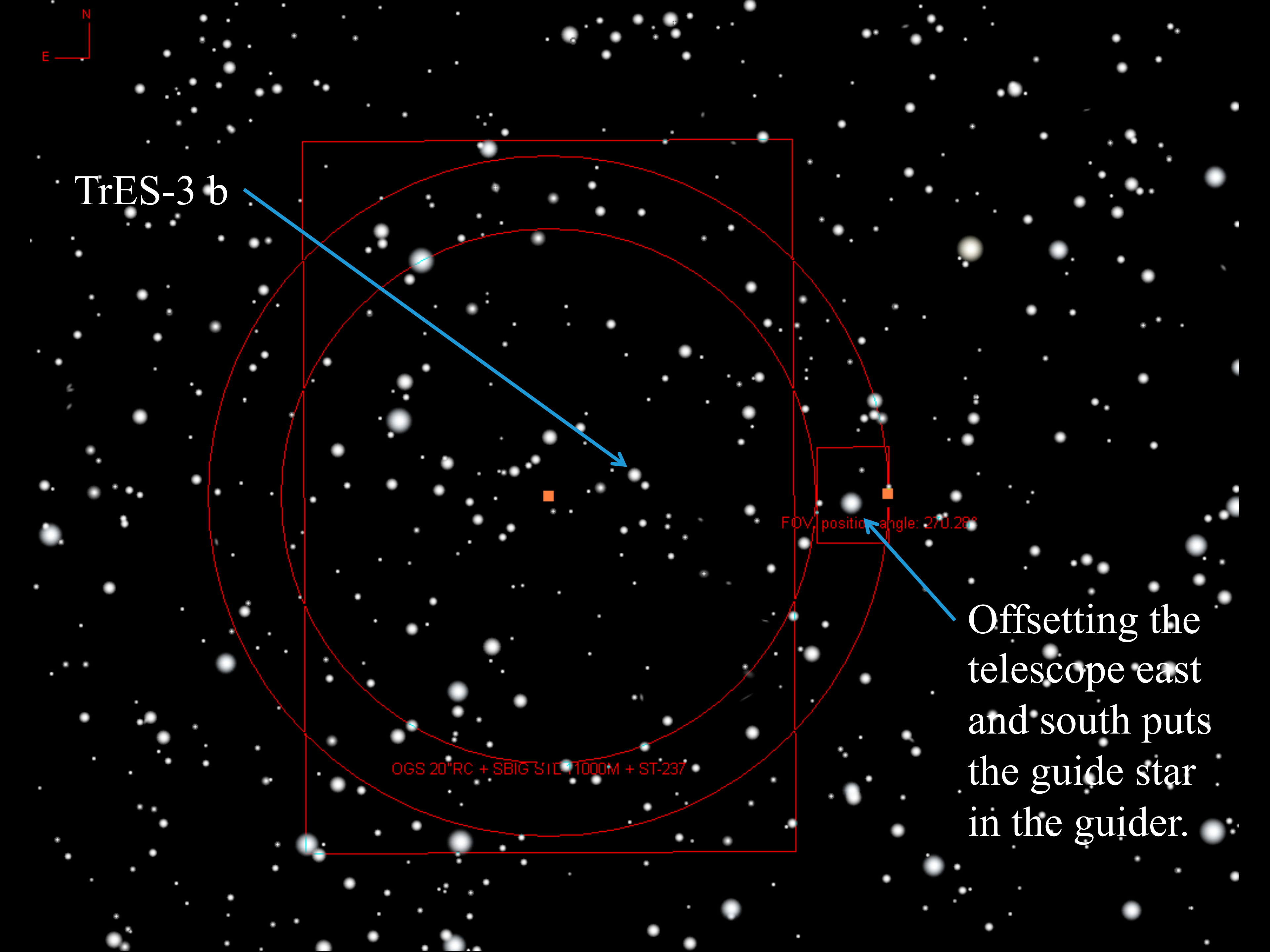


Normal-tad - TheSky6
File Edit View Orientation Data Tools Telescope Help
1 hour
N
E
CCD field of view in *The Sky*.
Rotation tool (in *Orientation* menu)
N
0.99°
OGS 20" RC + SBIG STL-11000M + ST-237
+37°45'00"
+37°30'00"
17h 54m 00s
17h 52m 30s
Object Information
General
Multimedia
Utility
Telescope
Object (1 of 3): GSC 3089:929
Item Value
Object name GSC 3089:929
Magnitude 12.2
Equatorial RA: 17h 52m 33s Dec: +37°32'58"(curren
Equatorial 2000 RA: 17h 52m 07s Dec: +37°32'46"
Horizon Azim: 273°43'06" Alt: +64°57'09"
Visibility Rise 08:39, Set 02:19
Transit time 17:27
Object type Star
Source catalog GSC catalog
For Help, press F1
RA:17h 54m 37.8s Dec:+37°44'53"
FOV:00°51'00"
10/11/2012 7:35 PM


N
E
Main CCD field of view
FOV position angle: 270.28°
OGS 20"RC + SBIG STL-11000M + ST-237
Guide CCD field of view; When the telescope is pointing west of the meridian, the position angle of the guide CCD is 270°.

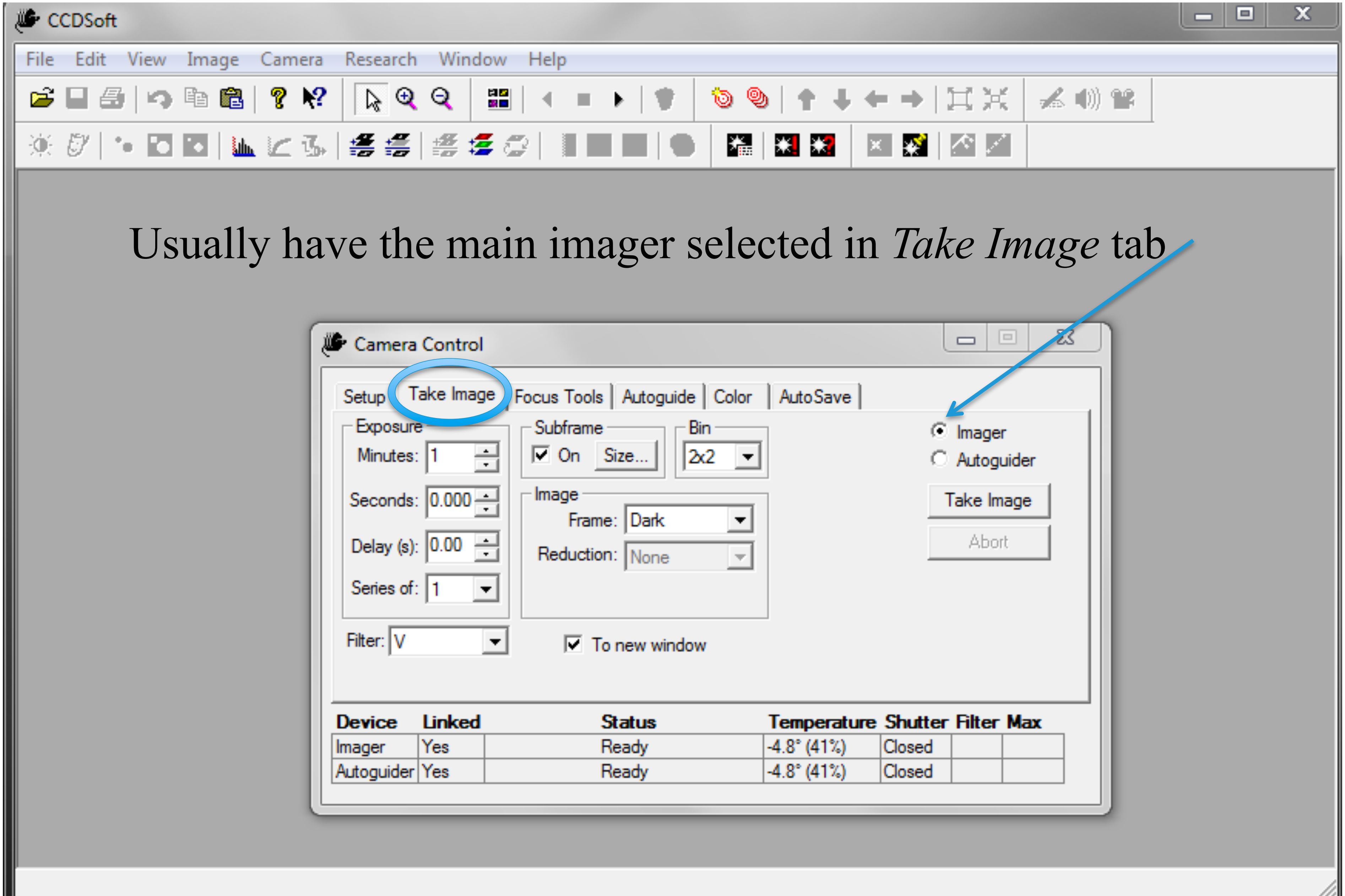
When the telescope is pointing east of the meridian, the position angle of the guide CCD is 90°.


N
E
TrES-3 b
FOV position angle: 270.28°
OGS 20"RC + SBIG STL-11000M + ST-237
A 10th magnitude star that would be a good guide star.


N
E
TrES-3 b
OGS 20"RC + SBIG STL-11000M + ST-237
Offsetting the telescope east and south puts the guide star in the guider.

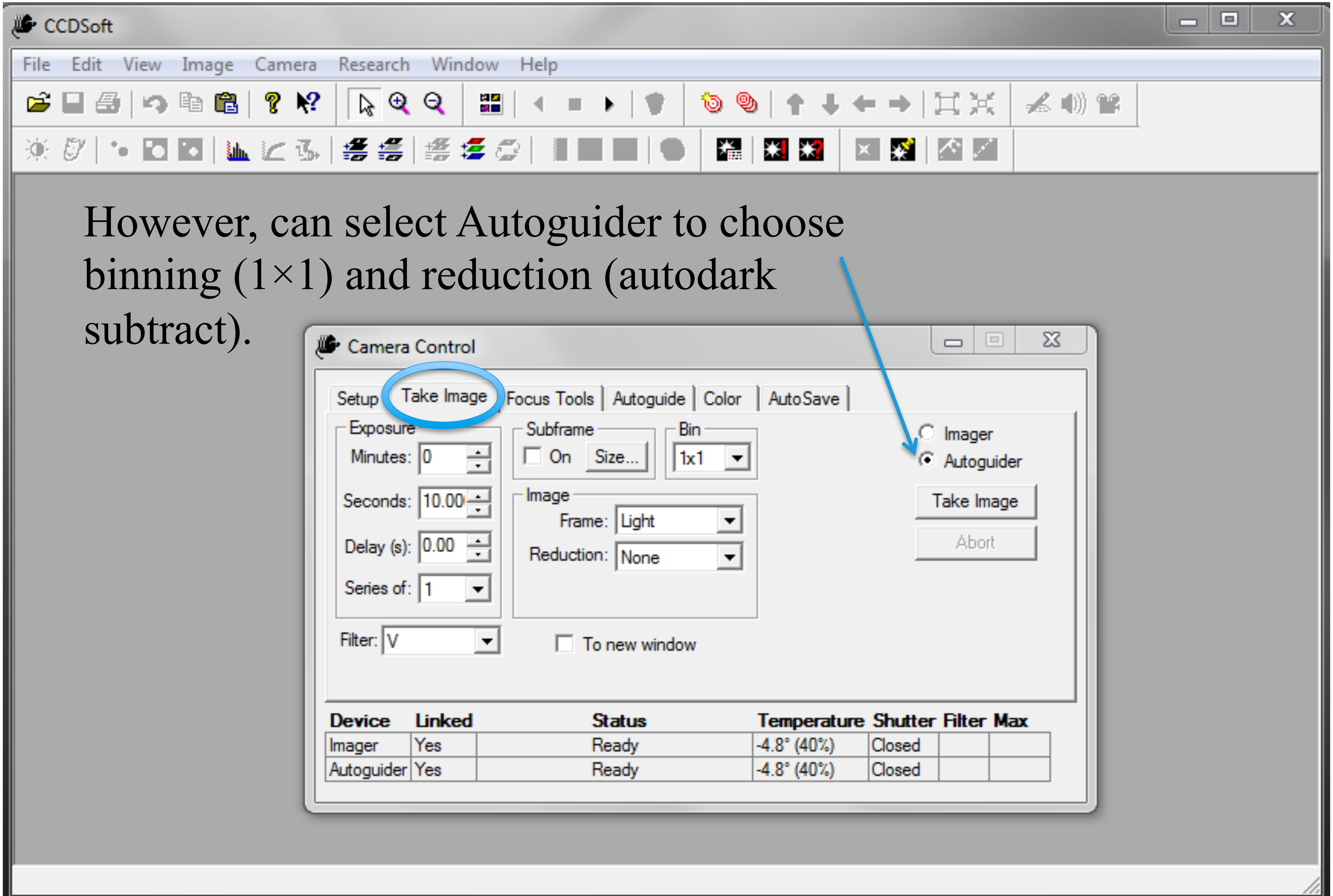
Guider Setup

Usually have the main imager selected in *Take Image* tab



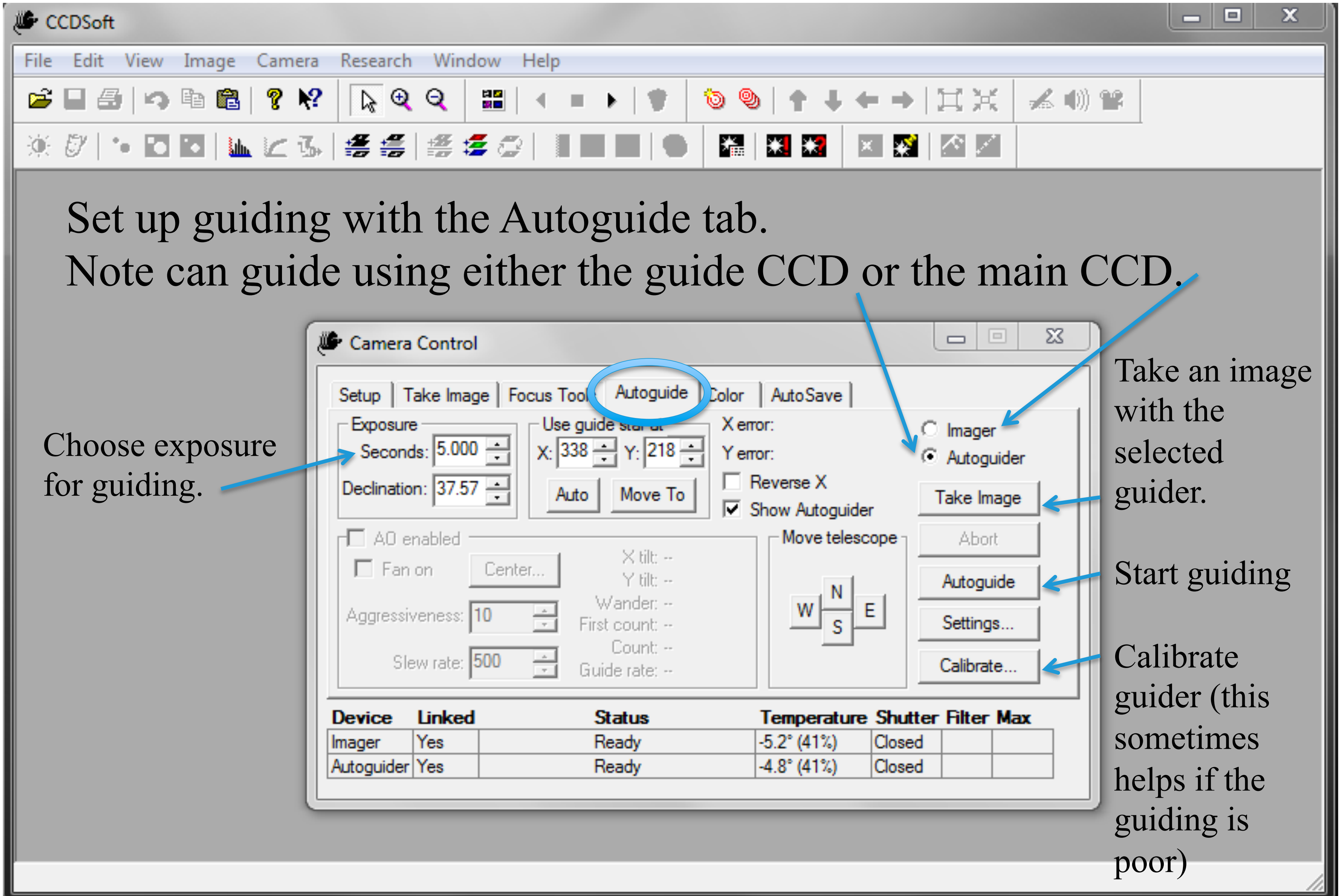
Guider Setup

However, can select Autoguider to choose binning (1×1) and reduction (autodark subtract).



Guider Setup

Set up guiding with the Autoguide tab.
Note can guide using either the guide CCD or the main CCD.



Choose exposure for guiding.

Take an image with the selected guider.

Start guiding

Calibrate guider (this sometimes helps if the guiding is poor)

- Select the Autoguide tab and take a test exposure of a few seconds.
- Click in the displayed image to select a guide star. White box flashes and coordinates appear in the tab.
- Start guiding with Autoguide button (will hear clicks of corrections being made).

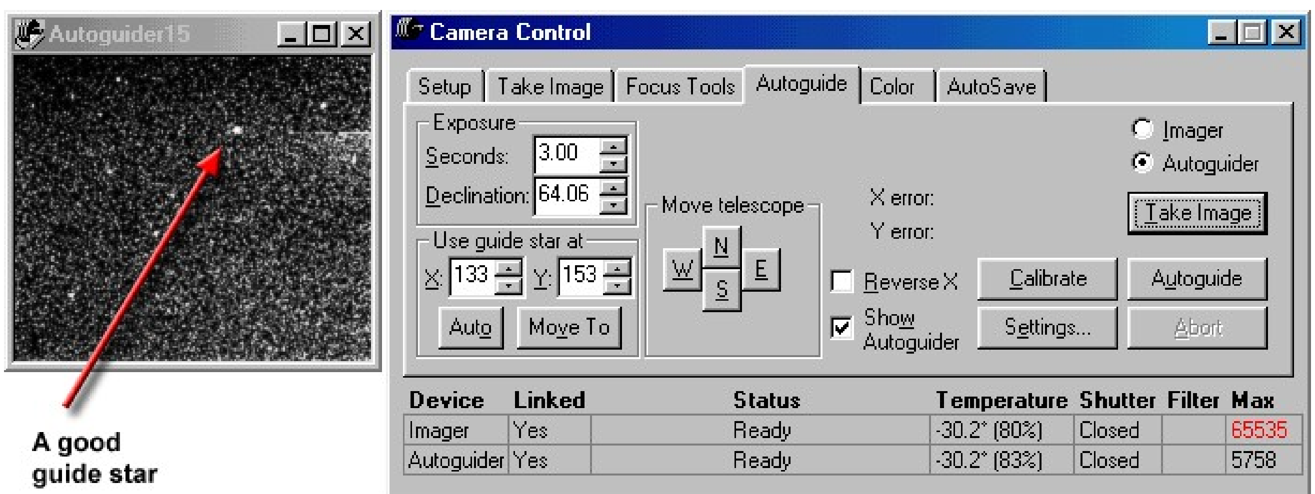
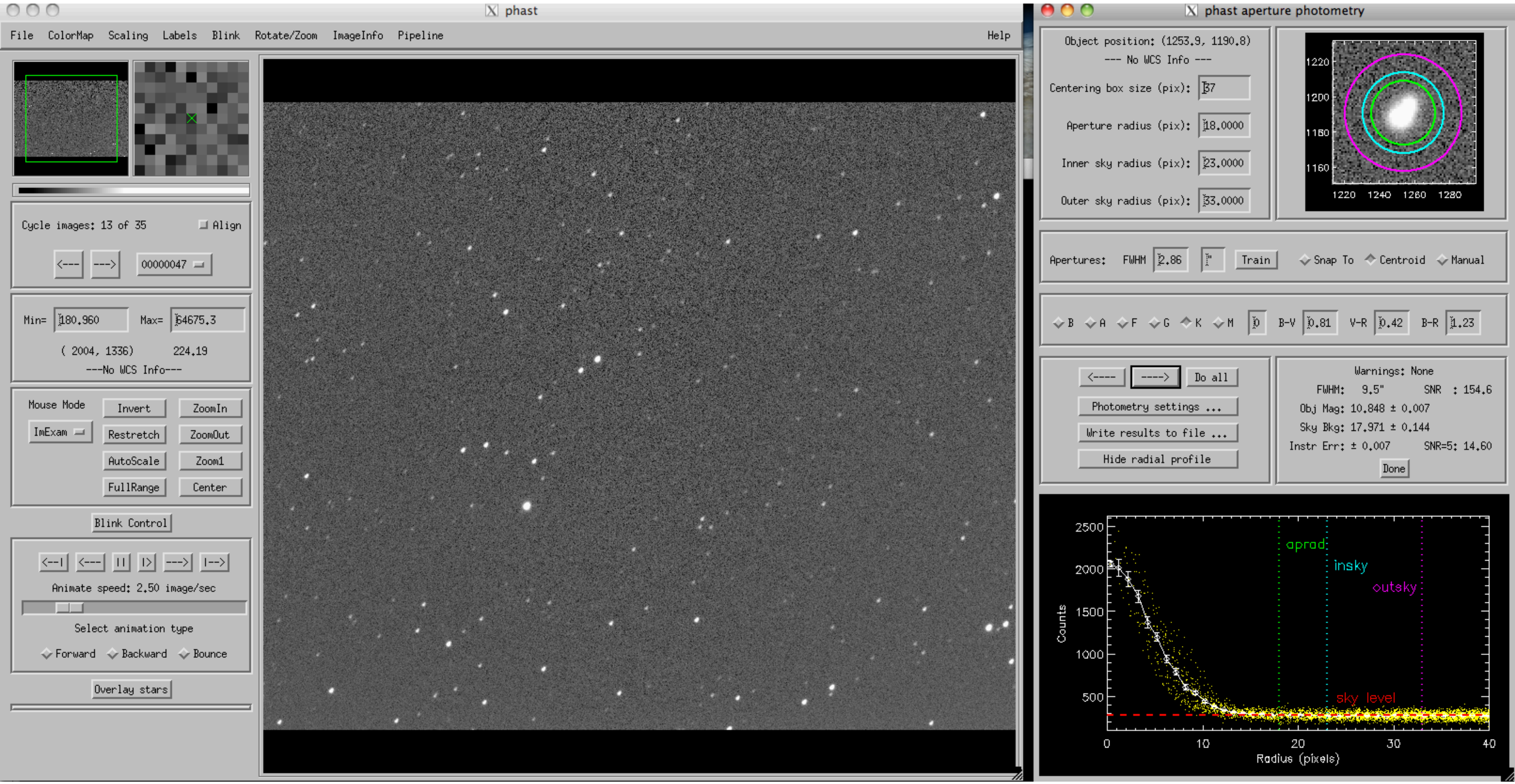


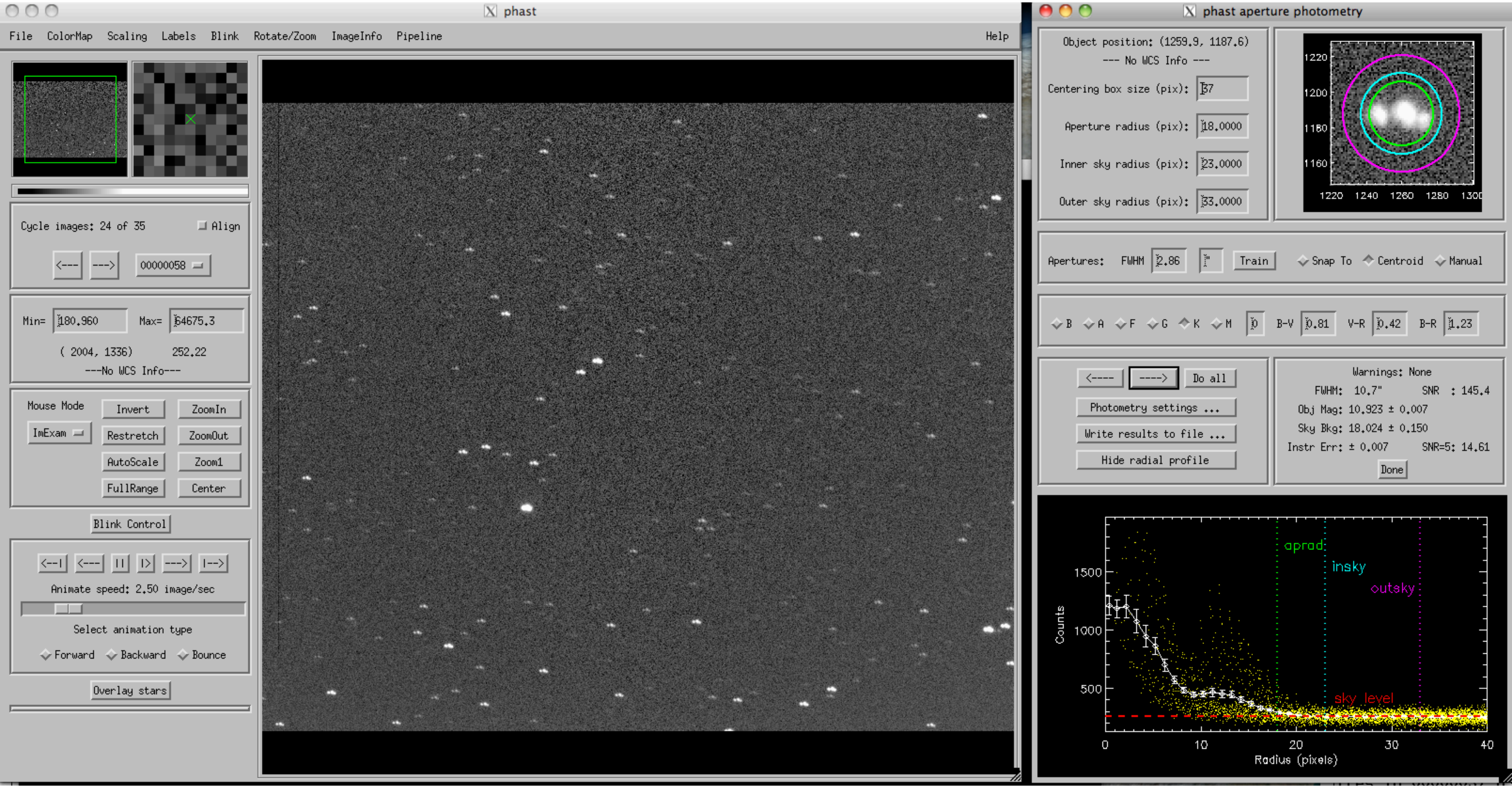
Figure 2: An autoguide image taken for reference. Note that there is one star significantly brighter than the others; this is a good choice for a guide star.

Guider Problems



Over-correcting by the guider can cause the telescope to oscillate back and forth. These images can still be useful if use a big aperture.

Guider Problems



Really bad guiding. Waiting a few correction cycles for the guiding to settle down before starting an exposure can help. If the problem persists, try doing a guider calibration.