Imaging detectors and applications

Lecture 6

Course of:

Signal and imaging acquisition and modelling in environment

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Federico De Guio - Matteo Fossati

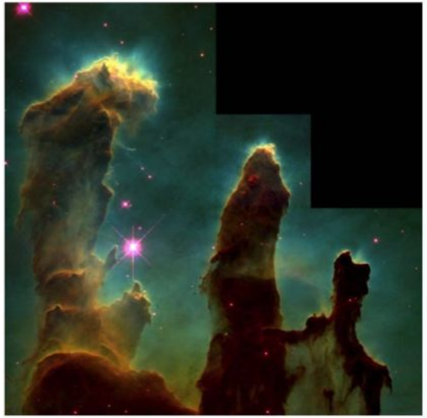
Image analysis is a powerful tool in nearly all fields of science and technology

- Biology
- Astronomy
- Medicine
- Security and biometric
- Precision agriculture
- Satellite imagery and terrain classification
- Meteorology
- Art
- …

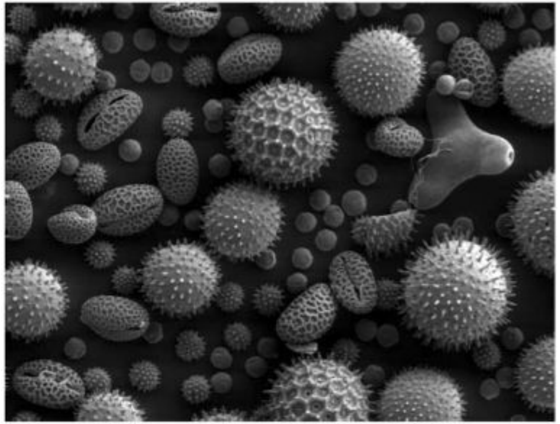
The best performing analysis tools are highly specific to the dataset characteristics.

We will learn the acquisition, calibration and analysis steps of an imaging dataset where we have full control of the instrument characteristics

Credit: NASA



Credit: NASA, Jeff Hester, and Paul Scowen (Arizona State)
More info here

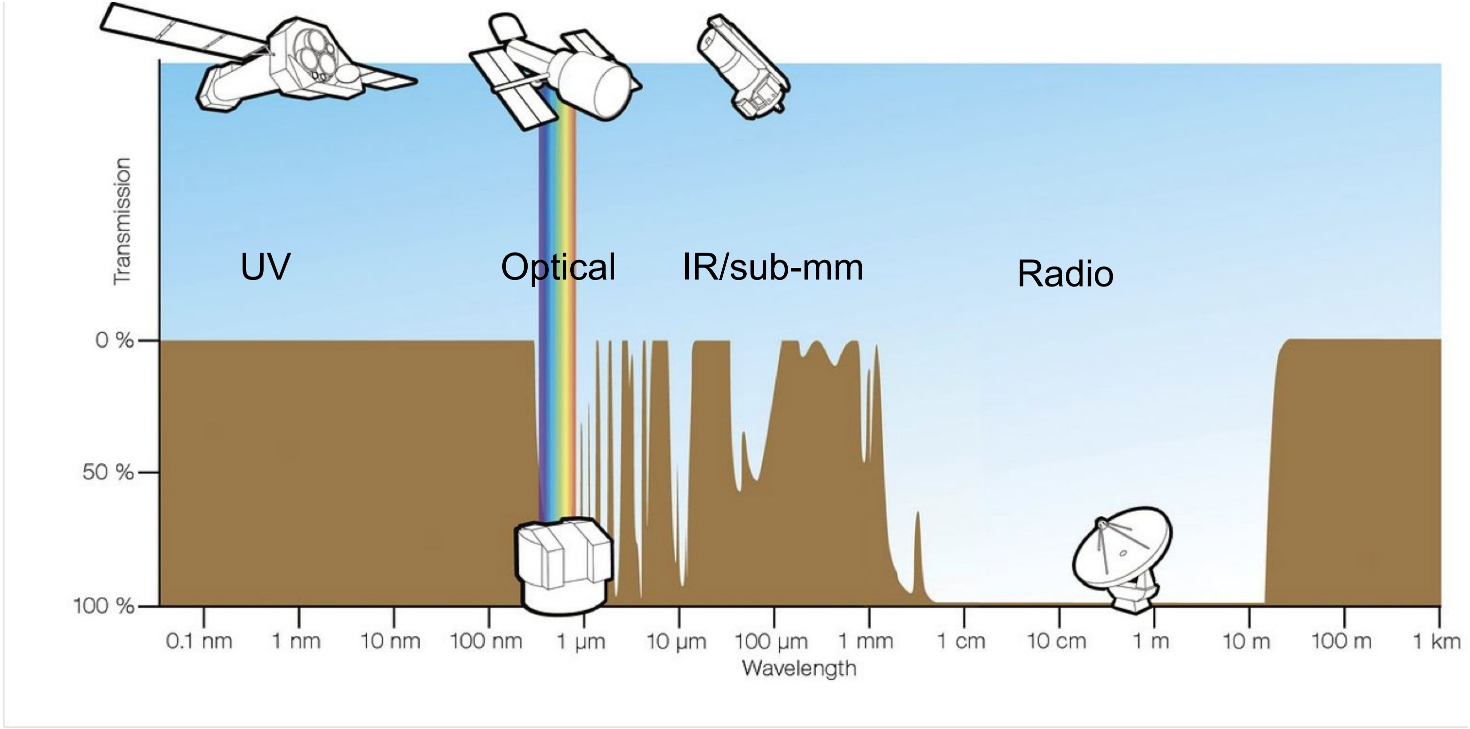


Credit: Dartmouth Electron Microscopy Facility

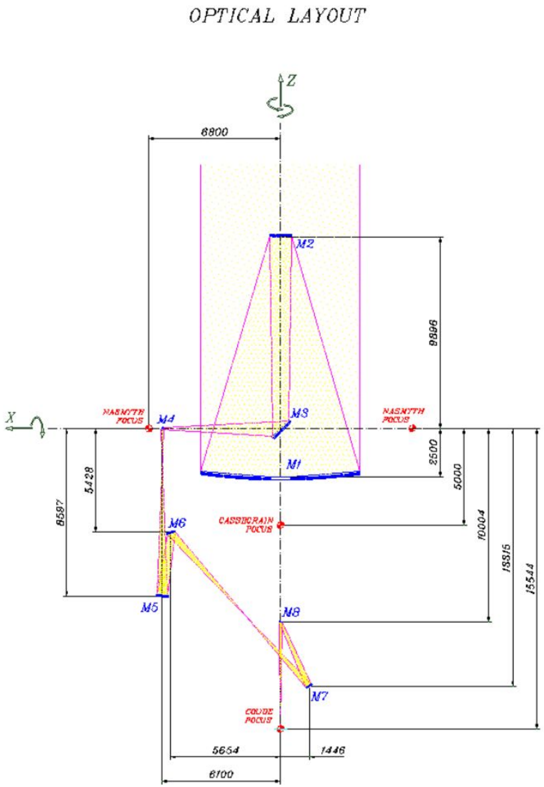
The Bicocca Optical Telescope

DEGLI STUDI DI MILANO
ICOCCA

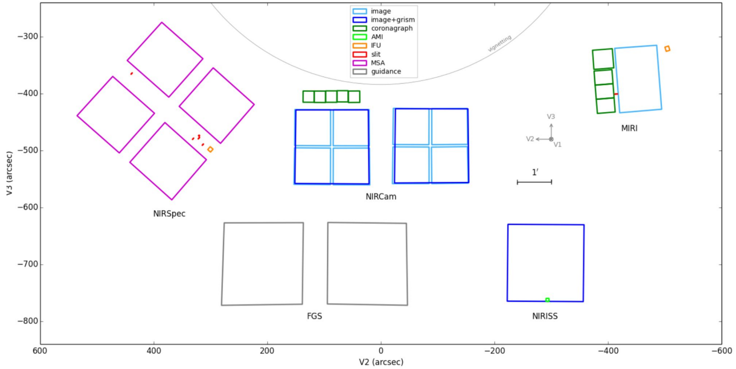
Which portion of the EM spectrum can be observed from the ground?

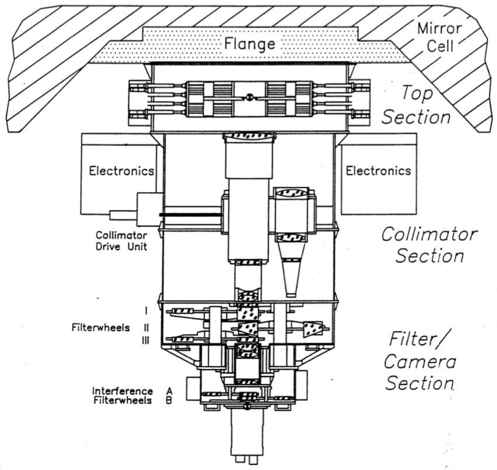


Optical design of a mirror telescope



Telescope schematics





Instrument schematics

Optical design of a mirror telescope

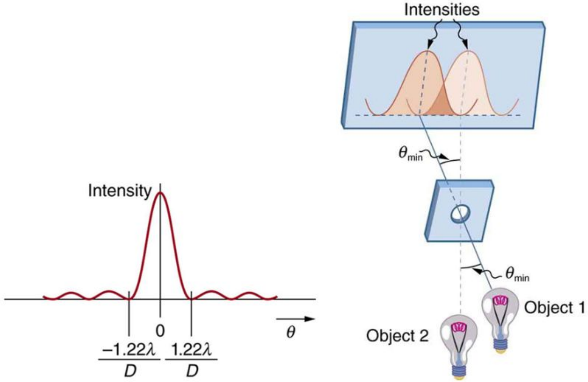
40cm primary mirror

Photometric Camera Atik 16200 mono

- Sensor Type: CCD - KAF-16200 APS cut (35mm diagonal)
- Horizontal Resolution: 4499 pixels
- Vertical Resolution: 3599 pixels
- **Pixel Size: 6 μm x 6 μm**
- ADC: 16 bit
- **Readout Noise: 9e- typical value**
- Gain Factor: 0.6e-/ ADU
- Full Well: ~40,000e-
- **Dark Current: >0.25 electrons/second at 0°C**
- Maximum Exposure Length: Unlimited
- Minimum Exposure Length: 200 ms
- **Cooling: Thermoelectric set point with max ΔT=>-50°C**

Diffraction limit

Telescopes are limited by diffraction, because of the finite diameter D of their primary mirror.



The Rayleigh criterion for the diffraction limit to resolution states that *two images are just resolvable when the centre of the diffraction pattern of one is directly over the first minimum of the diffraction pattern of the other*. Two point objects are just resolvable if they are separated by the angle

$$\theta = 1.22\lambda / D$$

Diffraction limit

What is the diffraction limit of the Bicocca Telescope? How does it compare to an 8m telescope?

Assume an average light wavelength of 550 nm

$$\theta = 1.22\lambda / D = 1.22 \times 550E\text{-}9 \,/\, 0.4 = 1.67E\text{-}6 \text{ rad} = 0.34 \text{ arcsec}$$

For an 8 m telescope this value is 20 times smaller ~ **0.02 arcsec**

Radio telescopes operate at meter wavelengths, despite their large apertures (up to 500m) their resolution is very poor ~ 500 arcsec.

(Almost) Only space telescopes/satellites can reach the diffraction limit. The atmosphere causes the seeing effect. As the light wave propagates through the atmosphere it experiences fluctuations in amplitude and phase. An image formed by focusing this wave exhibits a large point spread function (PSF) of a **few arcsec** (depending on the geographical location).

CCD Detectors

From photographic plates to Photomultiplier tubes and CCDs, the technology has advanced enormously

Detector properties

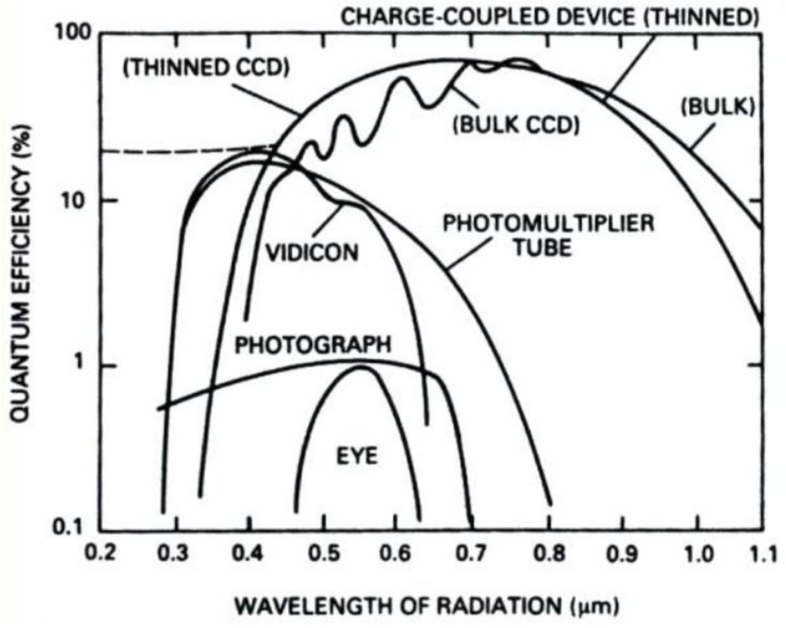
QE= Ndetected photons/Nincoming photons

Spectral range (where QE is above a certain threshold)

Full well capacity (amount of photons that can be collected)

Linear region (will be clear in a few slides)

Spatial resolution (pixel size, should be coupled to the optics diffraction limit or image PSF)



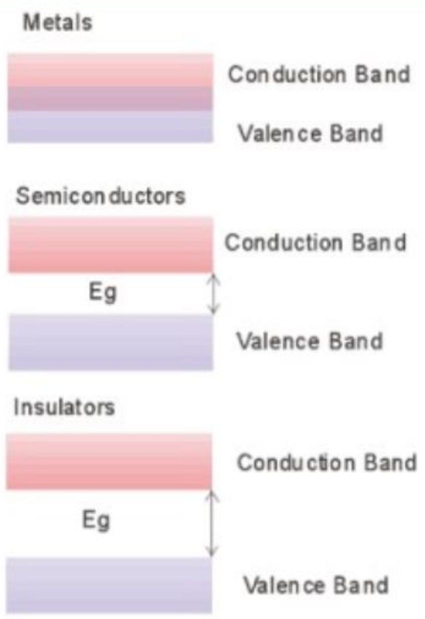
CCD Detectors

Semiconductors are crystalline materials which are not normally good conductors of electricity but which can be made to conduct under certain circumstances.

The electrical properties of pure semiconductors can be dramatically altered by adding ("doping with") small amounts (~1 part in 10^6) of an impurity.

Absorption of a photon can push a valence electron into the conduction band and produce an electrical signal. The photon energy must exceed E_g, which implies that there is a **maximum wavelength** for excitation given by:

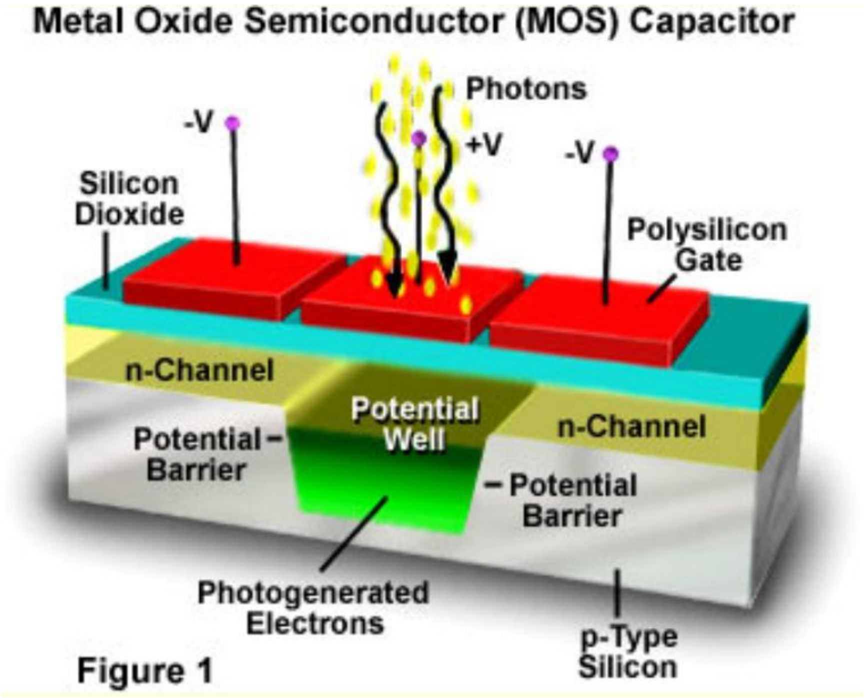
$Lam_{max} = 12{,}400\ \text{Å}/E_g(\text{eV})$



CCD Detectors

The basic element in a CCD design is a **"Metal-Oxide-Semiconductor" capacitor**. This serves both to store photoelectrons and to shift them during readout. The bulk material is p-silicon on which an insulating layer of silicon-oxide has been grown. region shown is about 10 μ thick.

p-silicon can be manufactured to have very few free electrons ("high resistivity") before exposure to light; this is important for best performance. A set of thin semitransparent conducting electrodes are applied. The central electrode is set to a positive BIAS while the two flanking electrodes are set negative. This creates a **"depletion" region** under the central electrode containing a potential well (like a "bucket") to trap electrons.



Reading CCD Detectors

The surface of the CCD is covered with MOS capacitors. Often, there are three electrodes per pixel. Typical pixel sizes are 10-40 μ. The **"parallel shift"** registers are shown as rows running across the whole face of the CCD. At one end of the CCD is a column of **"serial shift"** electronics and an output amplifier. Contemporary large chip designs involve several amplifiers (but always many fewer than the number of pixels!).

At the end of the exposure, readout of the collected electrons is accomplished by cycling (**"clocking"**) the voltages on the electrodes such that the charge is **shifted** along the rows. Each parallel transfer places the contents of one pixel from each row into the serial register column. This column is then shifted out vertically through the output amplifier and into computer memory before the next parallel transfer occurs.

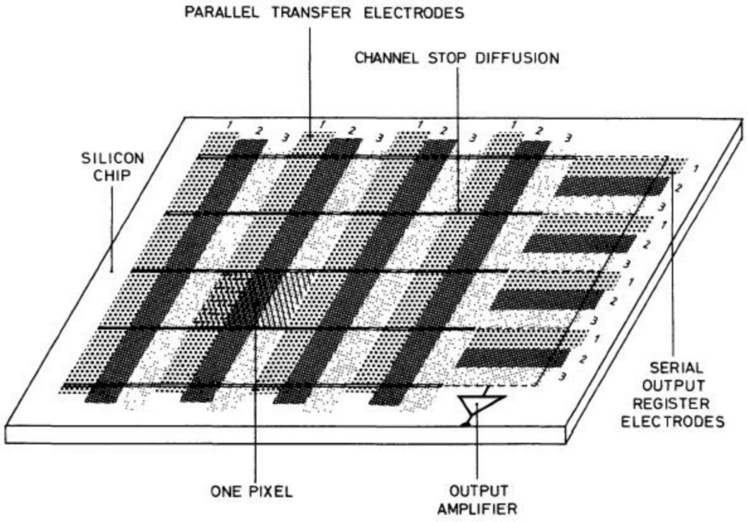
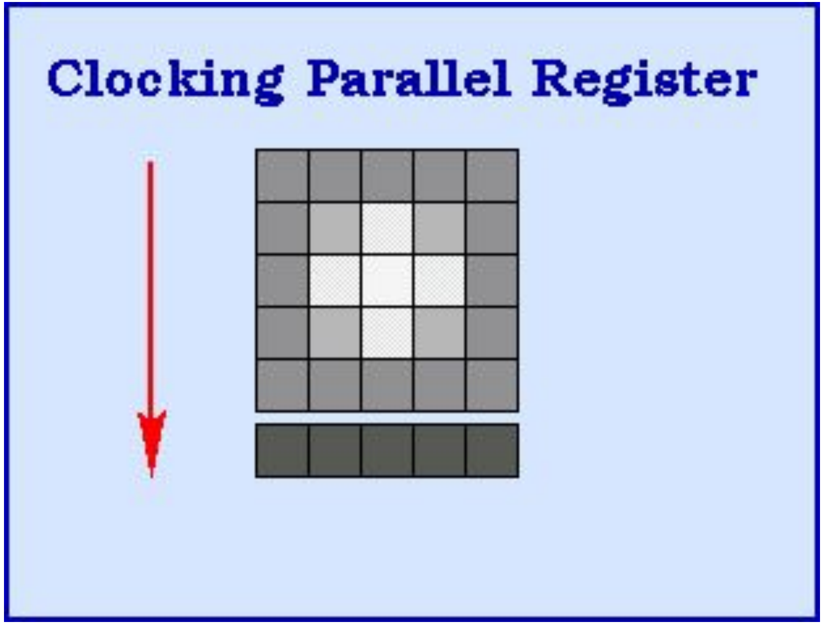


Figure 2b The basic layout of a three-phase two-dimensional CCD. The sequence 1, 2, 3 on each set of electrodes indicates the normal direction of charge transfer in the parallel and serial registers.

Reading CCD Detectors

The surface of the CCD is covered with MOS capacitors. Often, there are three electrodes per pixel. Typical pixel sizes are 10-40 μ. The **"parallel shift"** registers are shown as rows running across the whole face of the CCD. These are separated by insulating "channel stops." At one end of the CCD is a column of **"serial shift"** electronics and an output amplifier. Contemporary large chip designs involve several amplifiers (but always many fewer than the number of pixels!).

At the end of the exposure, readout of the collected electrons is accomplished by cycling (**"clocking"**) the voltages on the electrodes such that the charge is **shifted** along the rows. Each parallel transfer places the contents of one pixel from each row into the serial register column. This column is then shifted out vertically through the output amplifier and into computer memory before the next parallel transfer occurs.

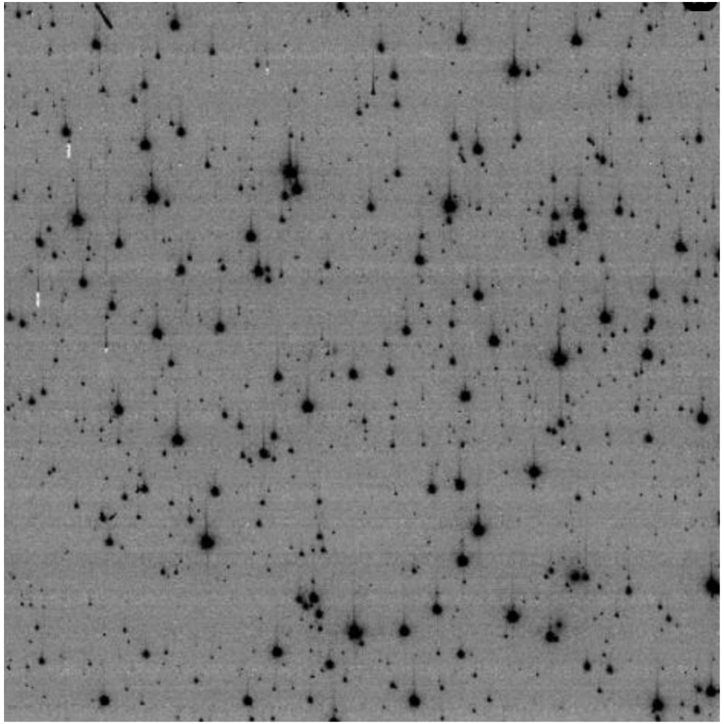


Reading CCD Detectors

Charge Transfer Efficiency (CTE) can be better than 99.999% per transfer from one pixel to the next, but it has to be, since the throughput of a chip with 2048 pixels required shifts = CTE^{2048}. This is one of the main limitations of CCDs.

Because of "traps" within the CCD's, good CTE is often possible only for signal levels above a threshold of ~10-50 e/pix. For good efficiency at low light levels, this requires adding a **"bias level"** electronically. Unfortunately, this also creates added noise.

Long-term exposure of CCD's to radiation in space on missions like HST or reconnaissance satellites systematically increases the trap density, meaning that CTE reduction is a serious problem that can be mitigated at the expenses of additional noise in the data.



Reading CCD Detectors

Charge transfer is an effective method of reading Si based CCDs, the signal is however sampled only at the end of the exposure and subsequently erased (‘**destructive readout’**)

IR detectors are based on a different technology (HeCdTe substrate that has a small energy gap, sensitive to IR photons). In this case a photodiode is placed behind each light sensitive pixel and the electron signal is continuously read. This method is called ‘sample-up-ramp’ or ‘non-destructive readout’

SIDE NOTE: IR detectors are very sensitive to the operating temperature because the small energy gap means that thermally generated electrons can reach the charge well. They need to be cooled near the absolute zero.

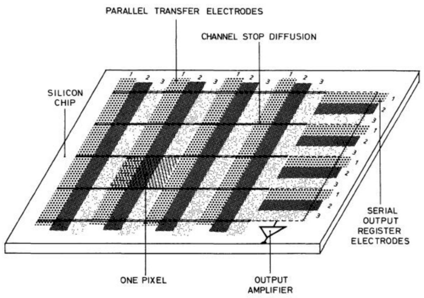
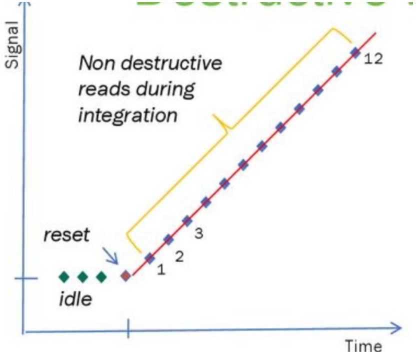
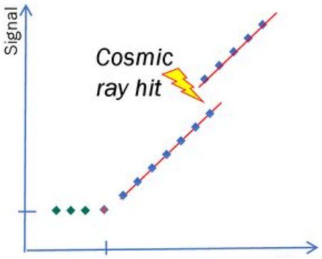
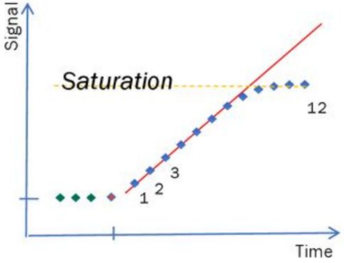


Figure 2b The basic layout of a three-phase two-dimensional CCD. The sequence 1, 2, 3 on each set of electrodes indicates the normal direction of charge transfer in the parallel and serial registers.







Reading CCD Detectors

For storage in memory, the electrical signal generated by the amplifier must be digitized. This is done by an **"analog-to-digital converter"**. This is normally adjusted such that one digital unit corresponds to **more** than one photo-electron. This is because CCDs can typically hold more than 100000 electrons before saturating and “bleeding” into the nearby pixels. Typical values of this conversion are 2 to 8 electrons per stored digital unit and the maximum digital value of a pixel can be 65536 (16-bit in a modern CCD) or 256 (8-bit in older detectors).

The stored values are called **"ADU's"**, for analog-to-digital-unit. The corresponding constant of transformation, normally quoted in units of "electrons per ADU", is often called the "Gain" (although this is confusing nomenclature because a larger Gain results in reduced ADU values).

Note that the use of such a conversion importantly affects the **statistical properties** of the recorded signal. If **x is the recorded signal in ADU's, y is the original signal in photo-electrons** (which follows Poisson statistics), and G is the gain, then:

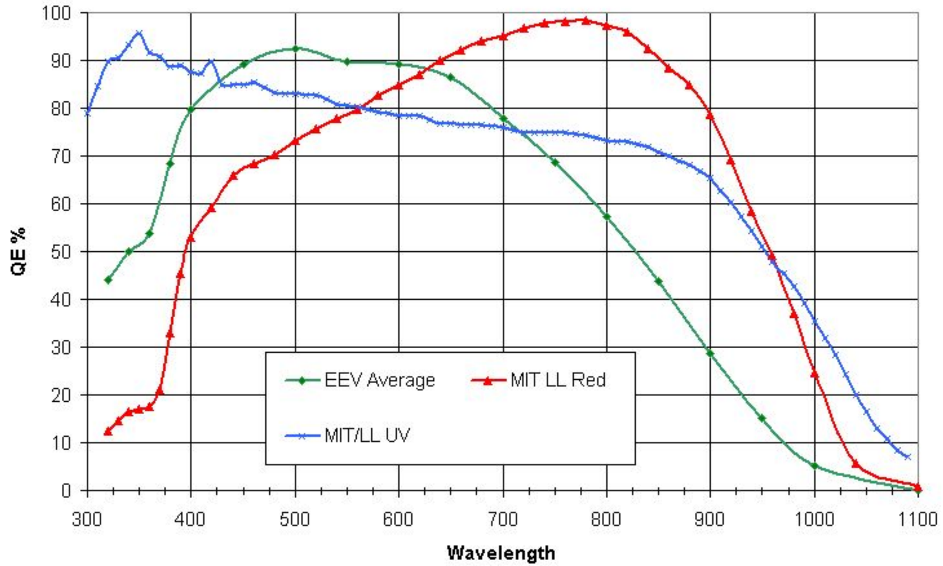
$$x = y / G$$

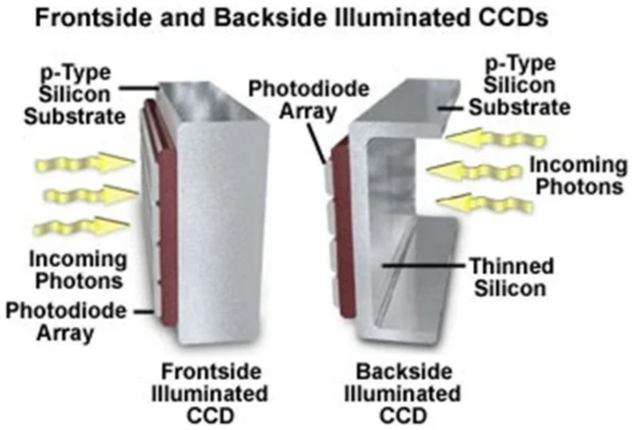
$$\mathrm{Var}(x) = \mathrm{Var}(y)/G^2$$

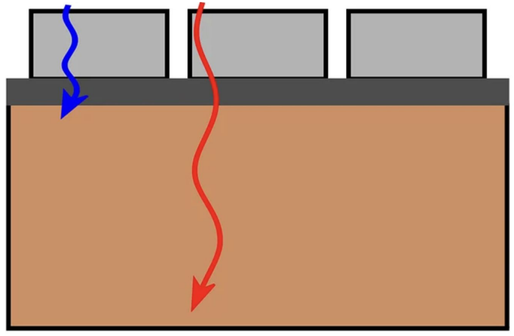
Blue sensitive CCD Detectors

Backside illuminated CCDs

Improved efficiency at short wavelengths, comes at a price
Increased manufacturing costs, higher electronic noise,
loss of sensitivity at longer wavelengths





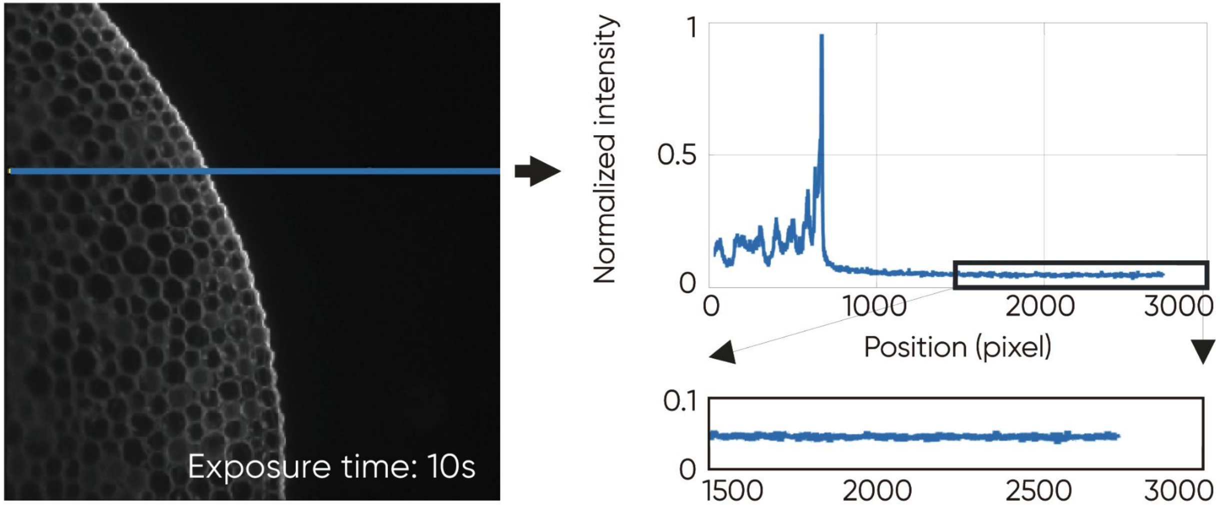


Your Turn

Today’s lab activity: The Dark Current

The Bicocca telescope has a front-side illuminated CCD. To work in linearity regime and to optimize the CTE, an electronic bias level is applied to the MOS capacitor.

During an exposure, a **dark current** (electrons generated by thermal excitation builds-up). You will familiarize with the format of CCD images and the concept of FITS files and you will study the properties of the dark current as a function of exposure time (is it linear?) and temperature of the CCD.

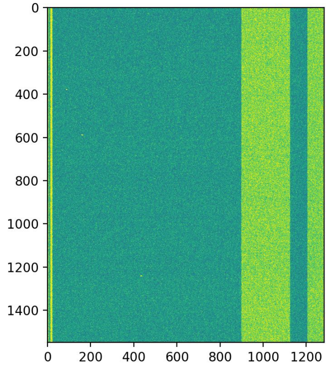


Today's lab activity: The Dark Current

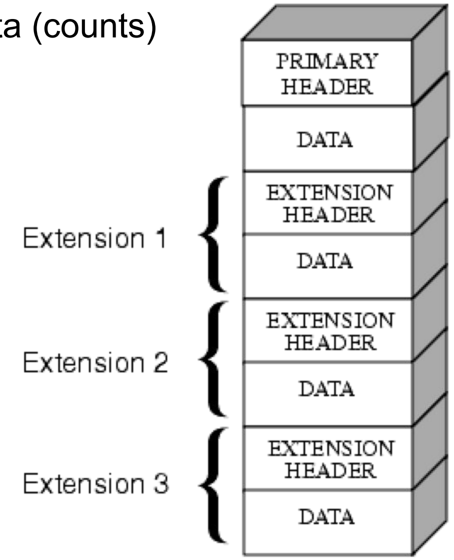
To facilitate interoperability and archival value of astronomical images, almost all observatories use the FITS (Flexible Image Transport System) file format.

Digital file format used to store astronomical images, data, and catalogs. Files consist of text header(s) and one or more data blocks, which can be images, arrays, cubes or even tables. Each data block is called an extension.

The images are monochromatic 2D arrays often made of 16-bit integers for the raw data (counts) and float values for the processed data.




```
====> file e130811_0067.fits (main) <====
SIMPLE  =                    T / file does conform to FITS standard
BITPIX  =                   16 / number of bits per data pixel
NAXIS   =                    2 / number of data axes
NAXIS1  =                 1284 / length of data axis 1
NAXIS2  =                 1550 / length of data axis 2
EXTEND  =                    T / FITS dataset may contain extensions
COMMENT   FITS (Flexible Image Transport System) format defined in Astronomy an
COMMENT   Astrophysics Supplement Series v44/p363, v44/p371, v73/p359, v73/p365
COMMENT   Contact the NASA Science Office of Standards and Technology for the
COMMENT   FITS Definition document #100 and other FITS information.
BZERO   =                32768 / offset data range to that of unsigned short
BSCALE  =                    1 / default scaling factor
COMMENT The following keywords came from KTL via watch_ccd
TEMPDET =        -120.09384155
UTBTEMP =           6.50000000
UTBFANS = 'on      '
PWRBLOK =           3.39926744
SHUTSTAT= 'closed R'
ERASECNT=                    1
```



Today’s lab activity: The Dark Current

The script can be found at:

https://colab.research.google.com/drive/1Hz78IKq1jIPXF4HZ5fba-695749BKSjp?usp=sharing

The relevant datasets can be found at:

https://drive.google.com/drive/folders/1ww4N4UmIwqkOrVRIlyG7ZOD2kp7Qvqra?usp=share_link