AGA5802
CCDs

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Charge Coupled Device

It is the most used type of detector in optical astronomy.

The Nobel Prize in Physics 2009

Charles Kuen Kao
Prize share: 1/2

Willard S. Boyle
Prize share: 1/4

George E. Smith
Prize share: 1/4

The Nobel Prize in Physics 2009 was divided, one half awarded to Charles Kuen Kao *"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"*, the other half jointly to Willard S. Boyle and George E. Smith *"for the invention of an imaging semiconductor circuit - the CCD sensor"*.

Why CCDs?

Here we see the "quantum efficiency" of different detectors with respect to wavelength.

"Quantum efficiency" is the ratio of photons detected with respect to the amount of arriving photons.

The eye was the first detector ever used in astronomy. Its QE is limited.Photographic plates could have longer exposure times than the eye and they cover a wider range of wavelength.

CCDs are more than one order of magnitude mroe efficient and they cover the whole optical range.

Comparing Detector QEs

Why CCDs

Good response over the whole optical range *(see later)*

Linearity *(see later)*

Low-noise *(see later)*

Immediately usable data [right after readout, you can already start making some basic assessment of your image]

How do I choose a CCD?

The main characteristics:

- Dimension
- Pixel size
- Quantum efficiency
- Readout noise
- Readout speed
- Cost! *(the detector is normally the most expensive part of an instrument)*
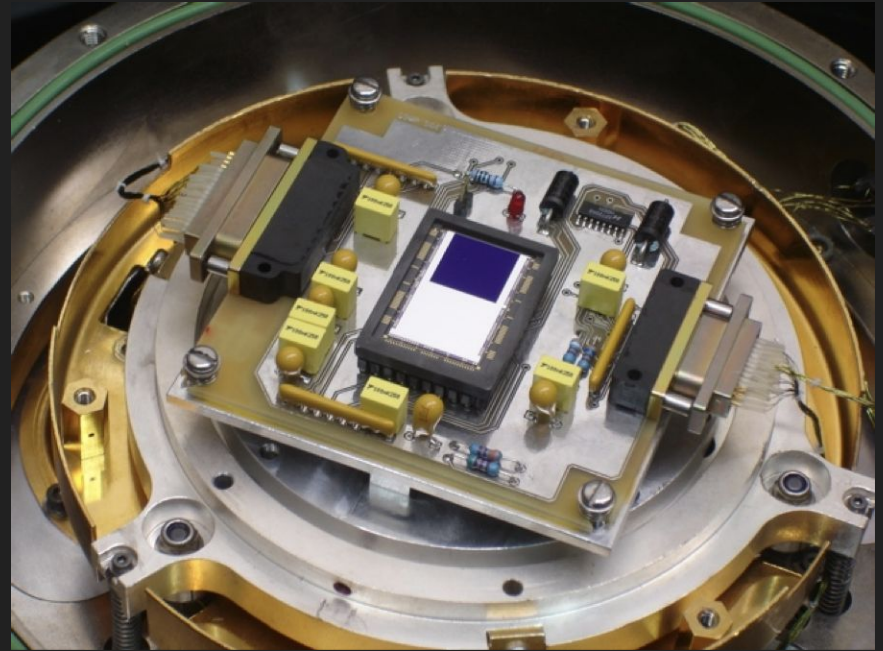
How does a CCD work?

These are the "valence band" (in green) and the "conduction band" (in yellow) of three different materials.For an insulator, the separation between conduction and valence band (the "band gap") is large, while in a conductor the gap is negligible.

For a semi-conductor the gap is small enough that it can be skipped with the energy coming from a photon. In the case of silicon, the gap is 1.14 eV.

Silicon is a semi-conductor between 1.1 and 4 eV (11,000 and 3,000Å). -> this is my definition of "optical range"
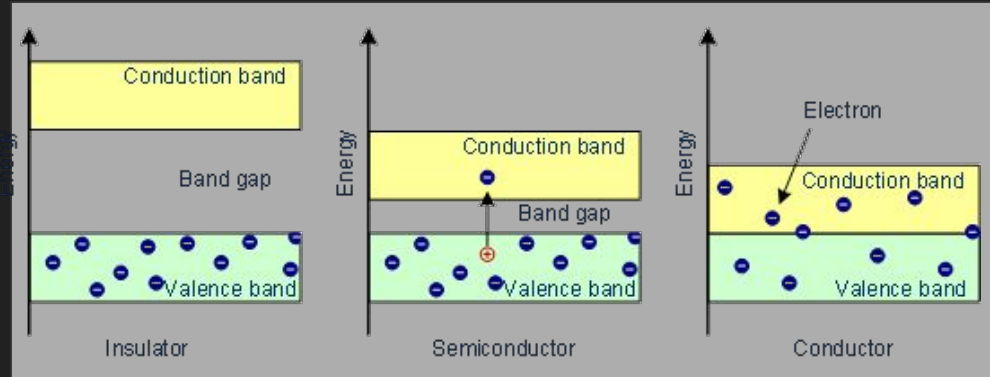
Coupling the charge

When I am exposing my CCD to light, I accumulate photons in each "pixel". (note the last column on the right, which is not exposed to "rain"; this special column is called "register") Roughly, for each photon you gen an electron.

Then I move the buckets by one line, so I fill the register. This you do by electronically moving the charge (it's the "charge coupling" which gives the name to the device).

Finally, I read each element of the register. Here, electrons are read and become "Analog to Digital Units" (ADUs)

Integration of Photon-Induced Charge / Raindrops / Parallel Bucket Array / Serial Bucket Array / (a)
Parallel Register Shift (1 Row) / (b)
Serial Register Shift to Output / Conveyer Belt / (c)
Figure 5
Bucket Brigade CCD Analogy / Calibrated Measuring Container
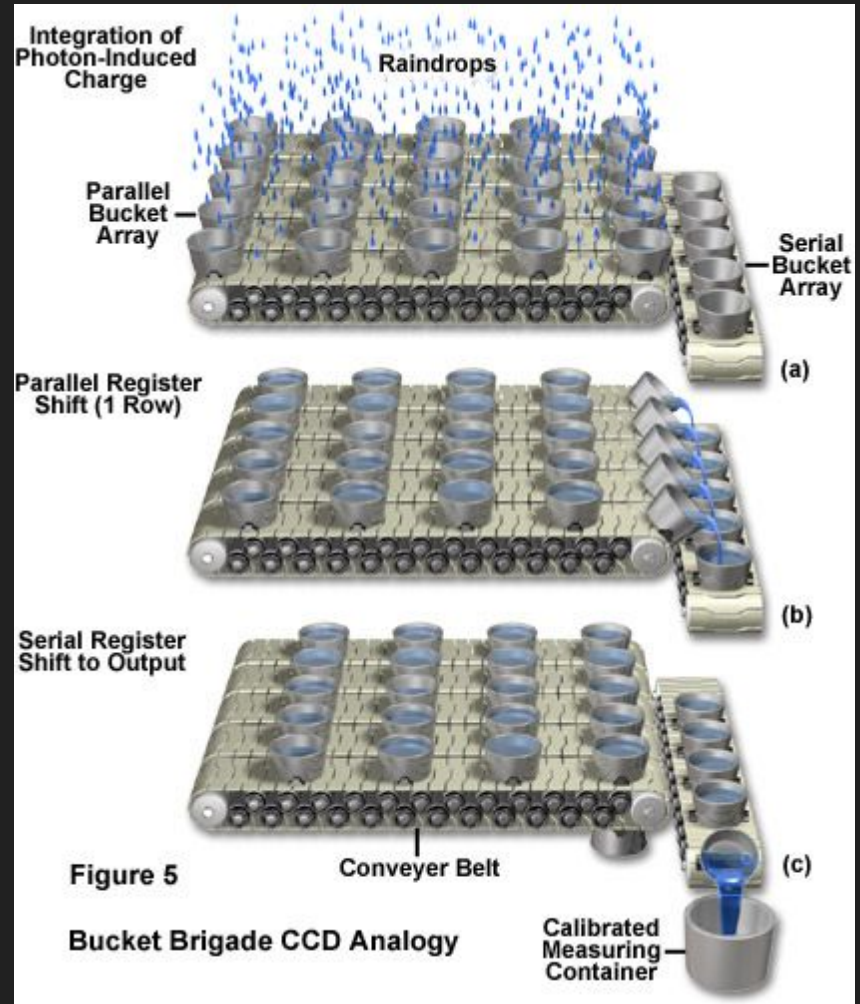
CCDs vs CMOS

You have probably heard of "Complementary Metal Oxide Semiconductor" arrays (CMOS)

CCDs have larger pixels and only have one readout electronics for the whole detector.

In CMOS, EACH pixel is read separately. This is still an optical device but its use in astronomy is still limited (spoiler: infrared detectors work like this)
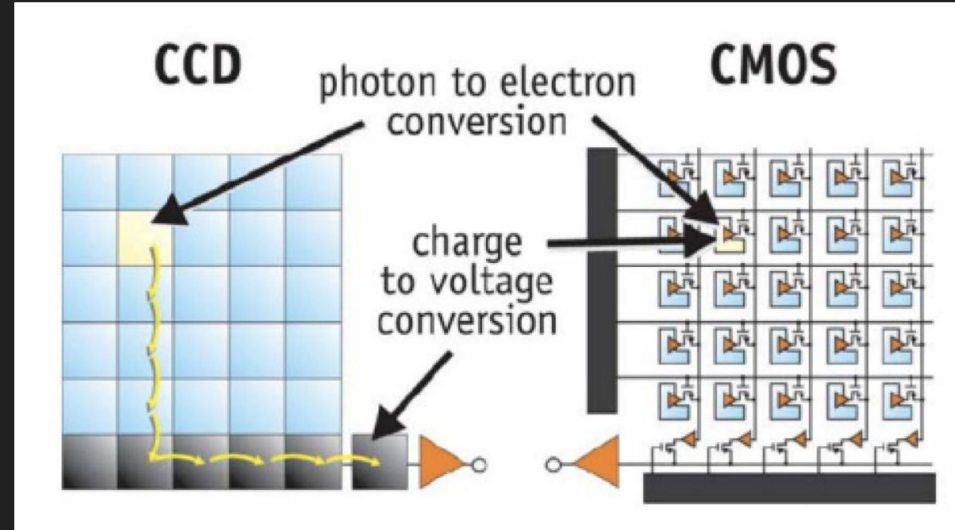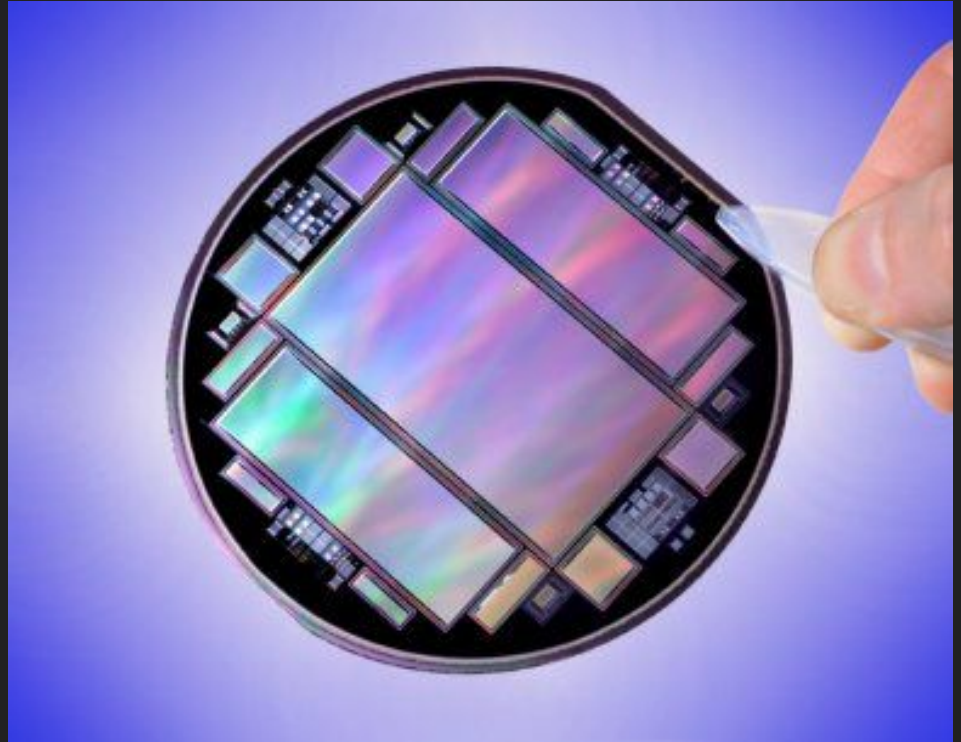
Fabrication

You make a big slice of silicon (called "wafer") and "draw" the circuits on it.

Depending on the quality of the pixels, you can have grade 0 (science grade) to grade 3 (mobile phone grade).

The largest wafer you can make can host a ~12cm squared CCD (only two companies in the world can make it and the first one was made less than 10 years ago…)
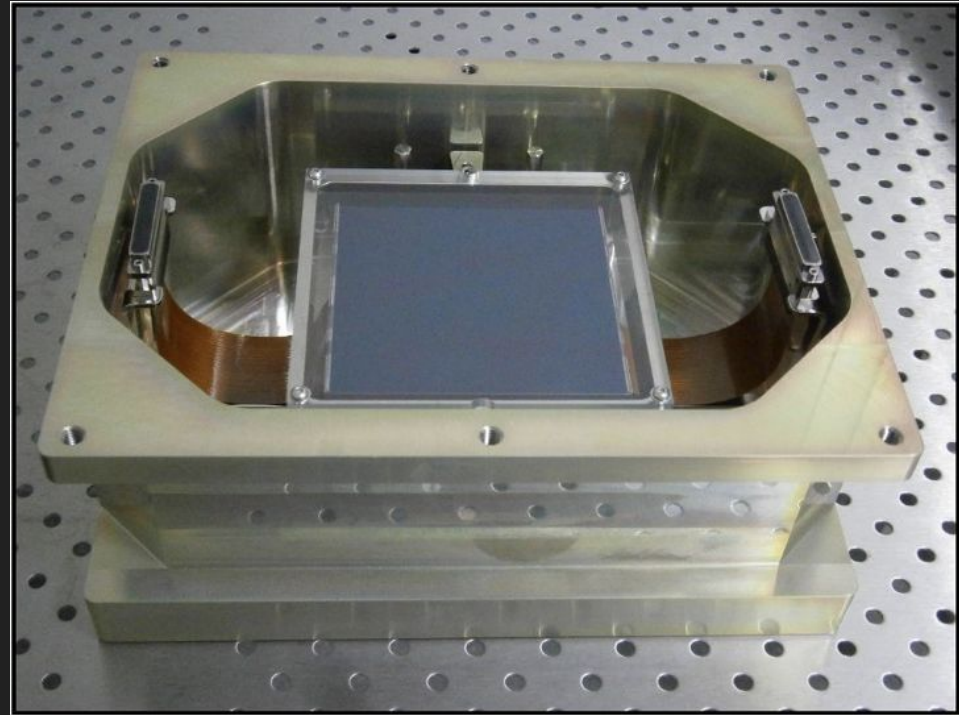
Sizes

The pixel of a CCD can be between 10 and 24 μm (1μm = 10^{-6} m)

In general, you want the pixel to measure **half the psf** of your telescope

Early CCDs had 256 x 256 pixels^2. Nowadays, CCDs can have ~10,000 x 10,000 pixels^2.

The size of the CCD will be (in a side): n_{pixels} x $size_{pixel}$

In general, you want the size of your CCD to match the field of view of your instrument.

Above, the CCD of OAJ/T80Cam; when it entered in service, it was the largest format CCD used in astronomy.

Wide Field Planetary Camera 2 (WFPC2)

(pronounced as "weepeek2")

Perhaps the most iconic instrument on the Hubble Space Telescope (which celebrates 30 years today; happy birthday, big boy!)
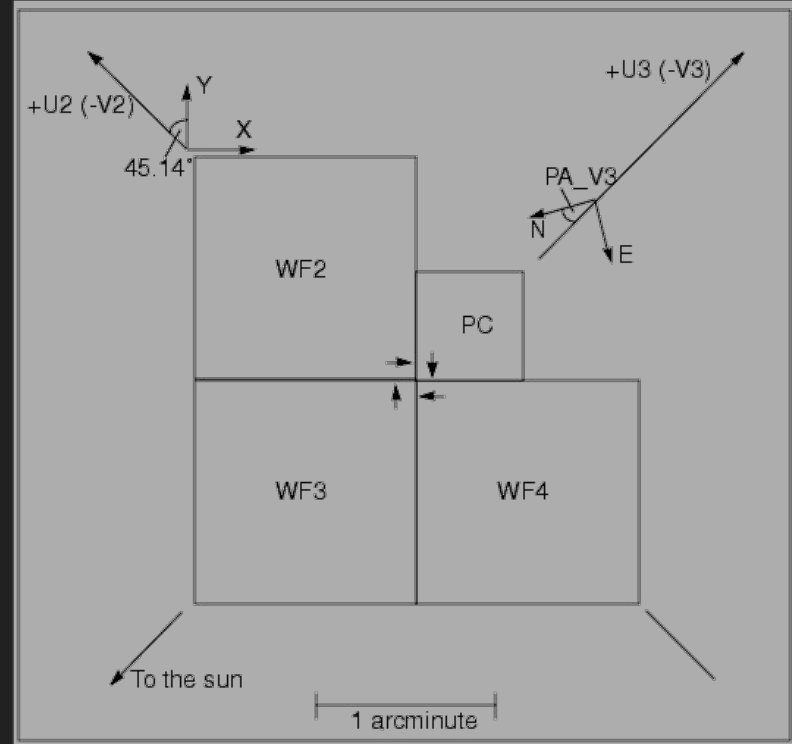
Operational between 1993 and 2009

4 CCDs: 800x800pixels

WF -> 0.1 arcsec / pixel

PC -> 0.046 arcsec / pixel

Diffraction limit of HST: 0.05" (undersampled!)

The Hubble Deep Field

It is hard to overstate the importance of this exposure in the history of astrophysics. It redefined astrophysics and was the birth of observational cosmology as we understand it today.

100 hours of exposure during Christmas 1995 (in fact, while I was celebrating my 18th birthday, HST was taking this image)

Williams et al. (1996)

Hubble Deep Field
ST ScI OPO January 15, 1996 R. Williams and the HDF Team (ST ScI) and NASA

HST   WFPC2

Quantum Efficiency

As we said, this is the ratio between the detecting photons and the incident ones.

On the right, two examples of measures of quantum efficiency.

In the following, the difference between "front" and "back illuminated" (the "gate" is the readout electronics).
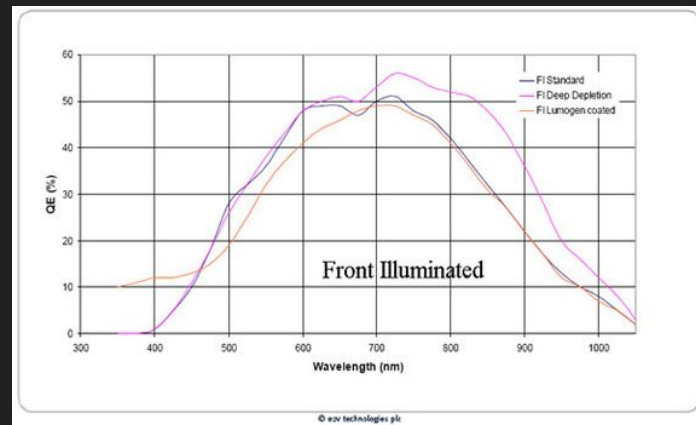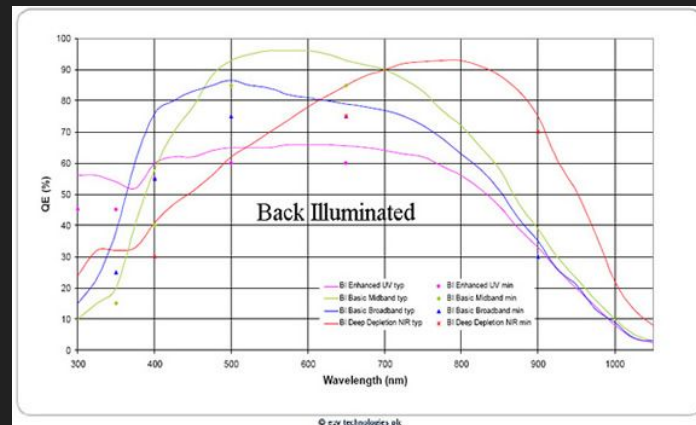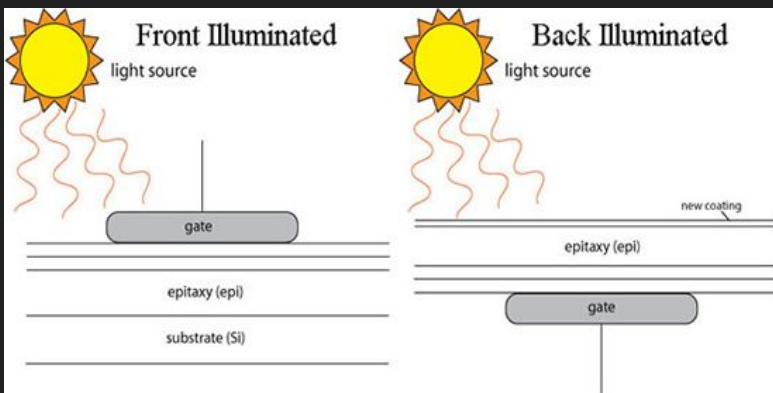
Coatings

You normally put a small surface on top of your CCD to avoid "undesired effects" (e.g. reflection). You can "tune" these coatings so that they maximise the quantum efficiency of your detector.

In particular, if you have a CCD in a spectrograph and you know that some pixels will always receive light at a specific wavelength, you can optimise the coating in these pixels for that wavelength.

E.g. the HERMES spectrograph

Fig. 14. Picture of the graded-AR coated CCD. The red-sensitive part at the top of the chip looks blue because red light is absorbed while blue light is reflected.
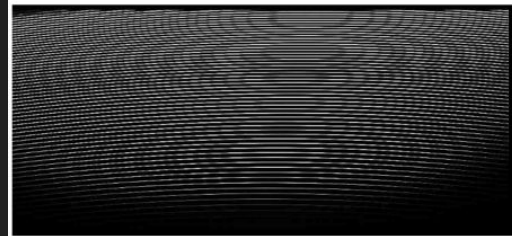

Fig. 15. Full-frame raw image of a flat-field spectrum in the low-resolution fibre.

HERMES: a high-resolution fibre-fed spectrograph for the Mercator telescope ★

Gert Raskin[1], Hans Van Winckel[1], Herman Hensberge[2], Alain Jorissen[3], Holger Lehmann[4], Christoffel Waelkens[1], Gerardo Avila[5], Jean-Pierre De Cuyper[2], Pieter Degroote[1], René Dubosson[6], Louis Dumortier[2], Yves Frémat[2], Uwe Laux[4], Bernard Michaud[6], Johan Morren[7], Jesus Perez Padilla[1], Wim Pessemier[1], Saskia Prins[1], Kristof Smolders[1], Sophie Van Eck[3], and Johannes Winkler[4]
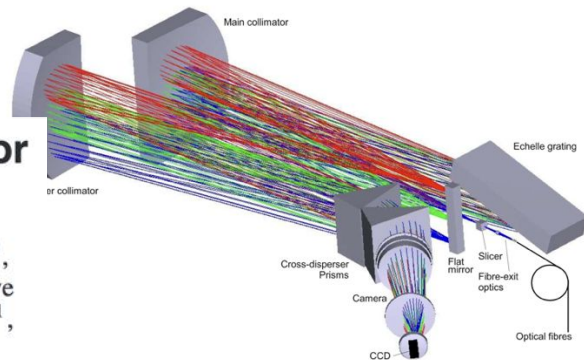
Linearity

This is a key characteristics of a CCD.

If I give twice as many photons, I must get twice as many electrons (and ADUs).

Twice as many electrons can be obtained with a source twice as bright or doubling the exposure time.

Non-linearity effects are often observed at low counts and at (very) high counts.

At some point, the potential well is full. Here the pixel is said to be "saturated" and cannot count more photons.
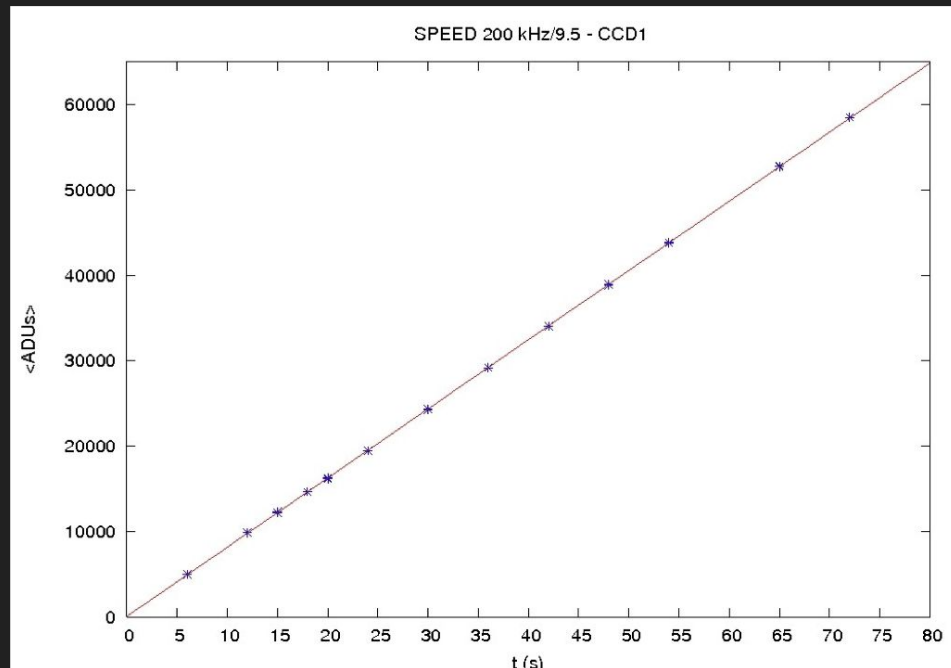
The controller

The "controller" is the brain of the CCD. It tells it when, where and how to read.

In particular, the controller is capable of "creating" a series of virtual lines which generate regions of pixels which are only electronic noise: the pre-scan and the over-scan (not all CCDs have them).

The controller allows observations which involve the simultaneous movement of the charge in the detector and the movement of the telescope (e.g. nod-and-shuffle in Gemini/GMOS)

prescan

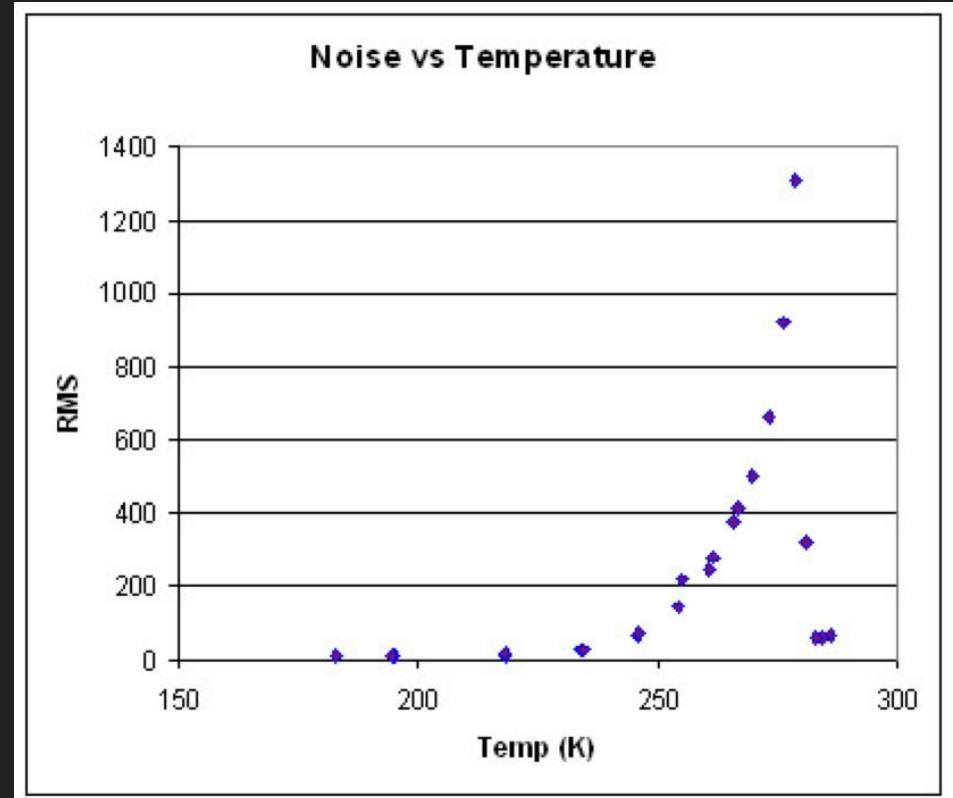Exposed region

overscan

readout

readout
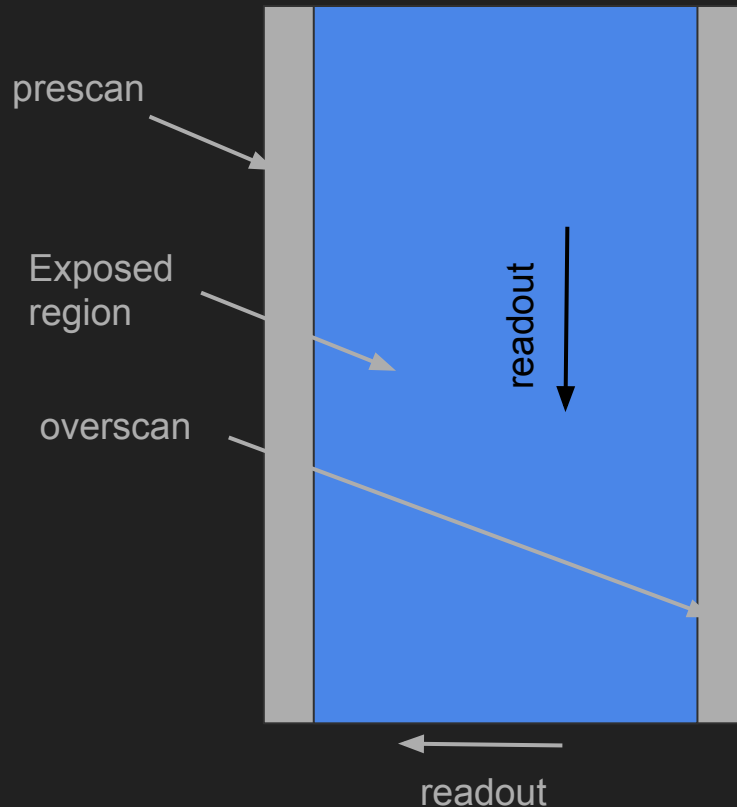
Noise

The noise of a CCD depends critically on its temperature.

These are electrons which pass the band gap because of temperature. Hence, the cooler, the better.

Most CCDs are cooled with liquid nitrogen (about -200°C).

"Wide field"

The detector of OSIRIS (the first instrument on the Gran Telescopio Canarias, the largest optical fully-steerable telescope of the world) is 2 CCDs 2k x 2k (model: Marconi CCD42-82).
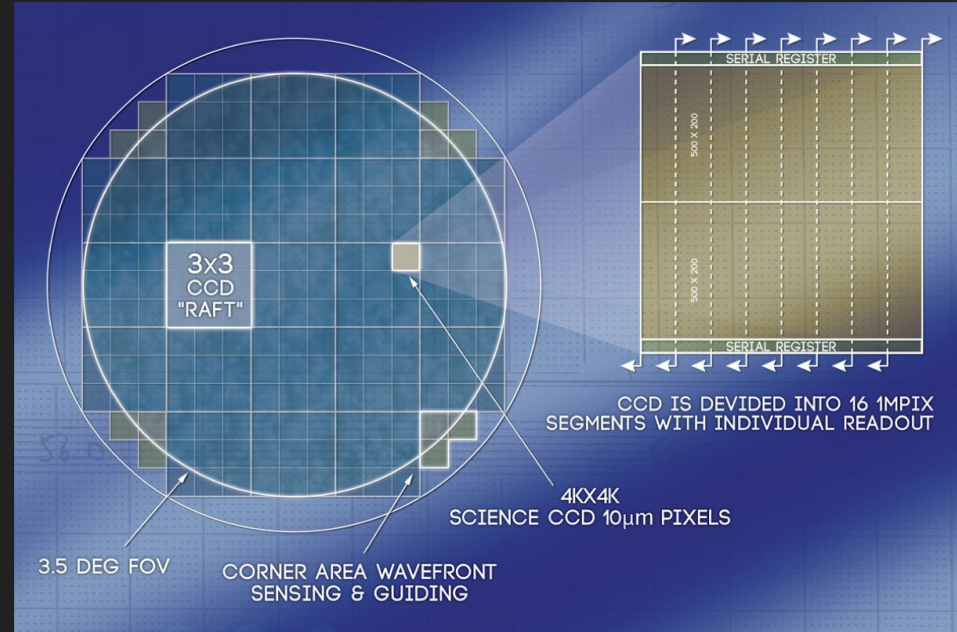
Pixel size: 15μm

Pixel scale: 0.125"/pixel

Since the typical seeing at Roque de los Muchachos is 0.6", the psf is oversampled (there are good reasons though).
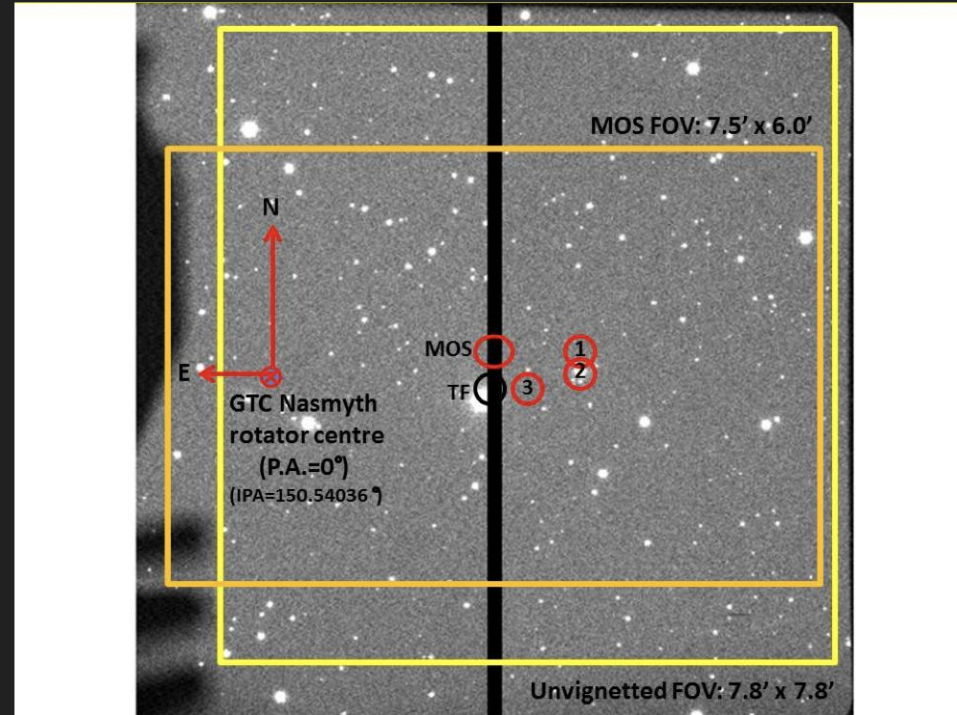
Vera Rubin Telescope (formerly LSST)

To cover the 3.5 degrees (diameter) field of view, they chose to have 21 "rafts", each with 9 CCDs of 4k x 4k.

How many pixels does this make?
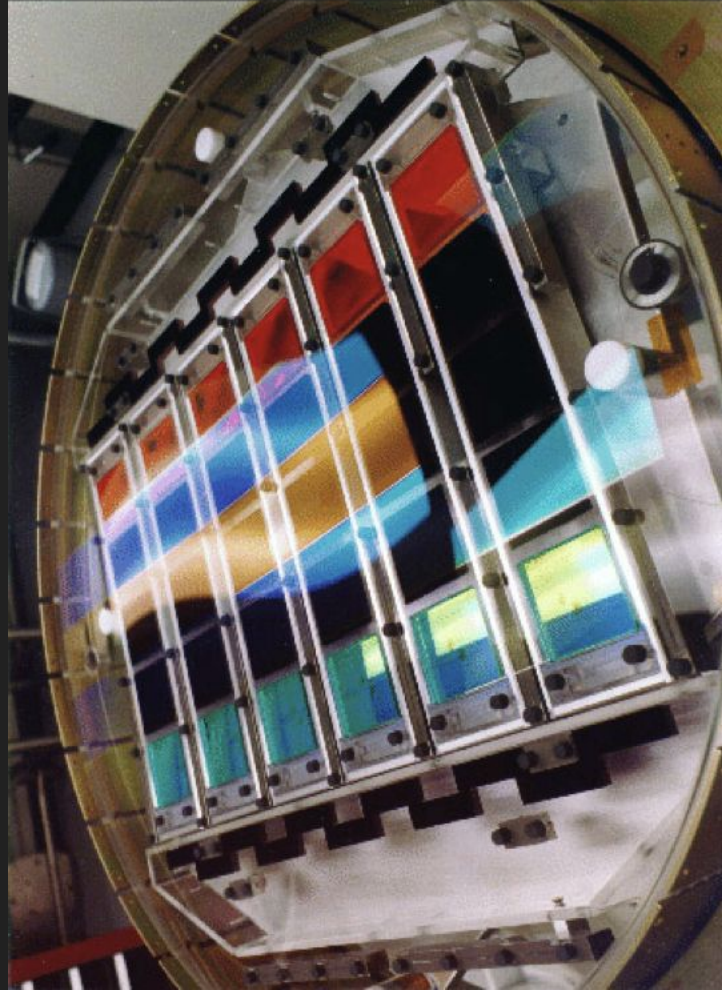
Sloan Digital Sky Survey

Observations from a dedicated 2.5m telescope at Apache Point (USA).

30 CCDs 2k x 2k

Pixel size: 24μm

Pixel scale: 0.396"/pixel

Operated in "drift scan" mode...

Meridian Circle at Observatorio Abrahão de Moraes

The CCD at the meridian circle at Valinhos works in drift-scan mode… just like the SDSS one.


In drift-scan, the telescope does not move to compensate the rotation of the Earth but the charge on the CCD is.

The result are long strips whose depth depend basically on the declination of the object and the size of the telescope.

You have no control on the exposure time (unless you manage to slow down the rotation of the Earth, which is commonly considered a bad idea).

Gaia

The instruments on Gaia also work in drift scan.
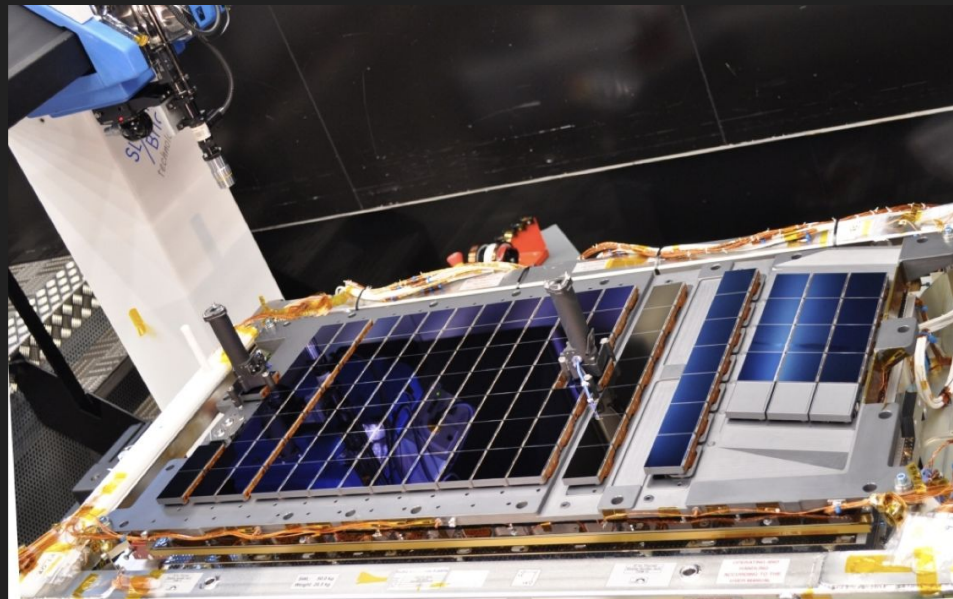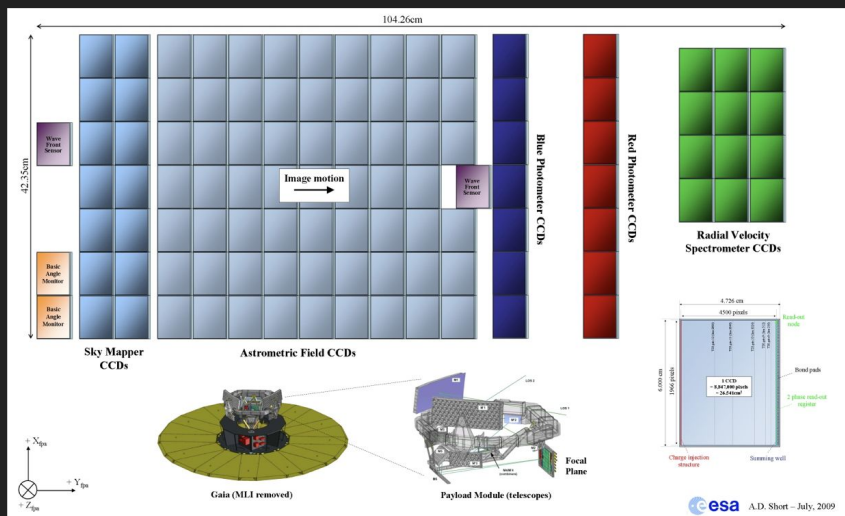
I wonder if we want a dedicated lecture on Gaia.

Observing fast: ROIs

Regions of Interest (ROIs) or "Windows" are groups of pixels that one can decide to read (instead of the full detector).

For example:

- the speed of my readout is 100kHz
- 1000 pixels in x
- 4000 pixels in y

How long does it take to read a CCD?

1000 * 4000 / 100 000 = 40s

But if I only read the lower half of the CCD (hence 2000 pixels in y), it takes 20 s!

If I select a small region of 10 pixels in x and 10 pixels in y, it takes

10 * 10 / 100 000 = 0.001 s!

(in fact it is a bit more complicated than this, it depends on the location of the ROI in the array)
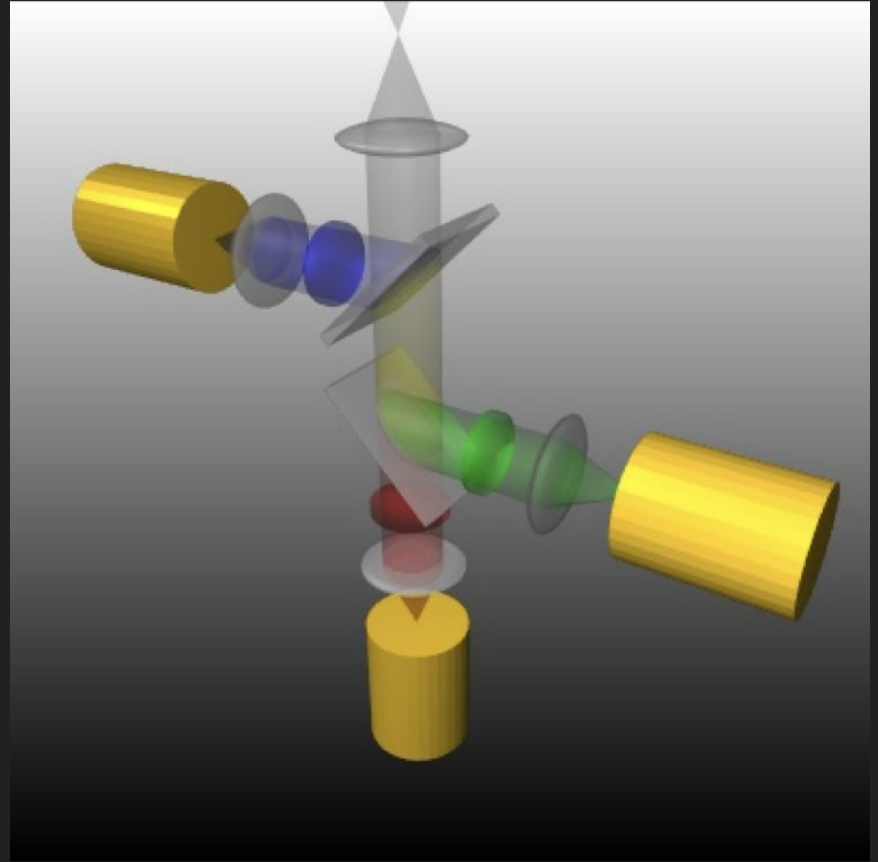
Reading fast: frame transfer CCDs

In this kind of CCD, half of the CCD is exposed to light and the other half is used for storage, before the data are read through the register.

The time to read the "storage area" is the minimum exposure time of the "exposed area".
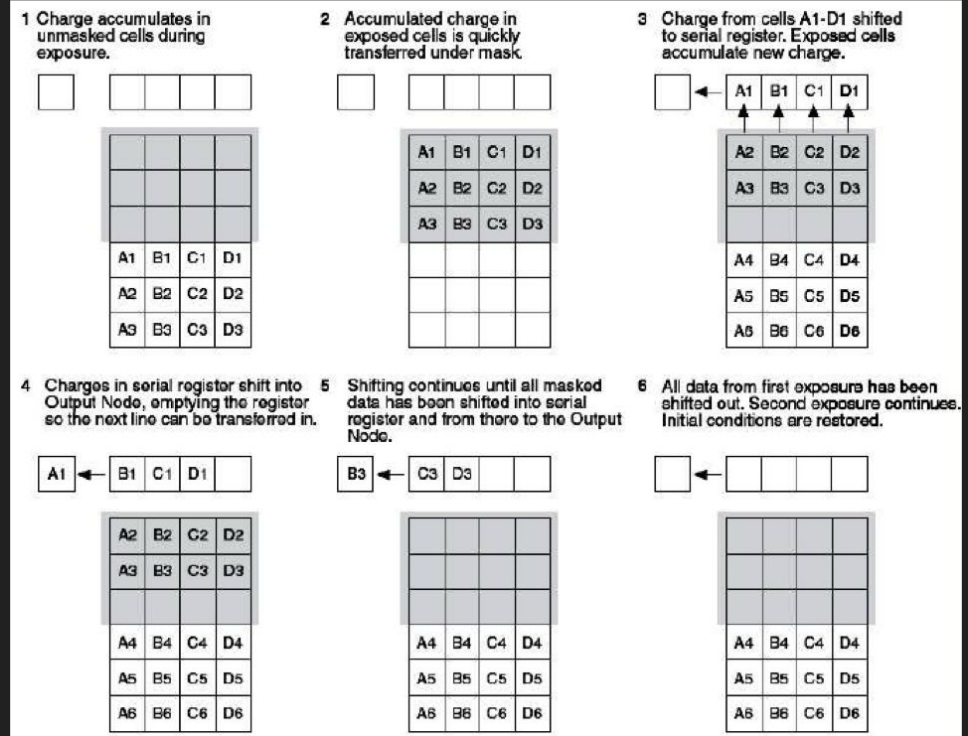
UltraCam

Frame-transfer CCDs are used in UltraCam
(Dhillon et al. 2007)

Exercises

Exercise #1

For a telescope in a site with typical seeing of 0.6"

You have two fields of view:

- FoV A: diameter of 13cm and scale 55.56 "/mm
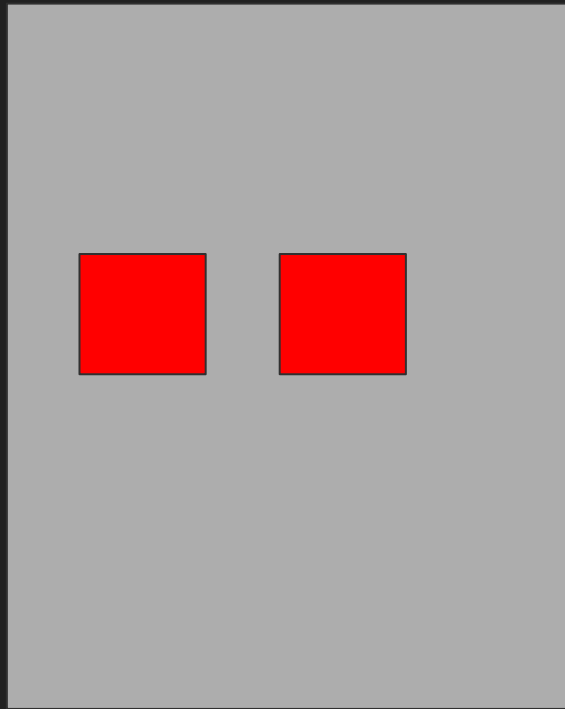- FoV B: diameter of 20cm and scale 5.41"/mm

Which of these CCDs do you choose?

CCD	N pixels x	N pixels y	Pixel size (µm)
A	2k	4k	13.5
B	2k	4k	10
C	9k	9k	10
D	4k	4k	13.5

Observing with 2 ROIs (1)

How long does it take to read your CCD if your
ROIs have:

- X1 500
- Y1 2000
- dX1 10
- dY1 10
- X2 100
- Y2 2000
- dX2 10
- dY2 10

Observing with 2 ROIs (2)

How long does it take to read your CCD if your ROIs have:

- X1 500
- Y1 1000
- dX1 10
- dY1 10
- X2 100
- Y2 2000
- dX2 10
- dY2 10