LESSON 2

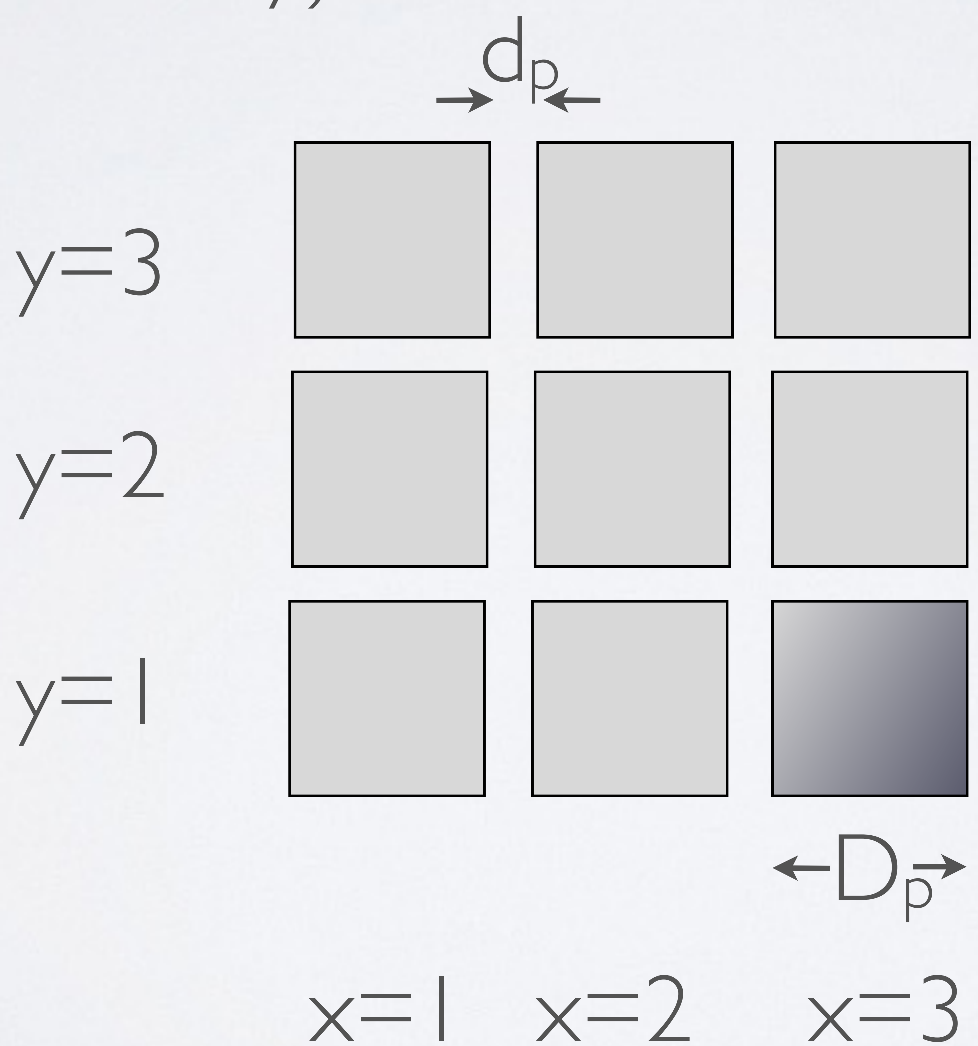
CCD II

THE PICTURE IN THE DARK

You would typically install a CCD at the focal plane of a telescope. This is in a general a 2-D plane: at each point in it, x and y, you'll see a brightness distribution that let you define a function B(x,y) which can be measured in Watts/m^2. This B is a rather imperfect representation of the source. This imperfection is due to several factors: telescope quality (chromatic aberration, coma, limited resolving power, etc), ambient conditions (dust, humidity, local seeing) and also the fact that electromagnetic waves are altered by the media they travel through. The CCD is an array which when positioned at the focal plane will also add to all of the above the imperfections due to all the noise sources that we will study in this chapter.

Arrays are rectangular necessarily ($\#_x$ columns and $\#_y$ rows). At each $\#_x$, $\#_y$ we have a "picture element", pixel, which is the actual "detector " in the CCD. In most CCDs pixels are square (i.e. the Apogee presented in Lesson 1 has 14x14 microns pixels.)In the case of square pixels they are separated by a distance d_p and each pixel has a size D_p. The light received by the pixel (F.R. Chromey) is: -on next slide but refer to picture below-

A 9 pixels squared array. The "illuminated" pixel is (3,1)



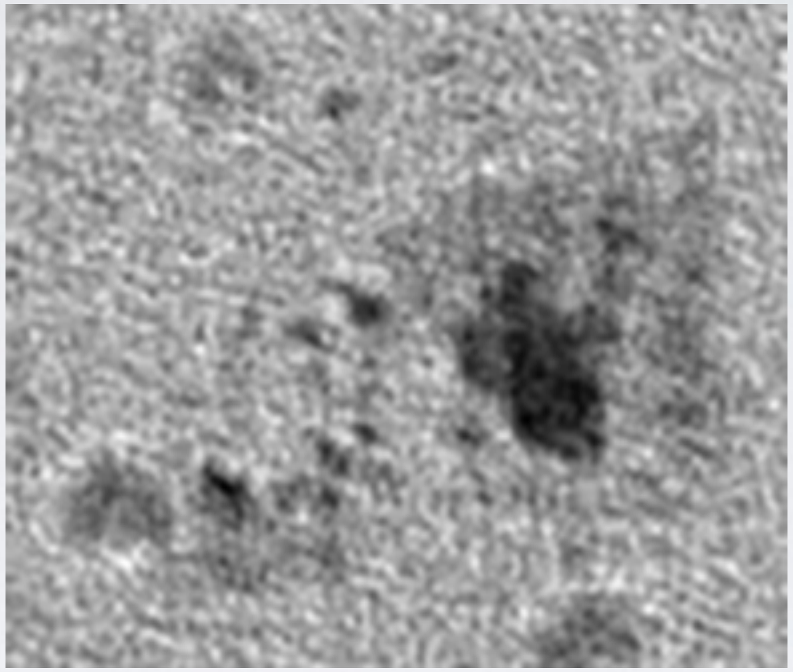
The space between pixels is d_p. The square pixels have a length (and height) D_p.

$$P(x,y)=\int_{(y-\frac{1}{2})D_p}^{(y+\frac{1}{2})D_p}\int_{(x-\frac{1}{2})D_p}^{(x+\frac{1}{2})D_p} B(x^{'},y^{'})dx^{'}dy^{'}$$

The pixel representation necessarily gives a discrete picture of an image that it's so more dense that it can be considered continuous. If the pixel spacing, d_p (see picture in the previous slide) is less than half the resolution of the original image we'll get necessarily less detail than desirable: this effect is called under-sampling and of course it is undesirable.

When observing we expose each pixel to a power W(x,y) for some interval of time. The process will generate electrons through the photoelectric effect. This effect is a response that can be called R(x,y). Notice that this function will depend not on the photons' energy but on the number of photons (assuming each photon produce one electron). But in real life we'll also get photons due to thermal noise, light pollution, cosmic rays, radioactivity.

DIGITAL IMAGES



The picture above was taken at UTRGV's observatory. Through the process described in Lesson 1 the CCD converts the analog video signal to an electronic representation through the ADC. Each pixel (x,y) has an integer value P(x,y). The entire array (Nx,Ny) is the digital image. The gray intensity levels correspond to different integer values for each pixel. Typically they are binary representations in 16-bit integers. (much better resolution than the human eye).

CCD GAIN

ADUs were defined in a previous slide. Each pixel value P(x,y) has units in ADUs. Sometimes ADUs are called counts.
Gain is the ratio of the differential value in R(x,y) that produces one ADU change in P(x,y):

$$g(x,y) = \frac{\Delta R(x,y)}{\Delta P(x,y)}$$

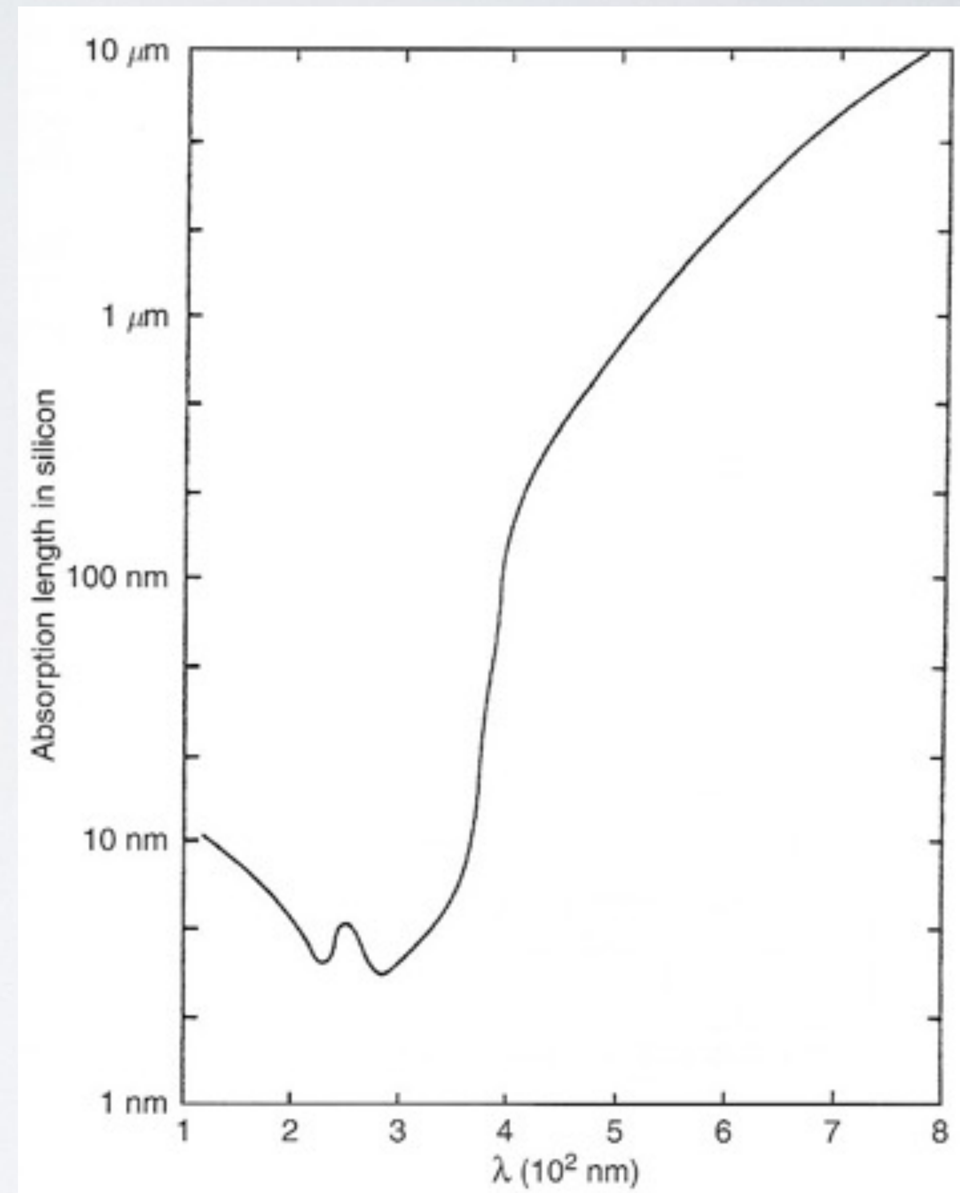
A gain of 10e/ADU means that for 10 electrons collected in one pixel the corresponding voltage output will produce a count of 1.

QUANTUM EFFICIENCY

Absorption length is defined as the distance for which 63% (1/e) of photons are absorbed. For light outside 350 to over 800 nm, the photons either pass right through the silicon, or get absorbed within the surface layers or the gate structures, or simply reflect the CCD surface. Thus the QE of a CCD is the QE of Si (see curve on this slide).

Look at the curves on pages 38-39 of Howell's book..

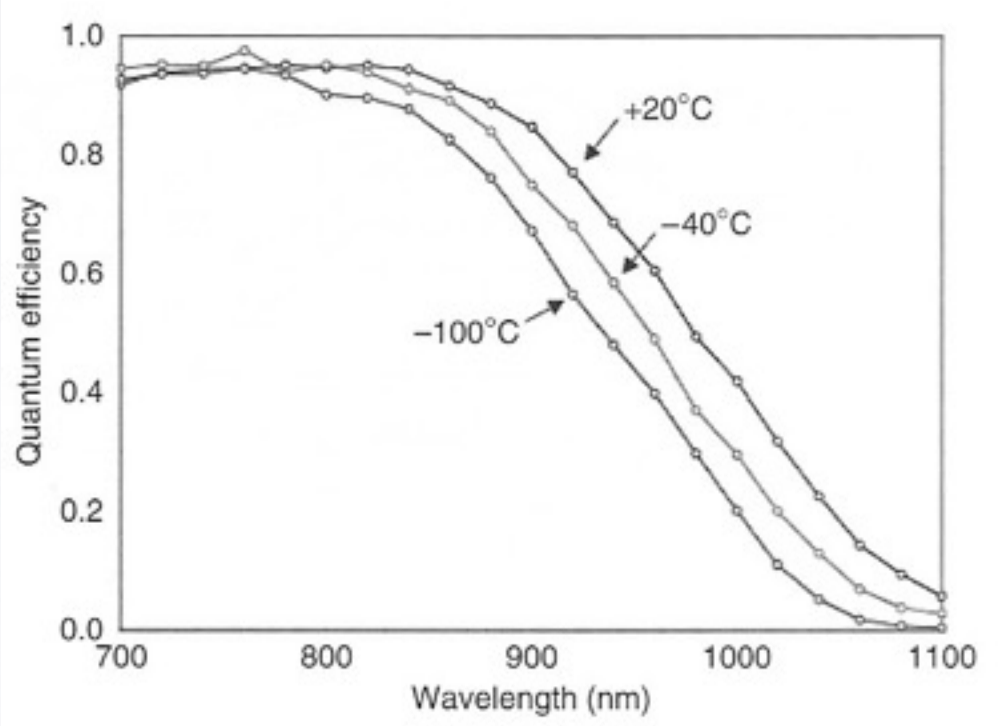
Compare with the curve for the Alta U10 on slide 9, previous lesson.



Photon absorption Si Reicke 1994
From Handbook of CCD Astronomy

QUANTUM EFFICIENCY II

QE varies with thickness of Si. Also the QE curve is not the same for each and every pixel.
It varies within same type of camera.
It also varies with the temperature.
Notice in the included plot that the curves p/each operating T above red (i.e. above 800 nm) can change by a factor of two as temperature changes as indicated.



From HB of CCD Astronomy MIT Lincoln Lab CCD

Coatings can make up for thinner devices. QE curves are crucial to understand the functioning of the CCD as a function of wavelength. Notice that a curve is a representative average of each pixel. In practice not all pixels are identical. They may also change from device to device. To compensate the "flat fielding technique" is needed.

The curves in the previous slide shows a higher sensitivity at +20 C degrees. But you need also to consider that at such high temperature thermal agitation in the material will also be high and the probability of electrons being freed in the material increases, increasing the chance of giving a false signal indistinguishable from a real one. The working temperature of CCDs is actually a compromise as we'll see later.

One way of preventing electrons from wandering outside the material is to use high resistivity Si.

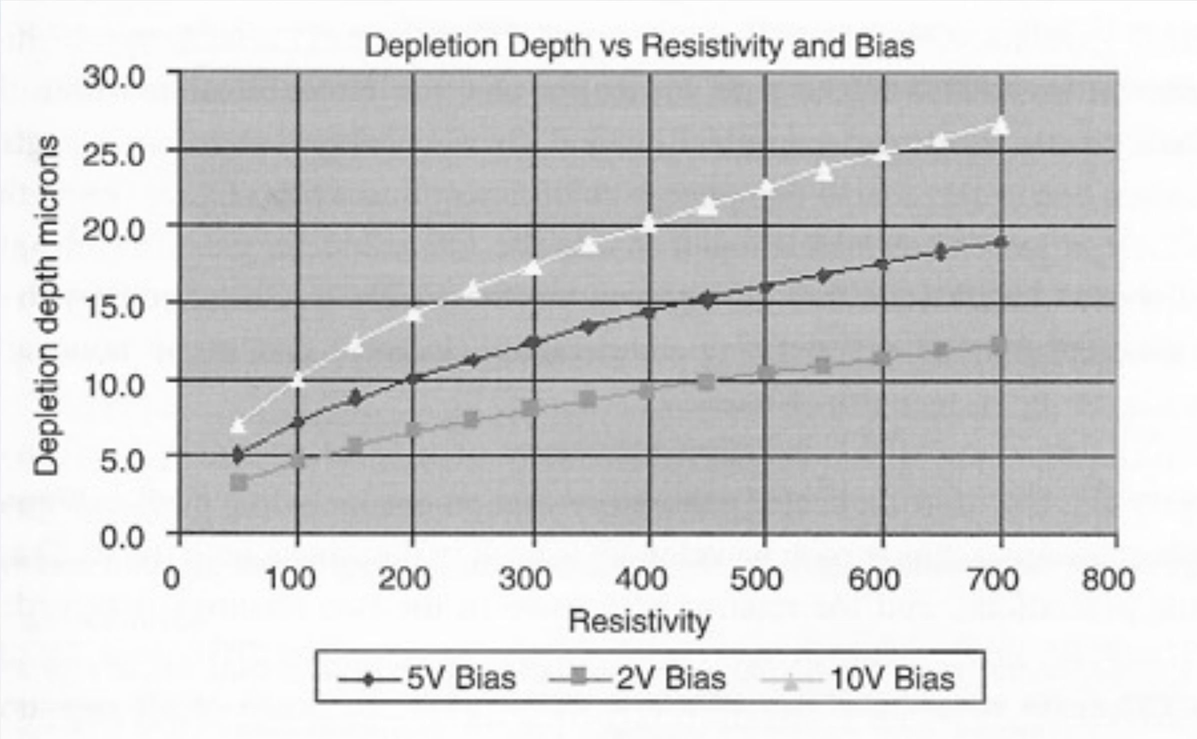
Old ones were 20-300 ohm/cm.

Nowadays resistivities of up to 5000-10000ohms/cm are used.

This resistivity would lead to a high depletion retaining more electrons (up to 300,000 photoelectrons per pixel). Depletion region refers to where the electron hole pairs created will be swept apart before they can recombined with the holes leaving the material

QUANTUM EFFICIENCY III

The idea is to deplete pixels by adding a bias voltage to the optically transparent back-side substrate. This would yield high QE in the red. This leads to an effective increase in electron collection in a pixel where they will remain due to the high resistivity.



The CCD shown in the figure (from Howell's) is a deep depletion one. Three different BIAS voltages are applied. The white corresponds to the application of 10V and clearly shows higher depletion. This would in turn improve QE around the red.

MEASURING QE

Measuring QE can be done in a couple of ways.
Using calibrated sources and photodiodes. The difference in reception of the source between the CCD and the photodiode is recorded and estimated.

Another way would be to measure it at the telescope.
The idea is to look at a set of standard spectrophotometric stars using a set of several (narrow-band) filters.

See i.e. http://adsabs.harvard.edu/abs/1977A%26A....61..679T
This paper describes the process used to calibrate the fluxes of α Lyrae and 109 Virginis from 329.5 to 904.0 nm using several filters.

CHARGE DIFFUSION

e^- captured in a pixel are kept in place by the voltages applied during integration. But there are situations in which it can end up in a neighboring pixel: charge diffusion.

There are many ways in which this can be corrected.

Always a compromise: i.e. utilization of higher voltages (problems: logic glow, array shorting), higher resistivity Si, smaller pixels (less sensitive to red).

A big problem with charge diffusion in Astronomy is the effect on the point spread function (PSF): the famous HST ACS wide field camera had a variation of 30-40% of the PSF at 500nm. this meant a loss of about 0.5 magnitudes in its limiting magnitude at short wavelengths. this more critical in thinned devices. See, i.e. http://authors.library.caltech.edu/17730/1/RHOapjss07.pdf

POINT SPREAD FUNCTION

The PSF describes the response of an imaging system, like a CCD to a point object. It can be called the impulse response of a focused optical system (in signal processing the impulse response is the response of any system to a step (or delta) function.) The PSF characterizes the device.

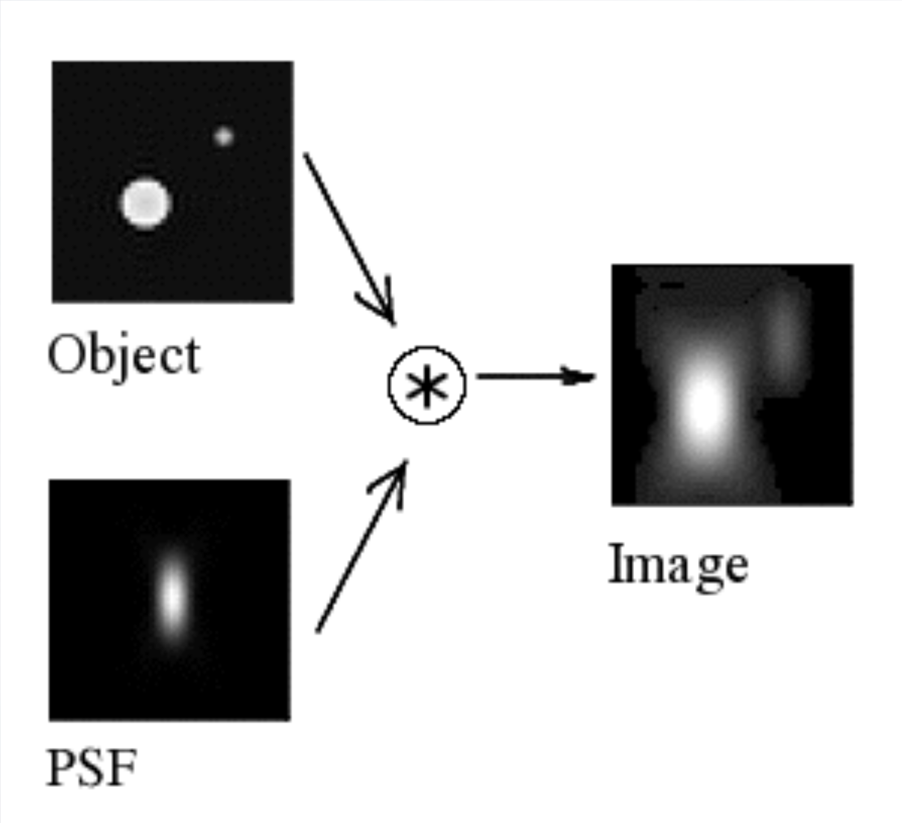


Image From WIkipedia

In this image on the top left you have the object to be imaged. Below is the system's response to a point source (in this case the system is a microscope). On the right there is the image obtained of the object by the system. Technically this is called the convolution of the PSF with the object.

CT EFFICIENCY

Charge Transfer efficiency is a measure of the charge that is successfully transferred per pixel. CTE values of 0.999995 are typical in modern CCDs.

The loss in charge from a pixel with N electrons that is shifted 1024 times vertically and 1024 horizontally is:

L(e)=N(1024*CTI(H)+1024*CTI(V)) or if only one CTE,

L(e)=2048*N*CTI (where CTI=1-CTE) and the I means inefficiency.

CCDs with limited CTE will show tails when imaging bright stars in the direction opposite to readout. The tails are charge left behind as the image is shifted out.

NOISE

There are three basic types of noise in a CCD: read noise, shot noise and fixed pattern noise (in Astronomy called r_n limited, s_n limited and flat field uncertainty).

Photon transfer curve: it is a plot of the log of the standard deviation of the signal (y) vs the log of the signal itself (x).

The Read Noise is the noise totally independent from the signal. i.e. Getting a reading in the CCD without any input from outside gives the r_n of the CCD. Above the read noise (i.e. upon illumination) shot noise adds a factor $\sqrt{N}$ where N is the # of photons.

Notice that if we assume QE=1 then the SNR is $\sqrt{N_{in}}$.

For large signal values, pixel to pixel variations dominate. This noise is proportional to the signal.

READ NOISE

Read noise is made out of the conversion of Analog to Digital (A/D) and also of rogue electrons introduced by the CCD electronics.

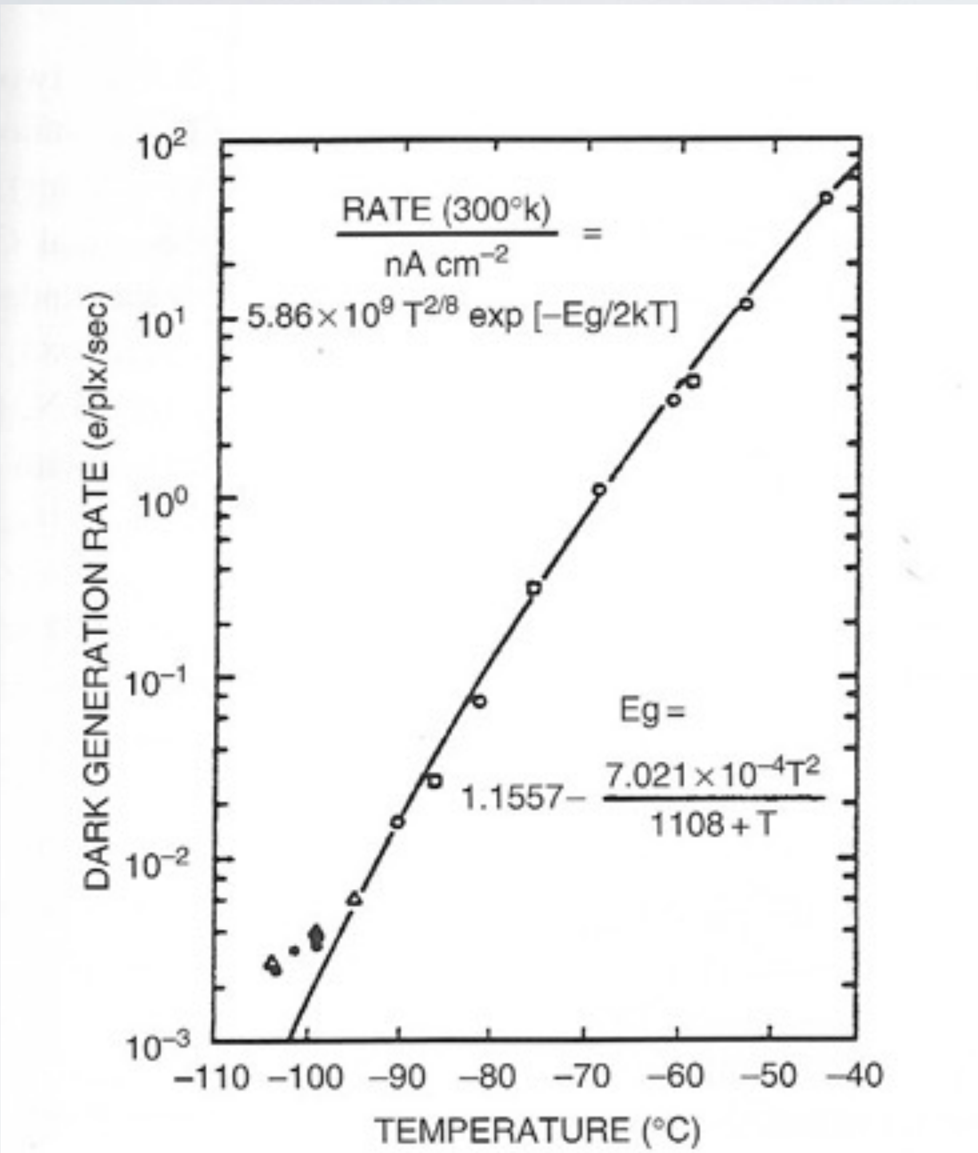
The one σ average of the total uncertainty combined is the read noise. σ

Modern CCDs have very low read noise.

The effect of the rn is added every time the CCD "reads". Co-addition of images for high rn CCDs is not useful. First CCDs had rn of up to 500 or more e^- p/pixel. Nowadays they are down to 20 or less.

DARK CURRENT

Thermal activity could be responsible for electrons freed from the valence band. If high enough electrons will free out of the valence band and get collected inside a pixel. When the CCD is readout these e⁻ become part of the signal: they are called dark current.



The plot to the left (from Howell) show the behavior with temperature of a CCD. The dark current is given in e p/ pixel p/second. Eg is the band gap energy for Si. The RATE given on the left upper corner is the theoretical one (dark curve). Plotted are also the experimental values. Dark current are kept at low levels lowering the temperature. Many CCDS use thermoelectric effect for cooling instead of expensive N or He.

PIXEL SIZE FULL WELL CAPACITY

The amount of charge a pixel can hold is called Full Well Capacity. There are CCDs with up to a million electrons FWC. During the readout process each row is shifted into the output register. Each time a pixel is readout its read noise is added. To reduce this a technique called **binning** is utilized: reading several pixels at once either in the vertical or horizontal direction. The binning consists in adding the charge of several pixels at once during the readout. Nowadays binning appear many times as a software option for certain CCDs. A binning of 2x2 means four adjacent pixels are readout at once. Binning decreases resolution but also read noise. Spectroscopic observations use many times 3x1 binning.

Windowing is a similar technique: a rectangular region of the CCD is selected for readout. They can be used combined.

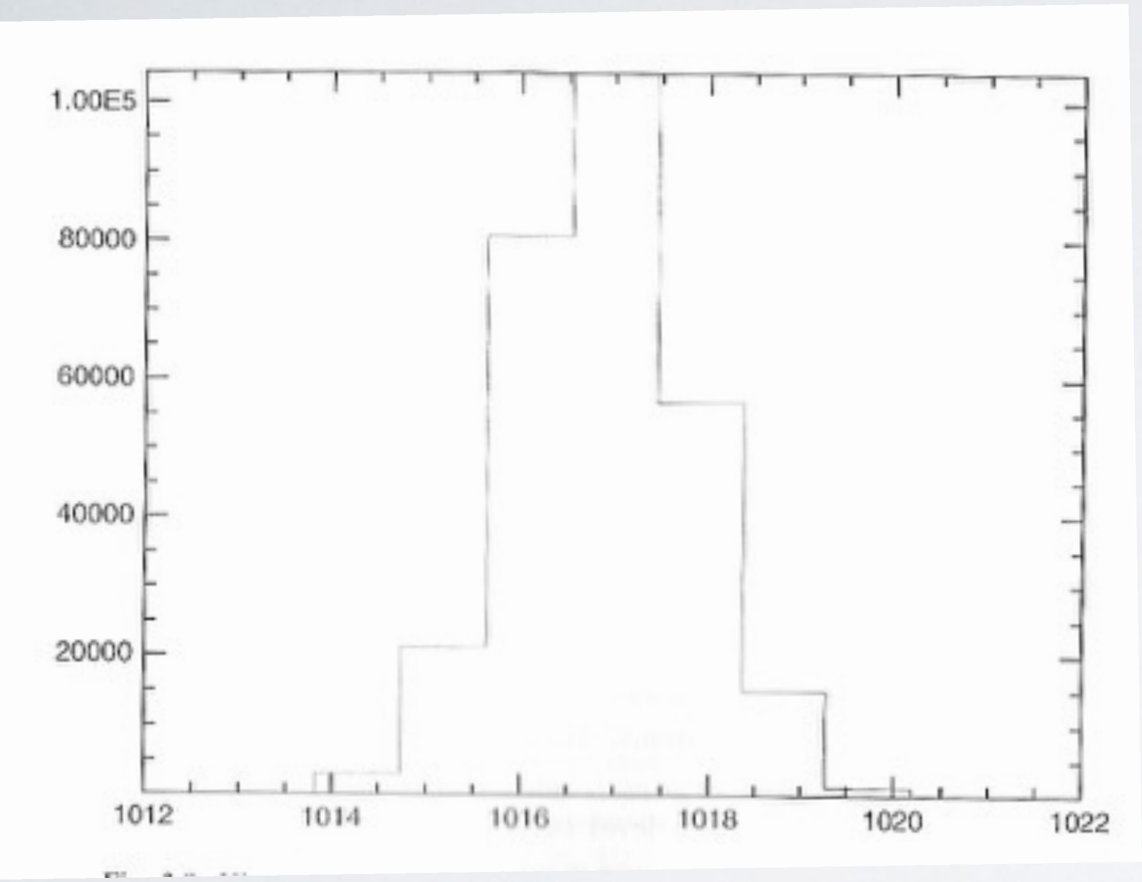
OVERSCAN AND BIAS

Bias images allow the measurement of the noise level of a CCD with no signal present. Pixels will show after A/D conversion counts distributed more or less following Gaussian distribution. There are 2 ways of calibrating a CCD: 1) overscan regions, 2) bias frames. Overscan strips are rows or columns added and stored with each image frame. These are additional clock cycles sent to the output electronics creating "pseudo-pixels". Bias frames are taken by observing with the shutter closed for an integration time of 0.000 seconds. The 2-dimensional image produced is called the bias.

Sometimes it's better to take 10 scans of the bias and average them. This may eliminate cosmic rays, radioactivity, read noise and other random fluctuations.

BIAS PLOT

A histogram of the bias frame for a given CCD (from Howell) is shown in the picture. The CCD has read noise of 10 e^- and a gain of 4.7 e^-/ADU.

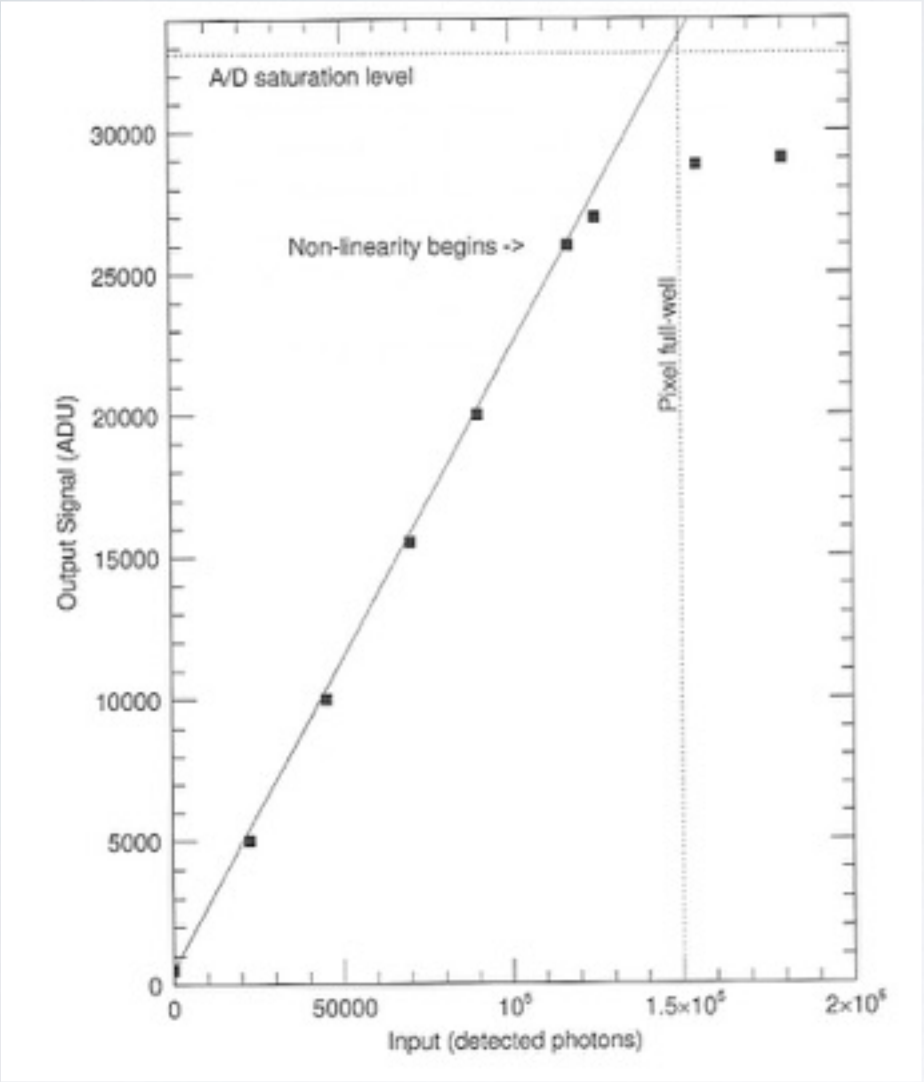


The width of the distribution is related to the read noise and the device gain by:

$$\sigma_{ADU} = \frac{rn}{gain}$$

The mean bias level in this CCD is 1017 counts and the **σ** is the width (Full width at Half maximum, FWHM) not the regularly defined **σ** of the gaussian distribution. On the vertical axis the units are number of pixels measure against ADUs.

CCD GAIN, DYNAMIC RANGE



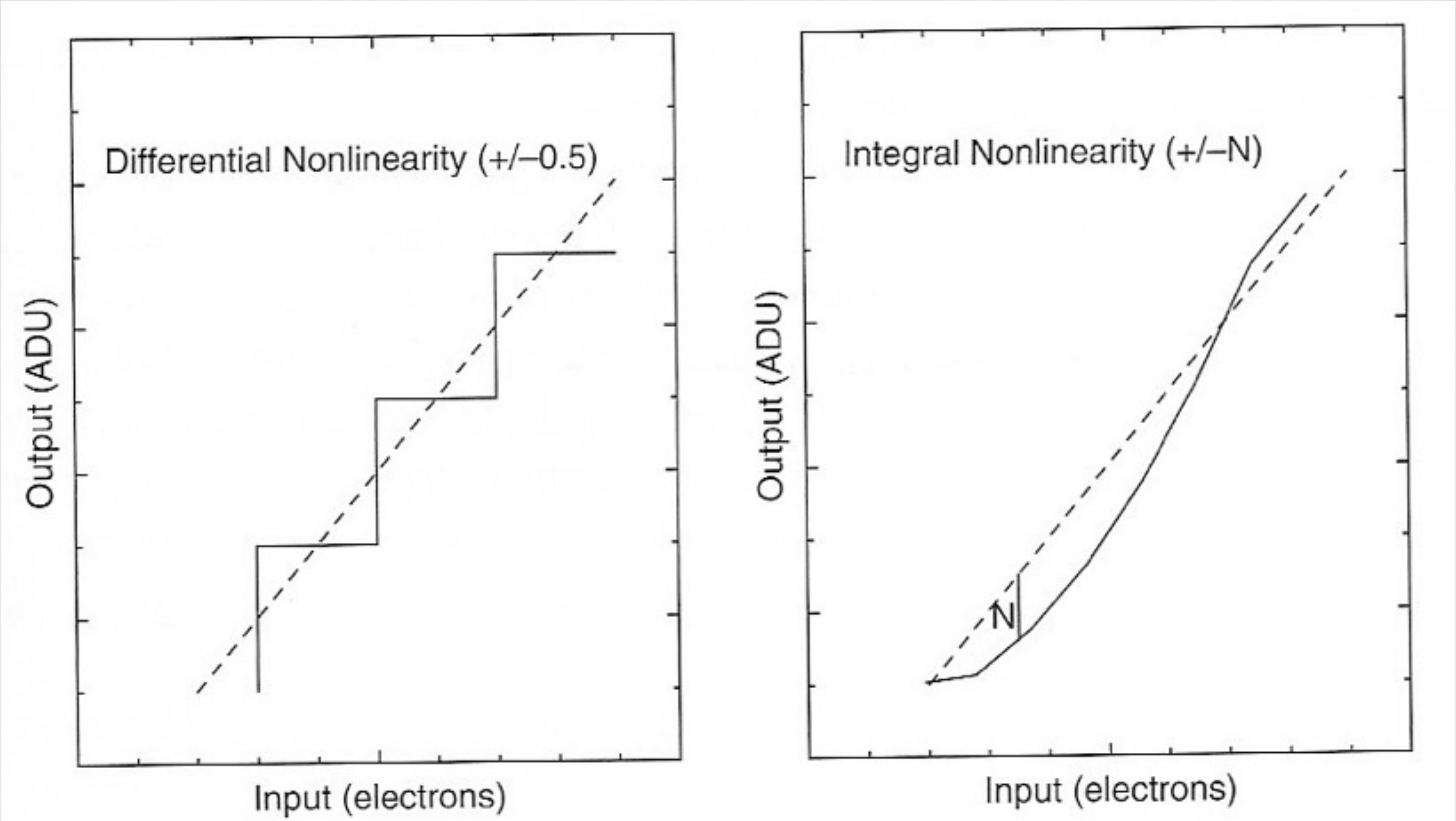
The gain of the CCD is determined by the output electronics. It sets how to assign an ADU to the charge collected. Given as electrons needed to produce 1 ADU. CCDS are more or less lineal in response. In the curve on the left a CCD's response with a 15-bit/ADU converter (0-32767 ADUs possible) is plotted. On the horizontal axis detected photons are represented and ADUs are counted on the vertical one.

From 500 to 20,00 + ADUs it's linear. Pixel FWC is 150,000 e^- and A/D converter can count up to 32767 ADU. The slope is the gain of the CCD.

NON LINEARITIES

The lowering of read noise and the improvements in CCD electronics have brought the possibility of bigger FWC pixels and a non linearity effect at higher ADUs.
There are two types of NL effects: integral NL and differential NL.
A/D converters provide a discrete conversion to the output DN (digital #). When extrapolating the response curve for a a CCD when smoothing out the discrete process, i.e. fractional counts of 20.1, 20.2 and even 20.49999 will give 20, while all the others above 20.5 up to 20.9999 will give 21. Sometimes this is also called digitization noise.
Integral NL is the maximum departure an A/D will produce at a given convert speed from the linear relationship.

DIFFERENTIAL AND INTEGRAL NON LINEARITIES



A CCD with an INL value of 16 LSB (least significant bits) means that the A/D has a departure from linearity of 4 bits (2^4). If the A/D is a 16 bit device and all are used bits 0-3 will contain any INL of the device.
This means that at a step that corresponds to the maximum deviation an uncertainty will occur. If the A/D has an INL of 16 LSB and the gain of the CCD is 4 electrons /ADU when the uncertainty is maximum up to a false count in excess or in shortage of 64 electrons will occur (see plot previous slide and the N marked at maximum deviation from linearity). Good devices will have INLs of less than 2 LSB.
It is crucial to know the linear range of the CCD and be aware of possible saturation. In addition to NL the other two factors that limits largest output pixel value are A/D saturation and saturation of the Full Well Capacity of a pixel.
The occurrence of these later two makes easier to avoid the NL regime of the CCD.

GAIN AND DYNAMIC RANGE

The dynamic range of a device is the total range over which it operates of for which it is sensitive.
It is customary to use decibels.

$$D(dB) = 20\times \log_{10}(\text{full well capacity/read noise})$$

i.e. a CCD with a FWC of 100,000 electrons and a read noise of 10 electrons would have a dynamic range of 80dB.
A more modern definition is

$$D=FWC/(\text{read noise})$$

HOMEWORK WEEK 3

1. ex 1 from chapter 3.10, Howell's book, 2nd ed. page 64.
2. ex 5 ibidem.
3. ex 7 ibidem.
4. ex 9 ibidem.
5. ex 13 ibidem, page 65.
6. ex 15 ibidem.
7. ex 18 ibidem.
8. Calculate the dynamic range for the CCD Apogee which is listed on slides 7 and 8 of Lesson I.

The specs sheets also list a dynamic range. Calculate the value according to the definition and compare with the Apogee listed estimate.