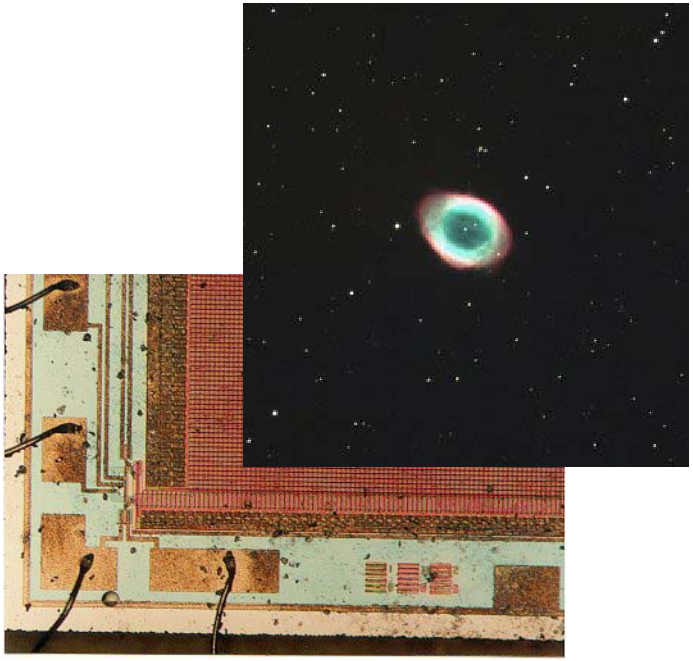
Introduction to CCDs.

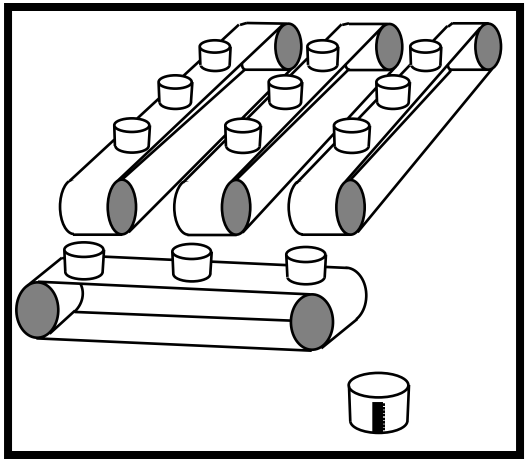
Thanks to Simon Tulloch smt@ing.iac.es



What is a CCD ?

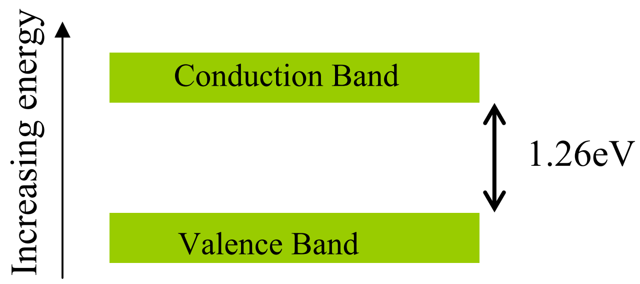
Charge Coupled Devices (CCDs) were invented in the 1970s and originally found application as memory devices. Their light sensitive properties were quickly exploited for imaging applications and they produced a major revolution in Astronomy. They improved the light gathering power of telescopes by almost two orders of magnitude. Nowadays an amateur astronomer with a CCD camera and a 15 cm telescope can collect as much light as an astronomer of the 1960s equipped with a photographic plate and a 1m telescope.

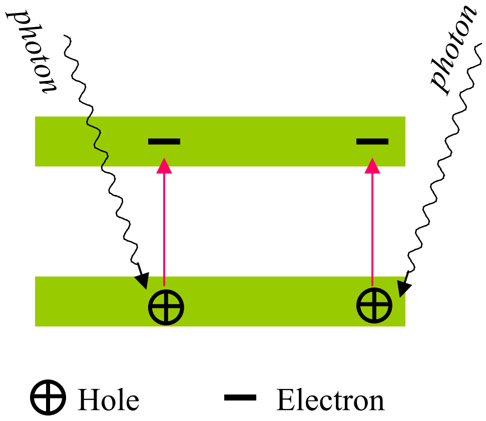
CCDs work by converting light into a pattern of electronic charge in a silicon chip. This pattern of charge is converted into a video waveform, digitised and stored as an image file on a computer.



Photoelectric Effect.

The effect is fundamental to the operation of a CCD. Atoms in a silicon crystal have electrons arranged in discrete energy bands. The lower energy band is called the Valence Band, the upper band is the Conduction Band. Most of the electrons occupy the Valence band but can be excited into the conduction band by heating or by the absorption of a photon. The energy required for this transition is 1.26 electron volts. Once in this conduction band the electron is free to move about in the lattice of the silicon crystal. It leaves behind a ‘hole’ in the valence band which acts like a positively charged carrier. In the absence of an external electric field the hole and electron will quickly re-combine and be lost. In a CCD an electric field is introduced to sweep these charge carriers apart and prevent recombination.





Thermally generated electrons are indistinguishable from photo-generated electrons . They constitute a noise source known as ‘Dark Current’ and it is important that CCDs are kept cold to reduce their number.

1.26eV corresponds to the energy of light with a wavelength of 1μm. Beyond this wavelength silicon becomes transparent and CCDs constructed from silicon become insensitive.

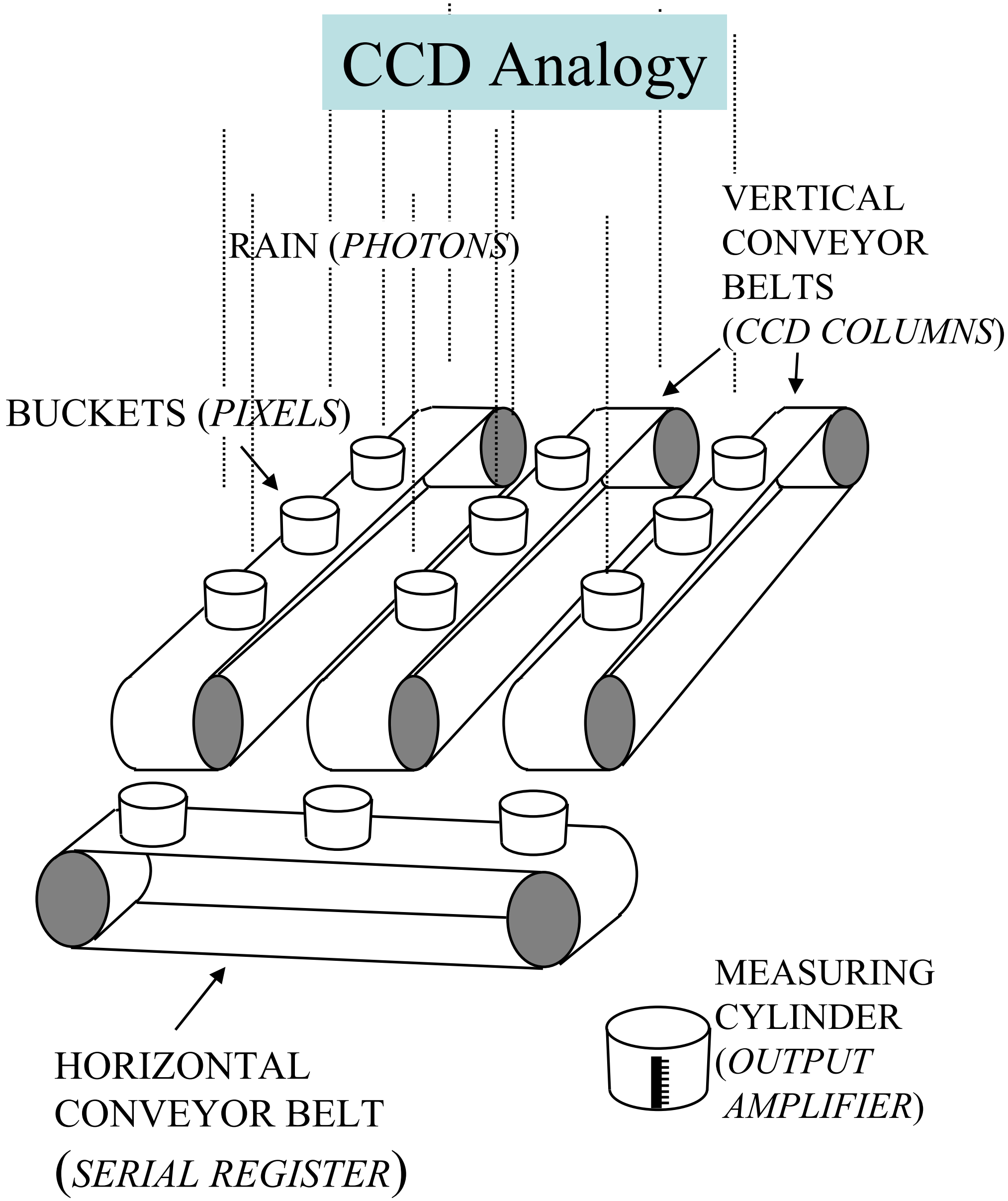
CCD Analogy

A common analogy for the operation of a CCD is as follows:

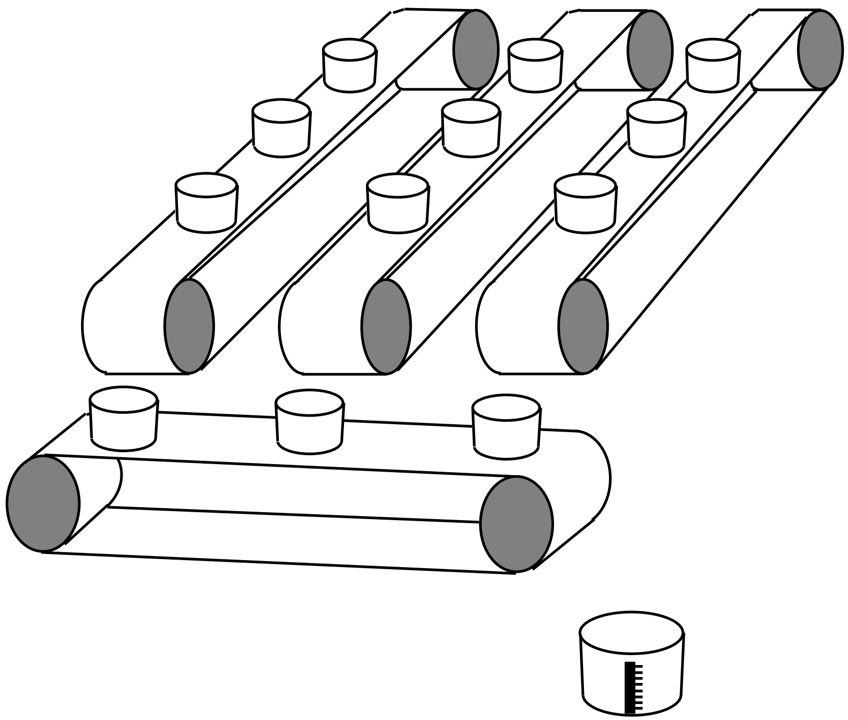
An number of buckets (Pixels) are distributed across a field (Focal Plane of a telescope) in a square array. The buckets are placed on top of a series of parallel conveyor belts and collect rain fall (Photons) across the field. The conveyor belts are initially stationary, while the rain slowly fills the buckets (During the course of the exposure). Once the rain stops (The camera shutter closes) the conveyor belts start turning and transfer the buckets of rain , one by one , to a measuring cylinder (Electronic Amplifier) at the corner of the field (at the corner of the CCD)

The animation in the following slides demonstrates how the conveyor belts work.

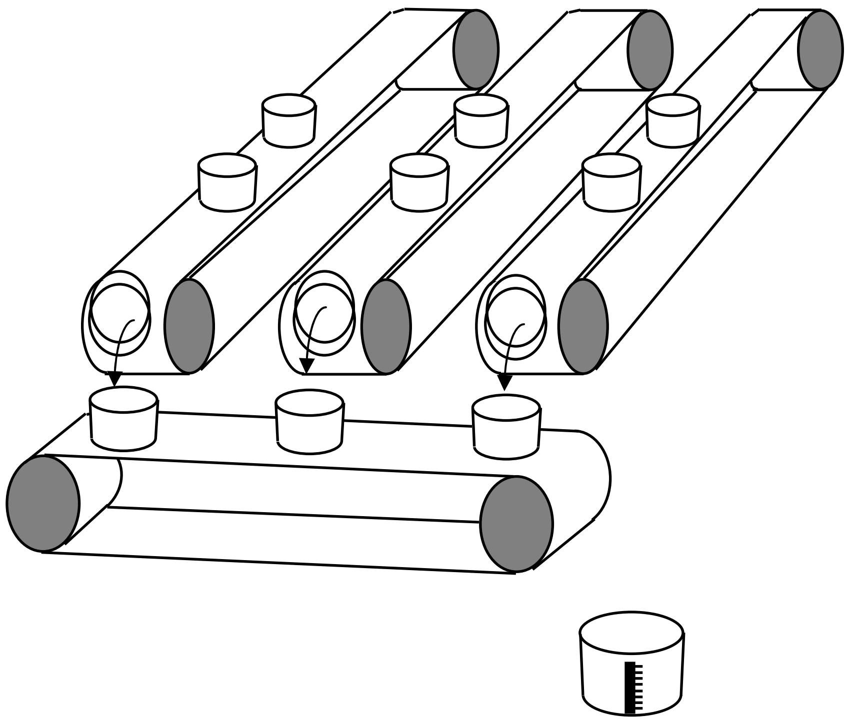
CCD Analogy


RAIN (*PHOTONS*)
VERTICAL CONVEYOR BELTS (*CCD COLUMNS*)
BUCKETS (*PIXELS*)
MEASURING CYLINDER (*OUTPUT AMPLIFIER*)
HORIZONTAL CONVEYOR BELT (*SERIAL REGISTER*)

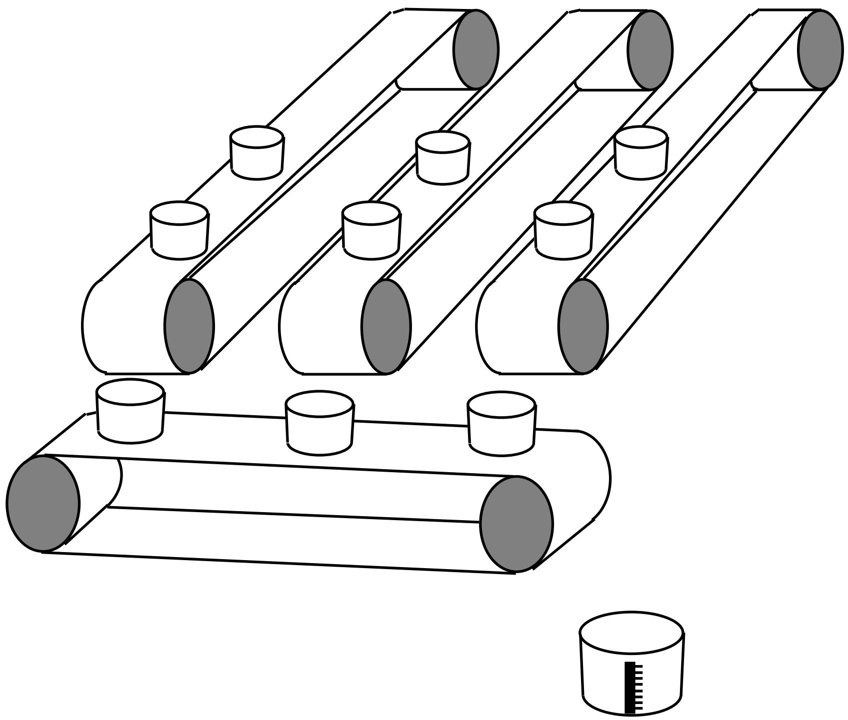
Exposure finished, buckets now contain samples of rain.



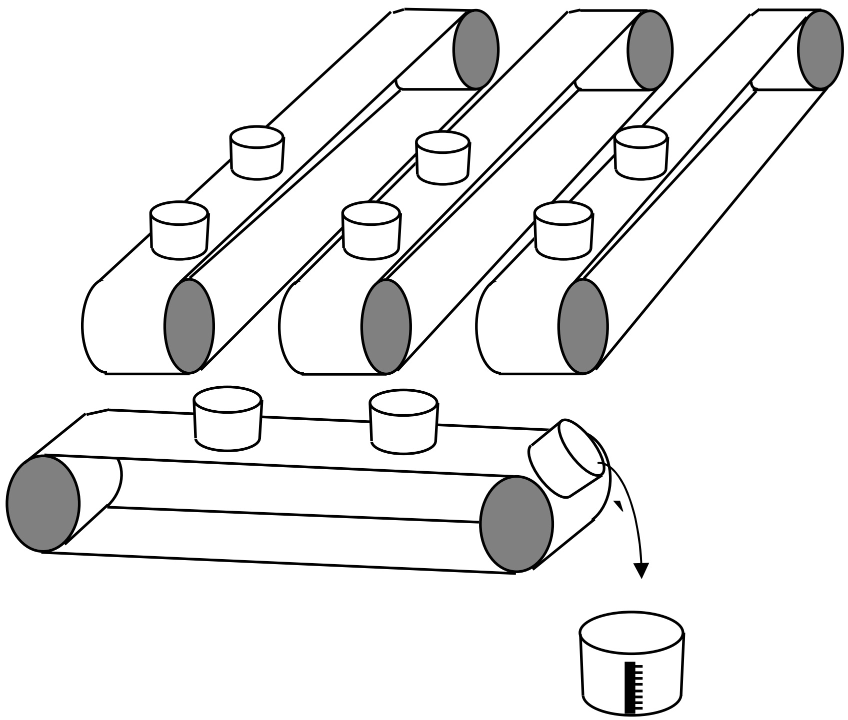
Conveyor belt starts turning and transfers buckets. Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.

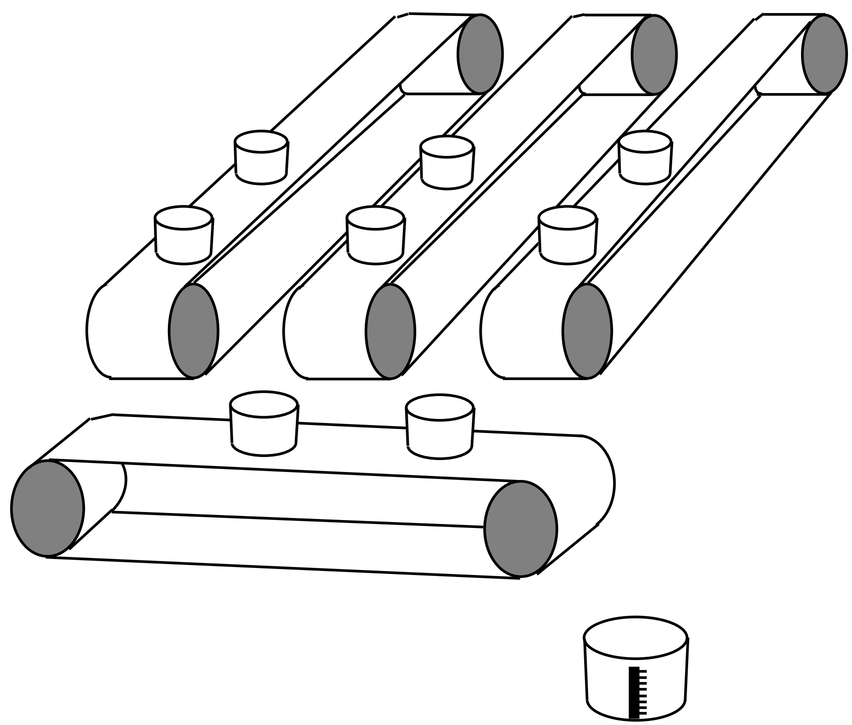


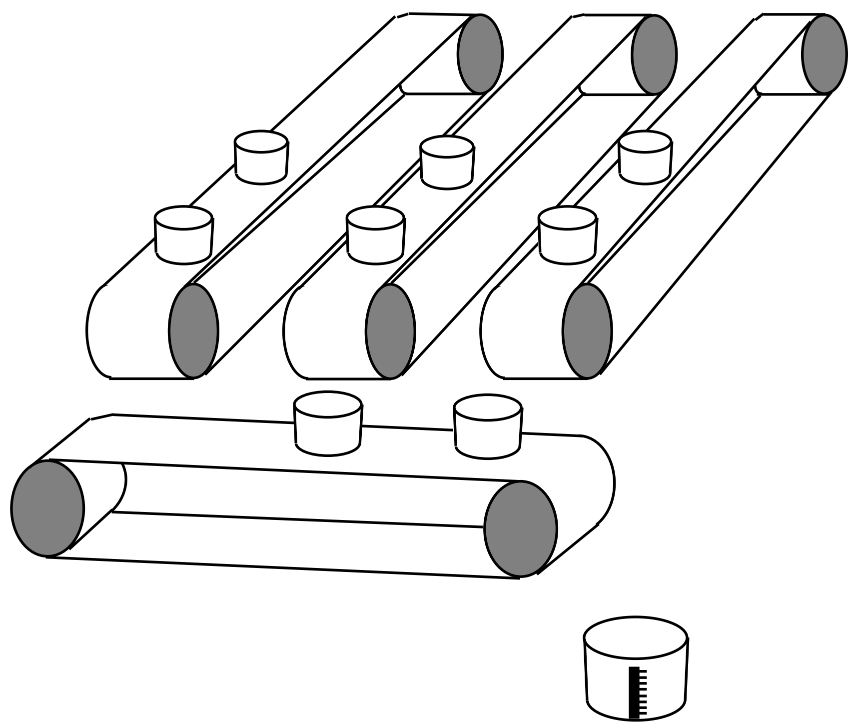
Vertical conveyor stops. Horizontal conveyor starts up and tips each bucket in turn into the measuring cylinder .

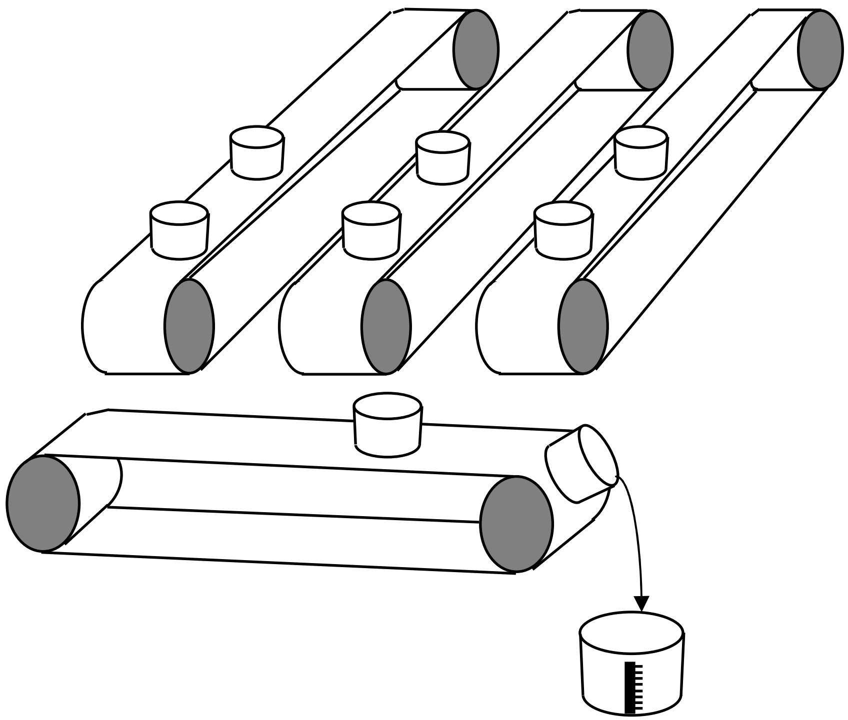


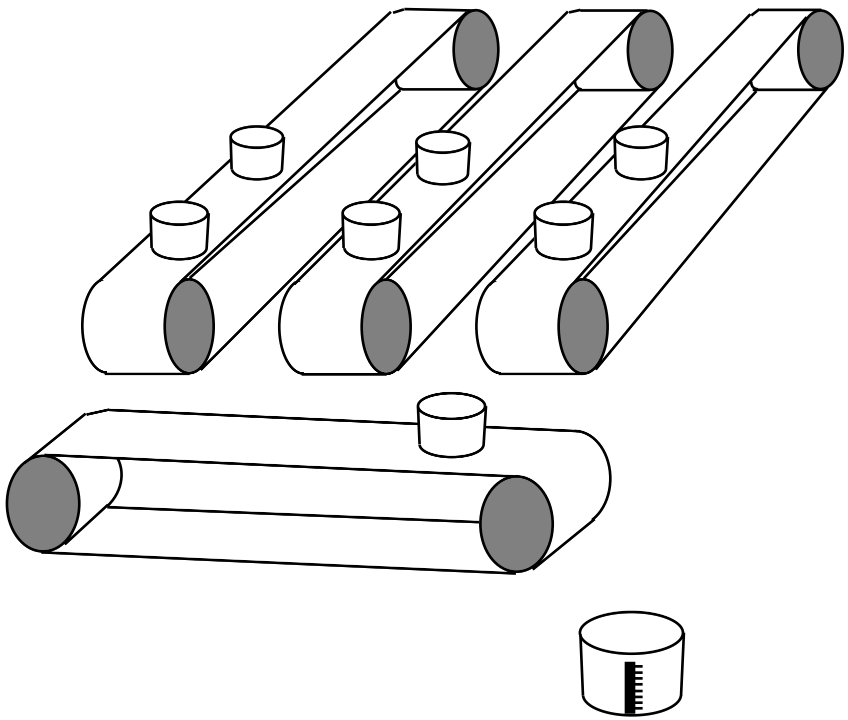
After each bucket has been measured, the measuring cylinder is emptied , ready for the next bucket load.

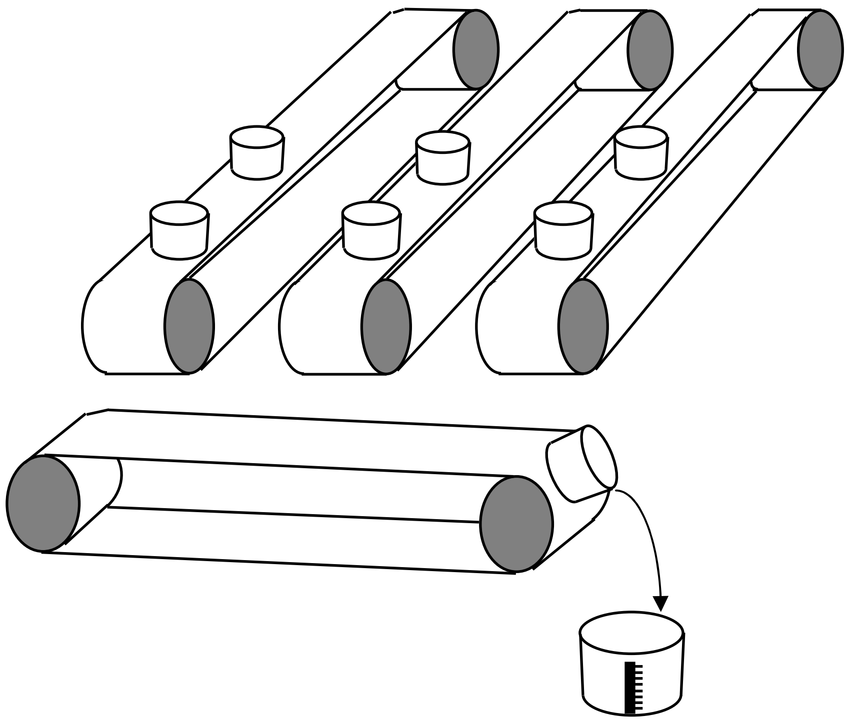


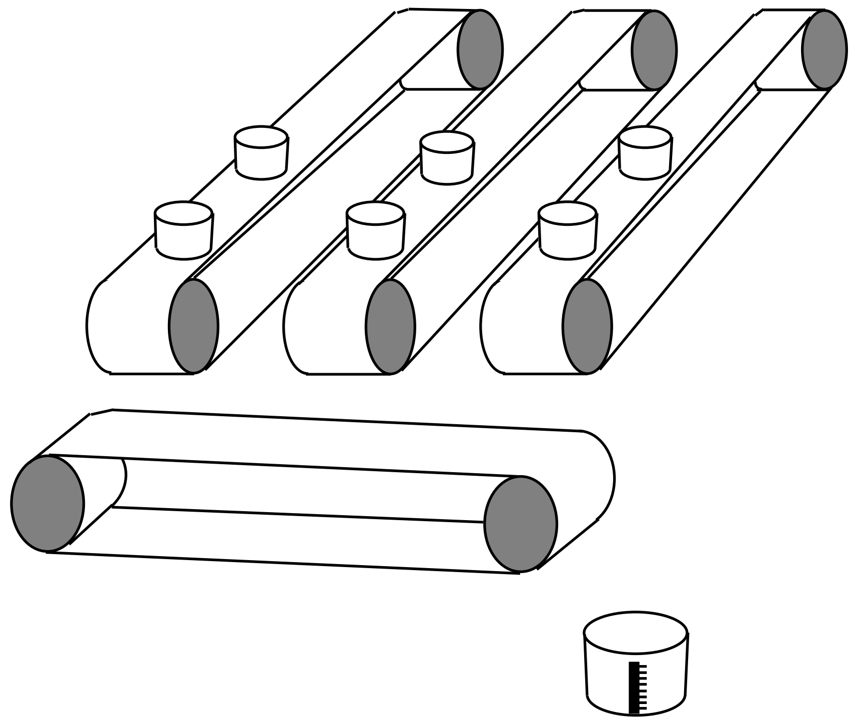




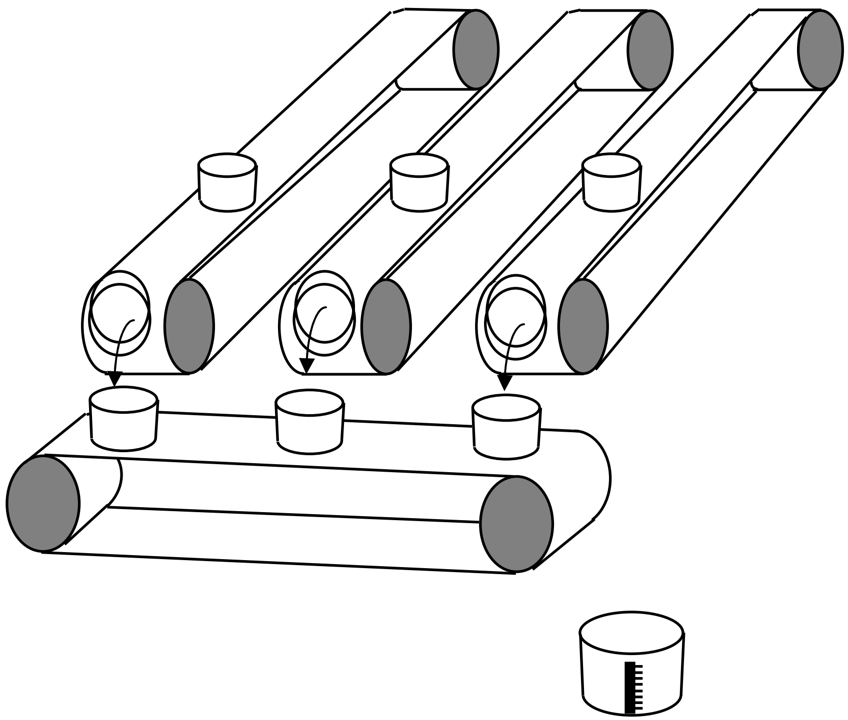


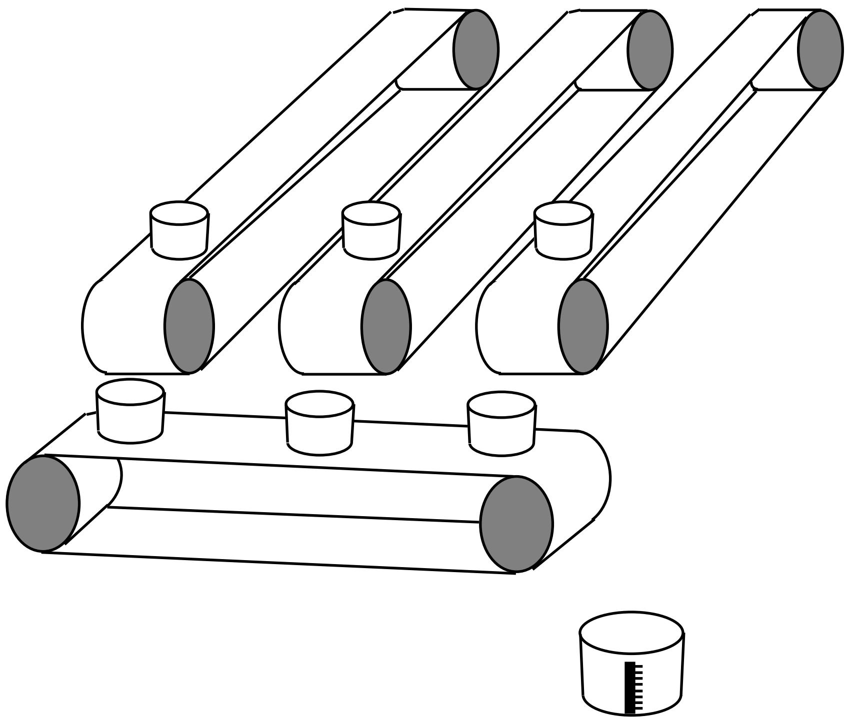


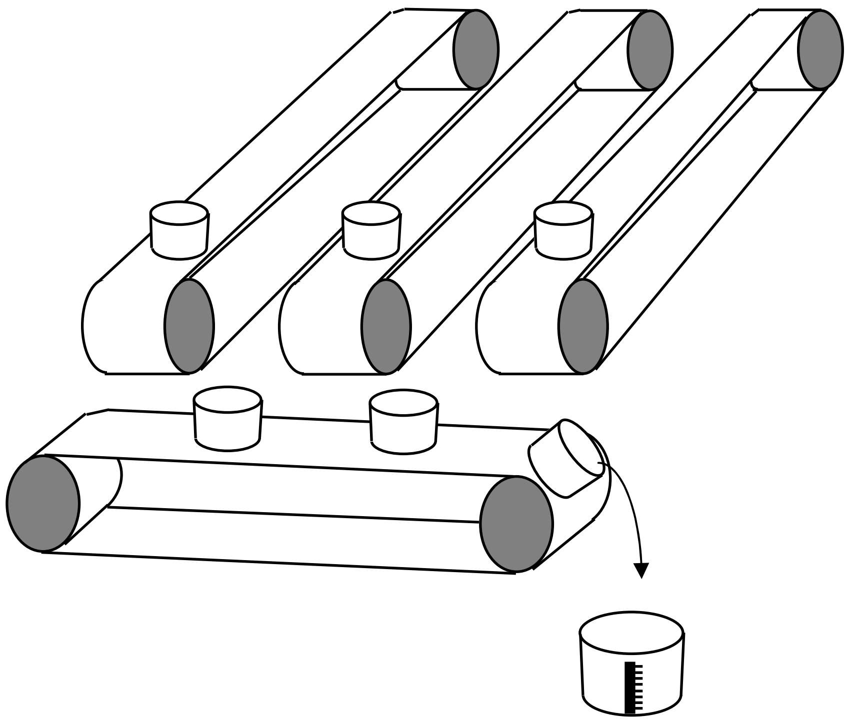


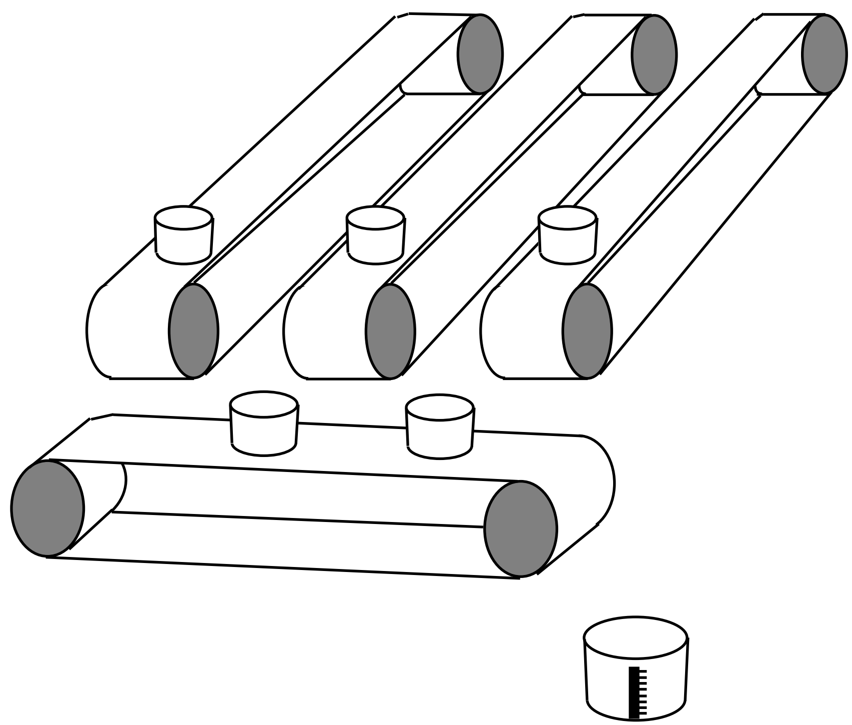


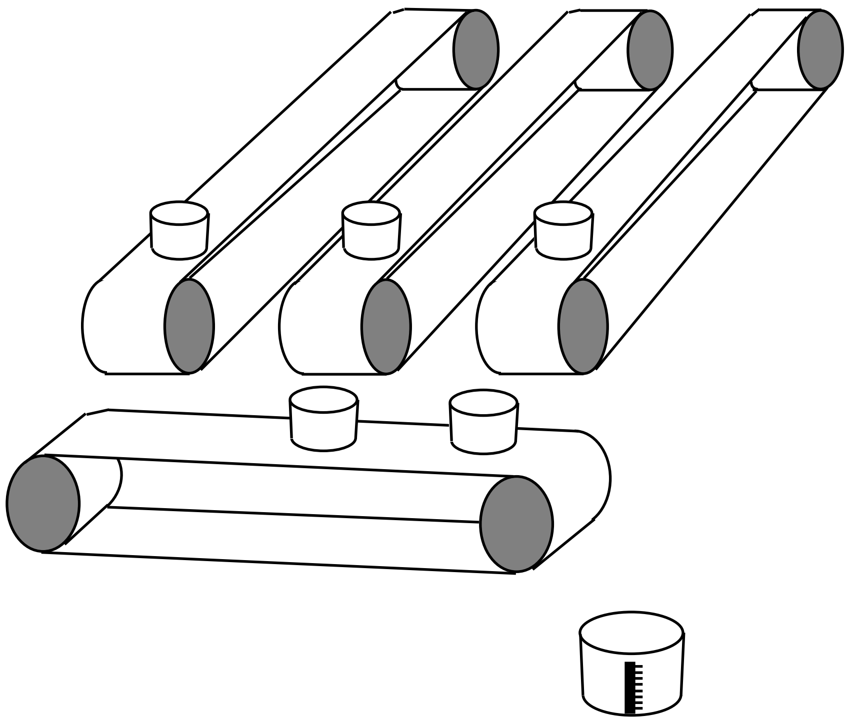
A new set of empty buckets is set up on the horizontal conveyor and the process is repeated.

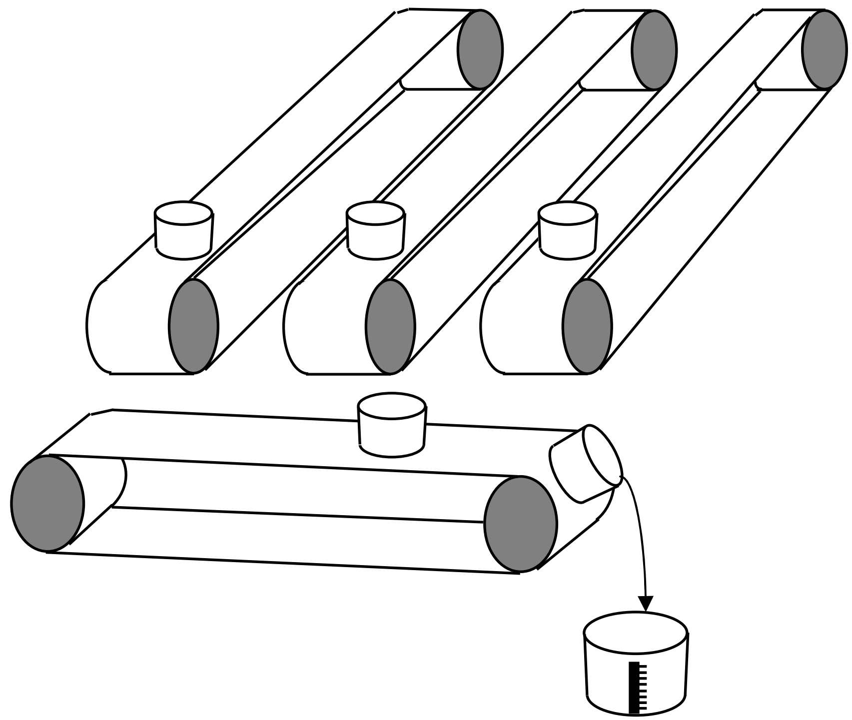


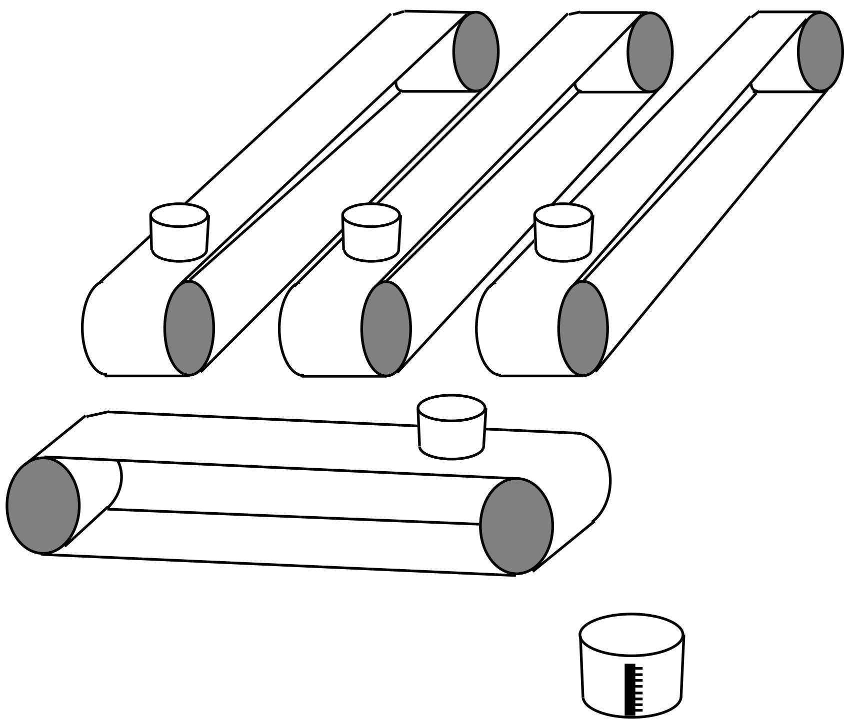


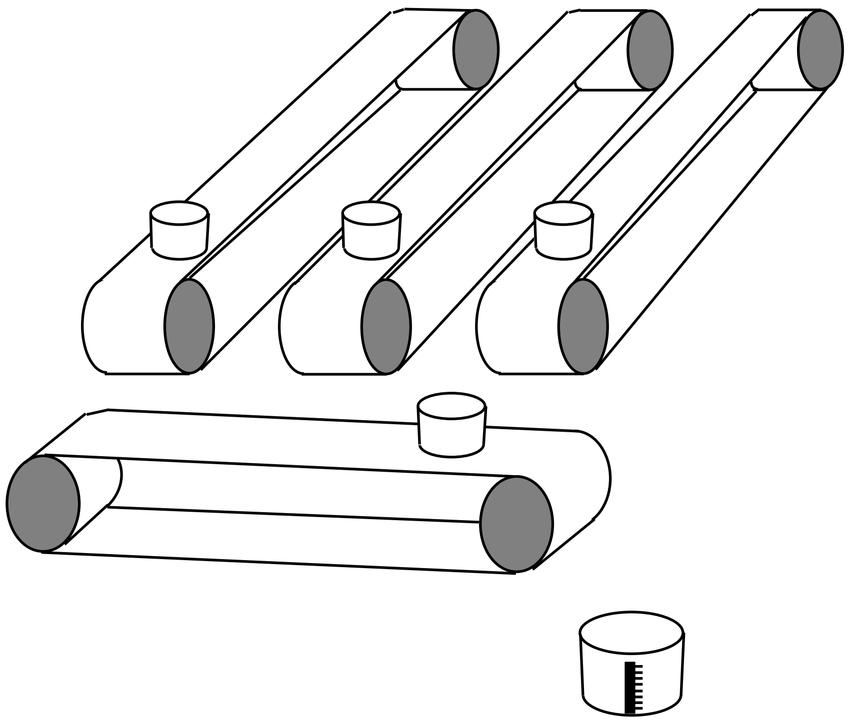


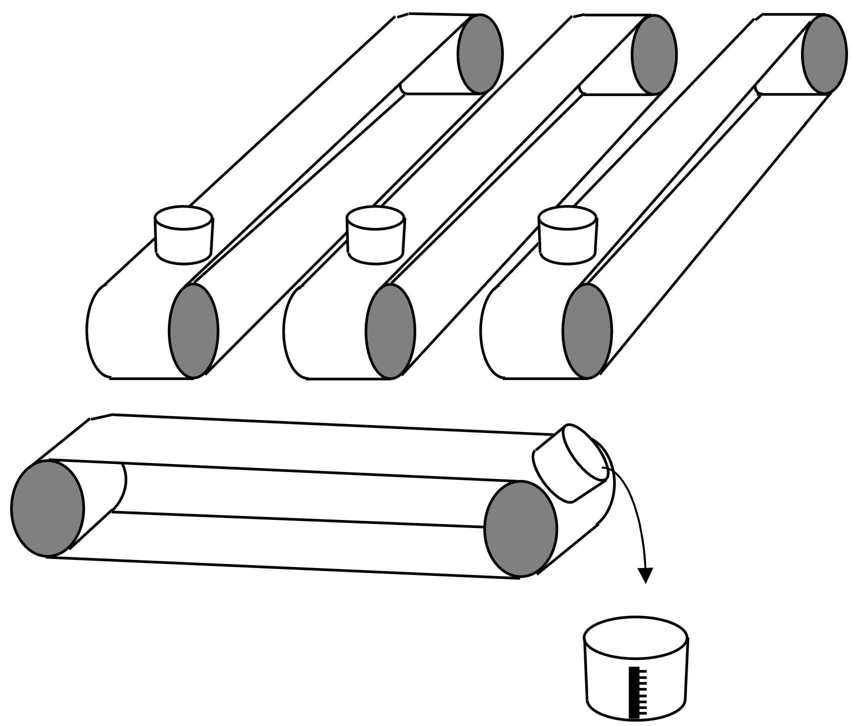


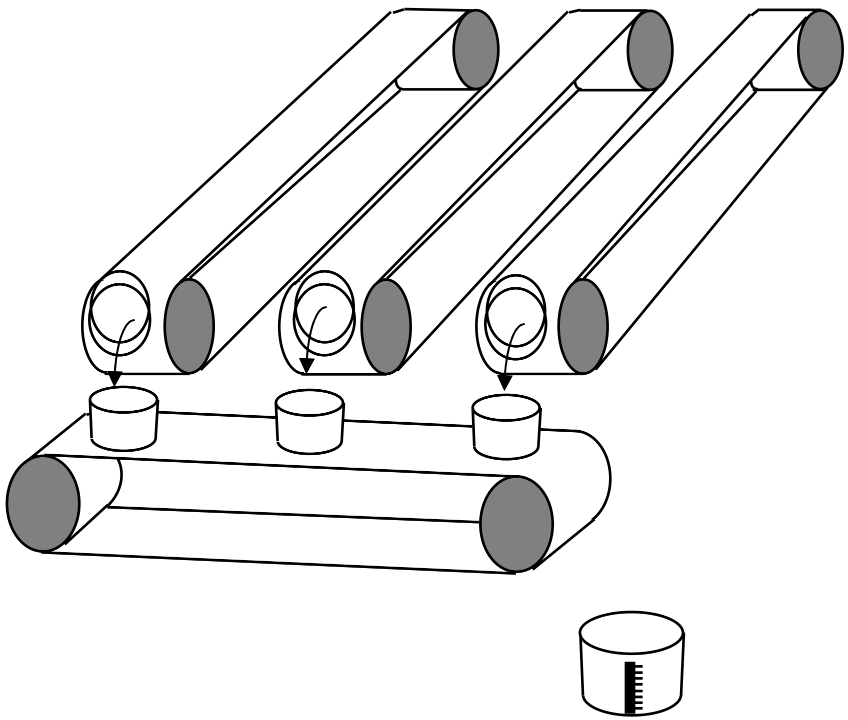


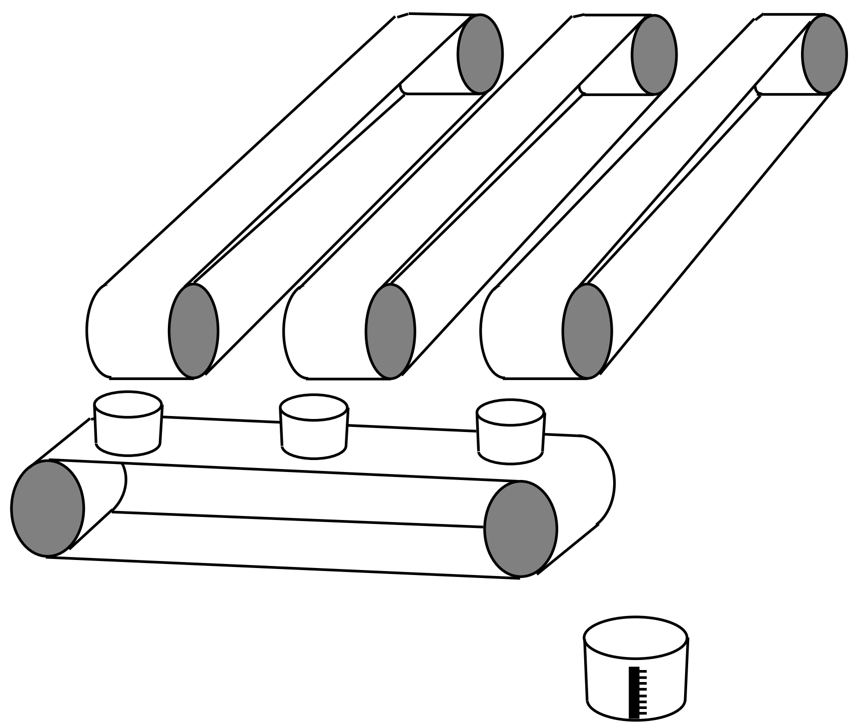


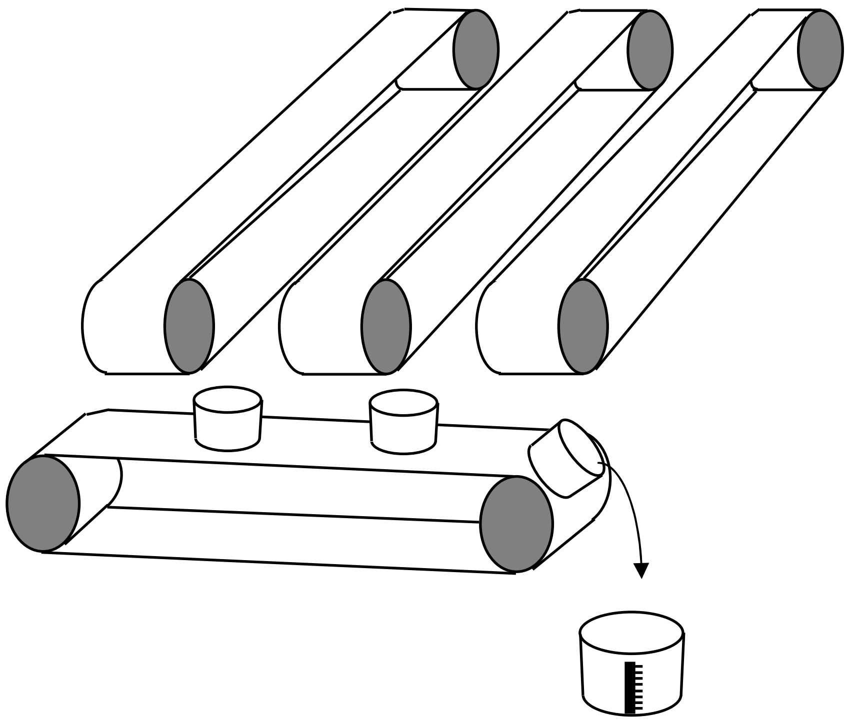


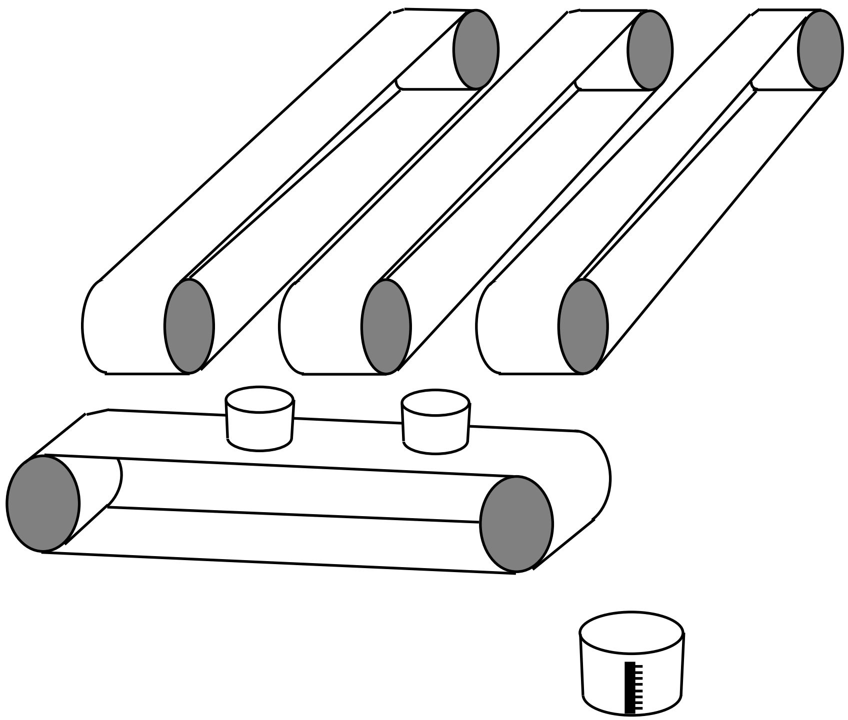


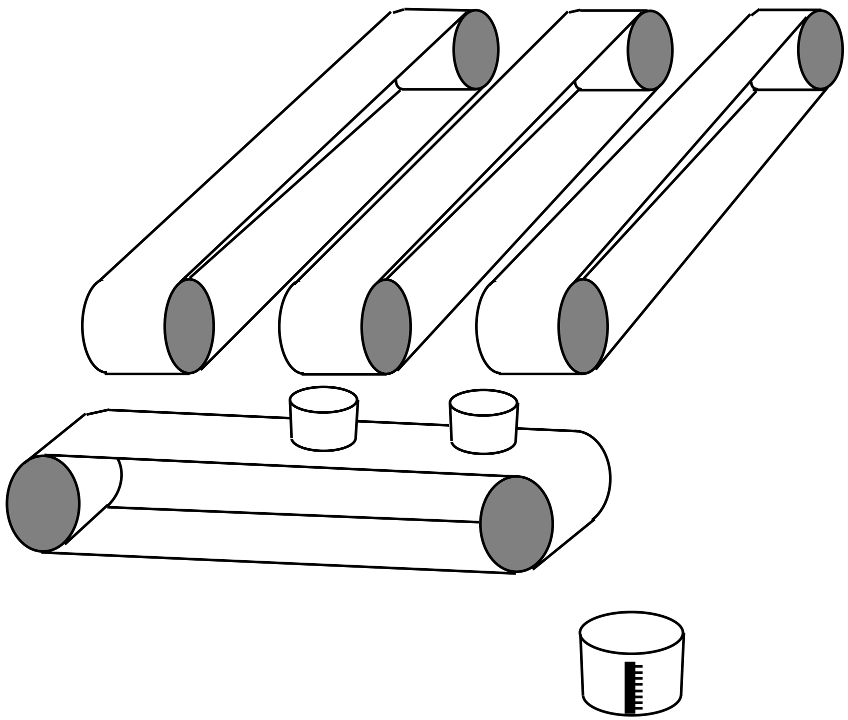


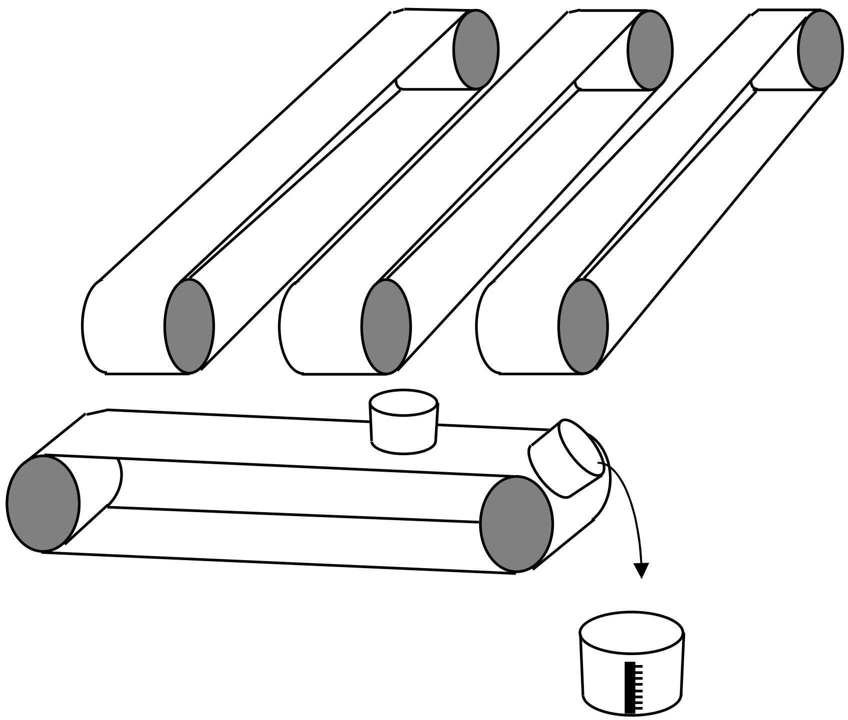


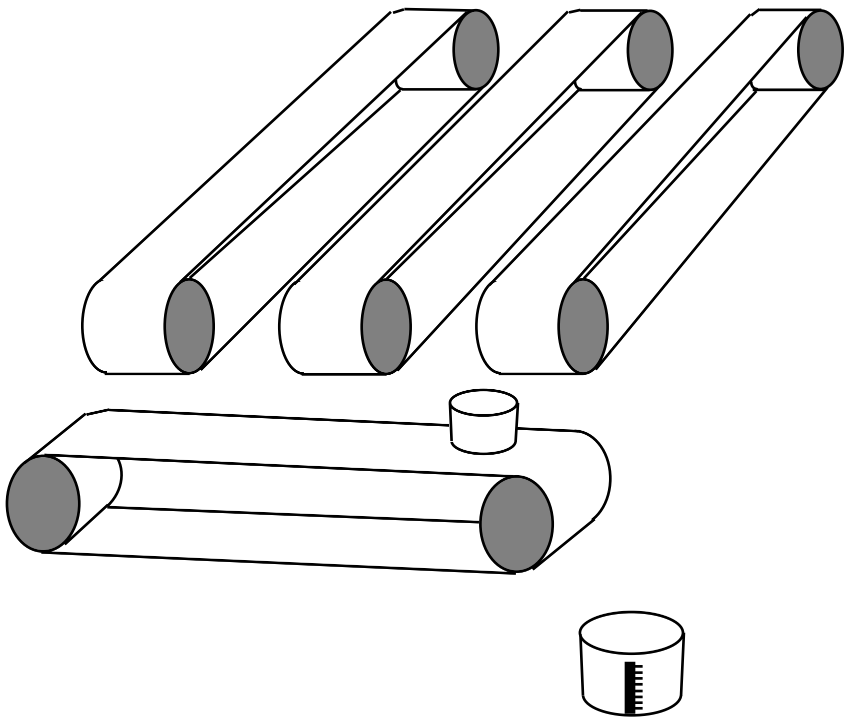


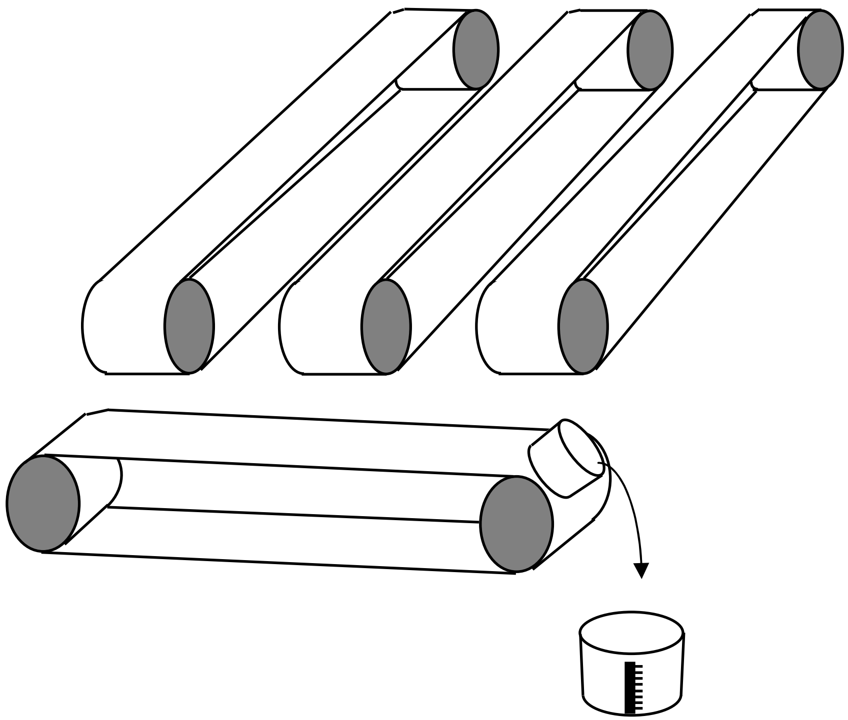




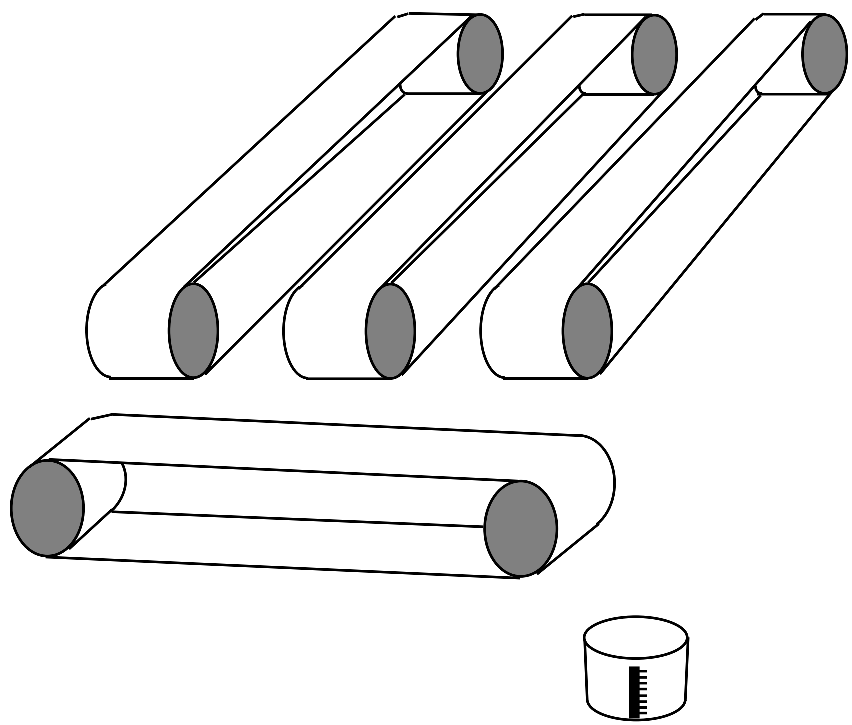






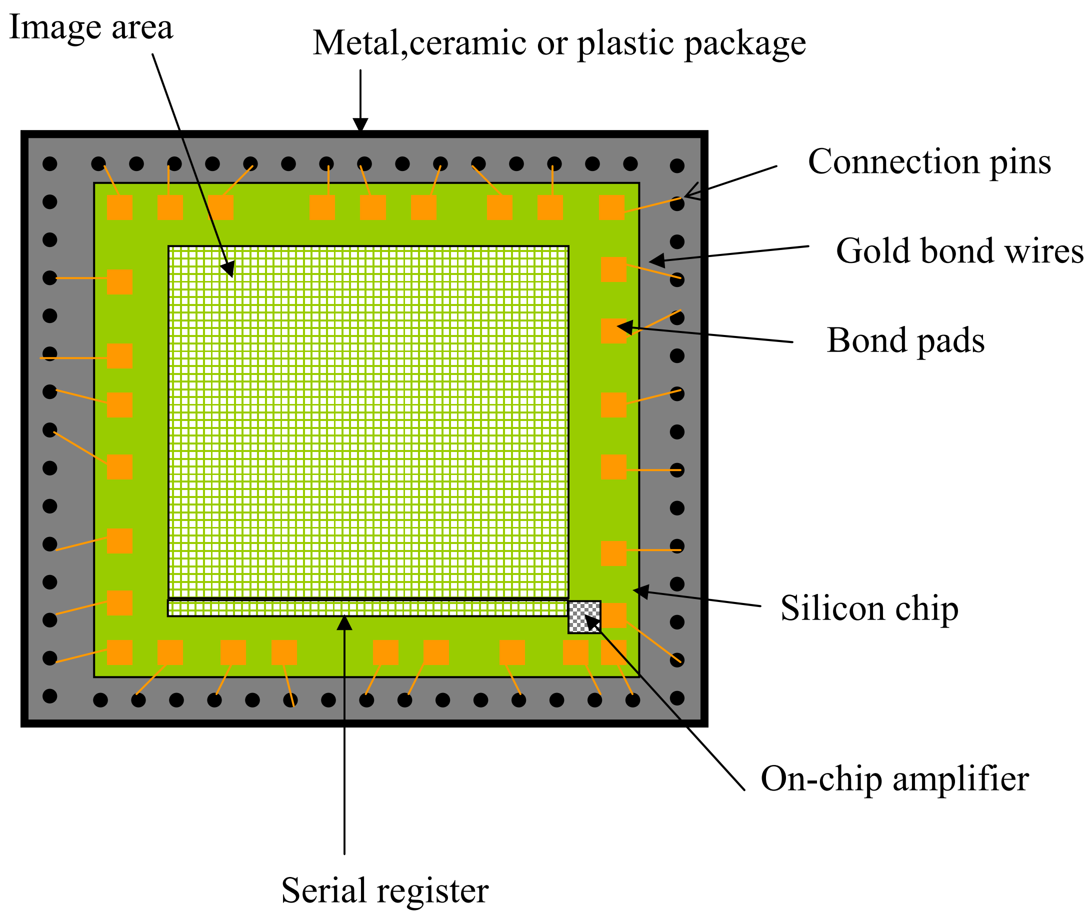


Eventually all the buckets have been measured, the CCD has been read out.



Structure of a CCD 1.

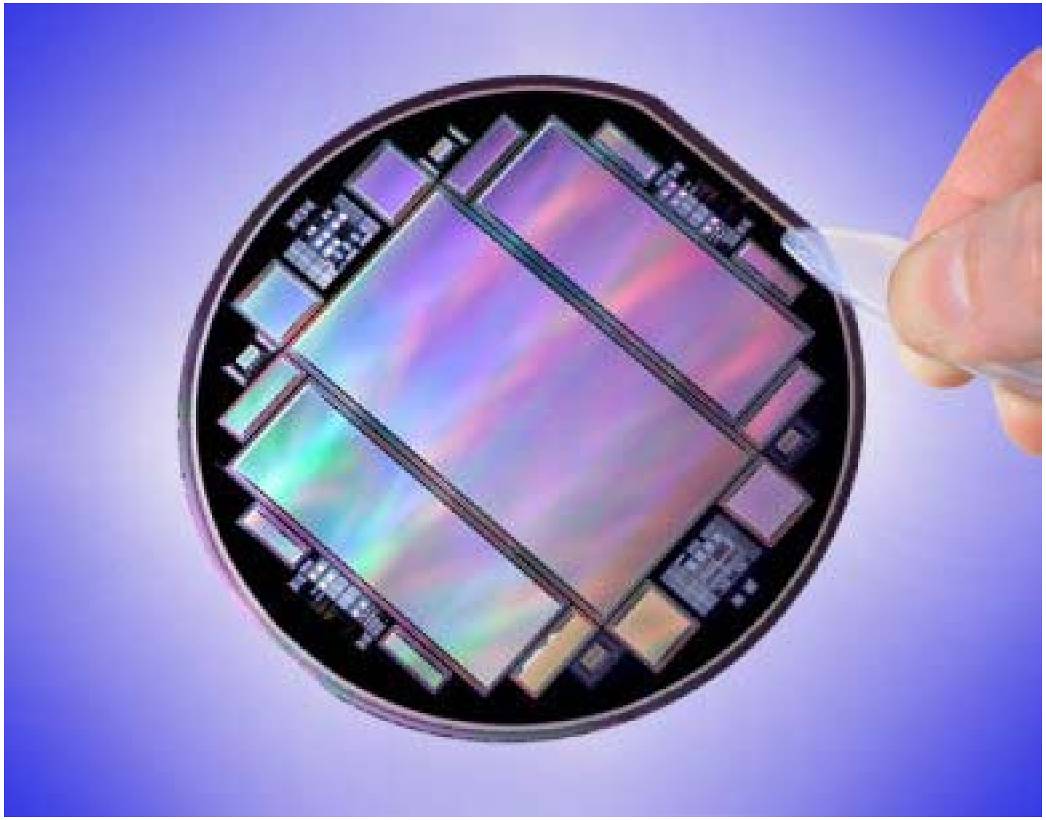
The image area of the CCD is positioned at the focal plane of the telescope. An image then builds up that consists of a pattern of electric charge. At the end of the exposure this pattern is then transferred, pixel at a time, by way of the serial register to the on-chip amplifier. Electrical connections are made to the outside world via a series of bond pads and thin gold wires positioned around the chip periphery.



Structure of a CCD 2.

CCDs are manufactured on silicon wafers using the same photo-lithographic techniques used to manufacture computer chips. Scientific CCDs are very big ,only a few can be fitted onto a wafer. This is one reason that they are so costly.

The photo below shows a silicon wafer with three large CCDs and assorted smaller devices. A CCD has been produced by Philips that fills an entire 6 inch wafer! It is the worlds largest integrated circuit.

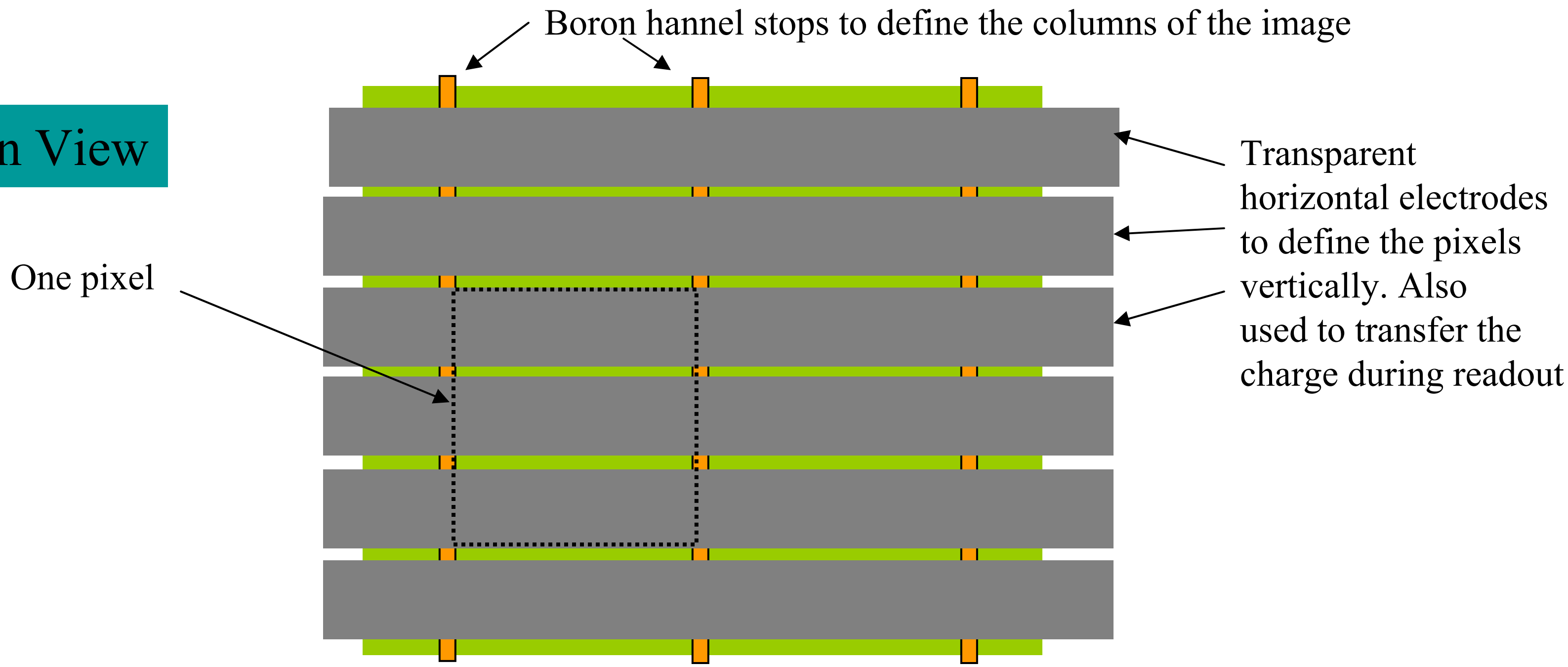


Don Groom LBNL

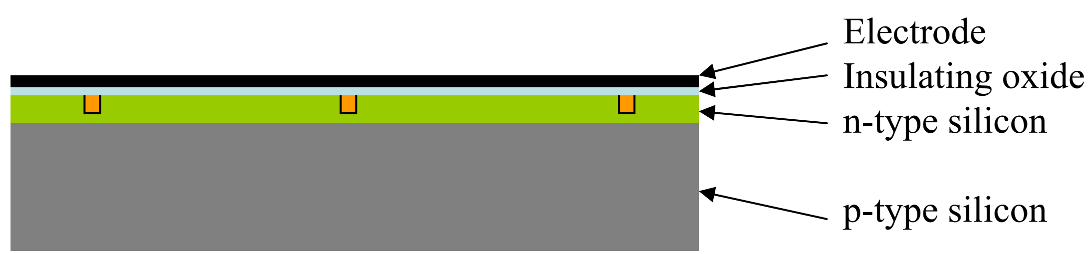
Structure of a CCD 3.

The diagram shows a small section (a few pixels) of the image area of a CCD. This pattern is reapeated.

Plan View



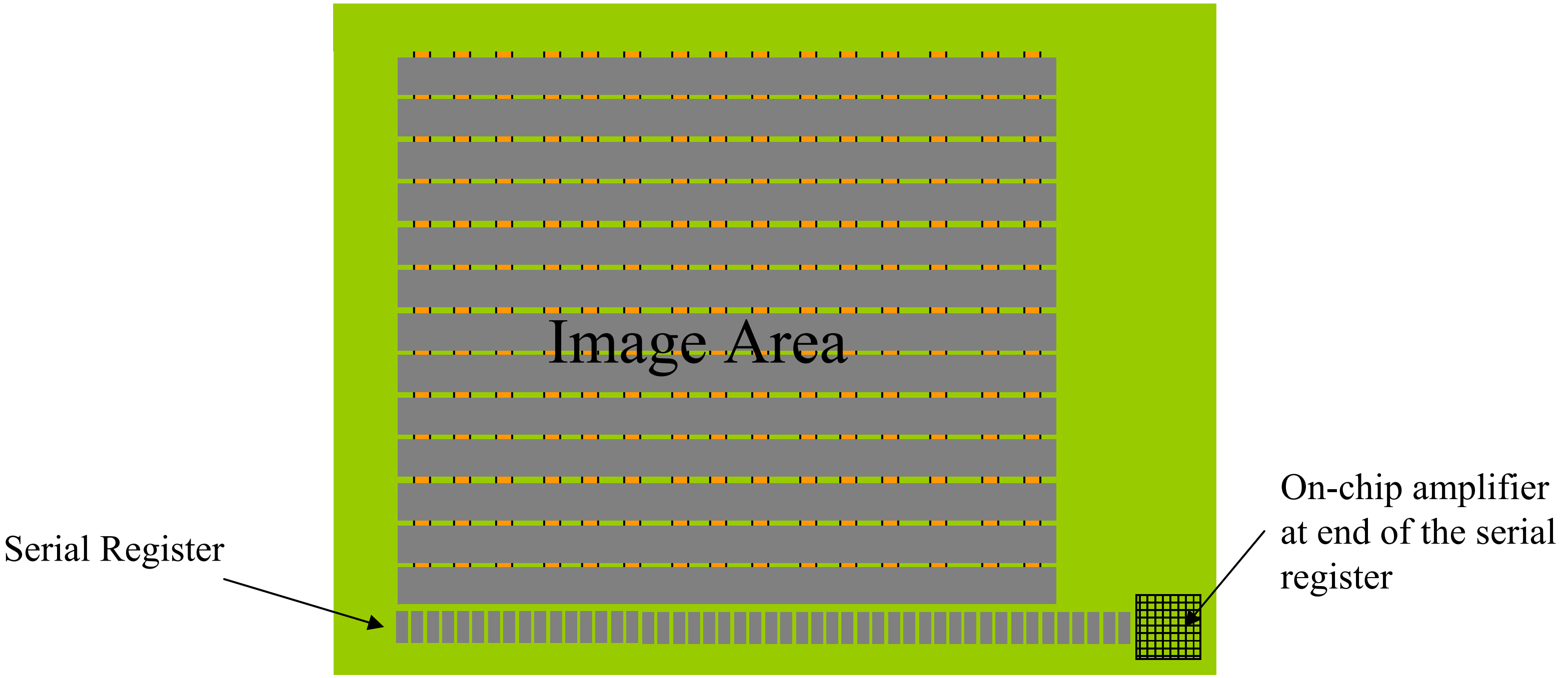
Cross section



Every third electrode is connected together. Bus wires running down the edge of the chip make the connection. The channel stops are formed from high concentrations of Boron in the silicon.

Structure of a CCD 4.

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

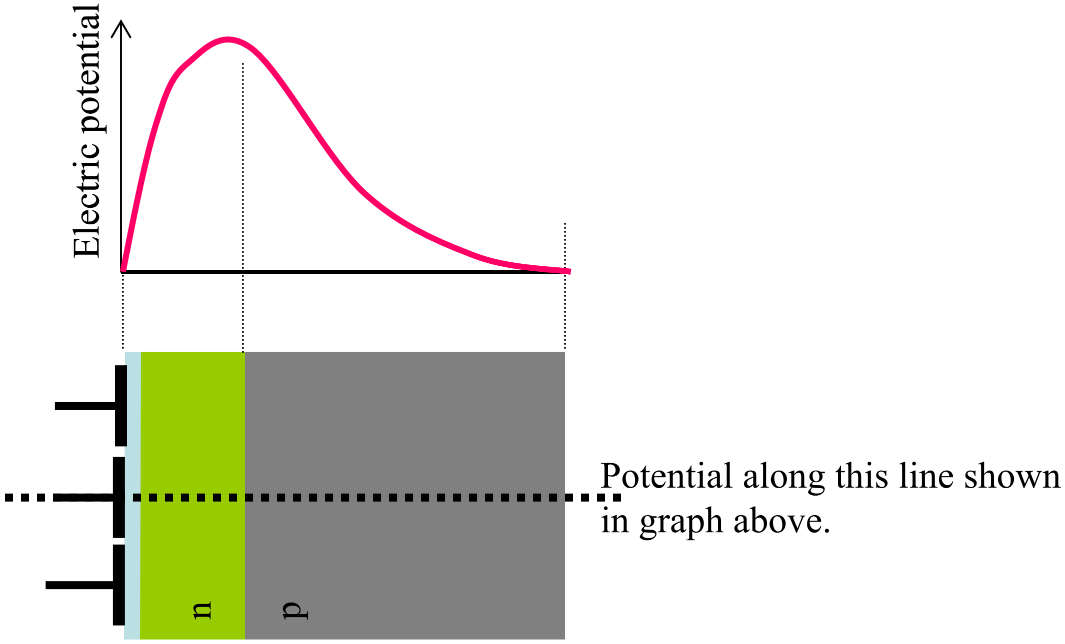


Cross section of serial register

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

Electric Field in a CCD 1.

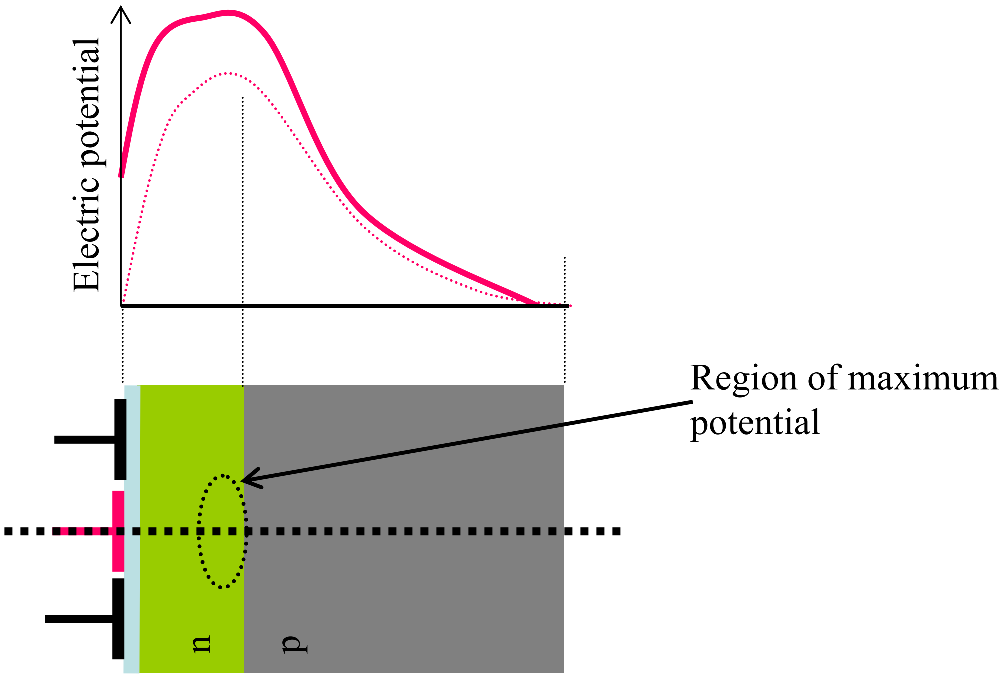
The n-type layer contains an excess of electrons that diffuse into the p-layer. The p-layer contains an excess of holes that diffuse into the n-layer. This structure is identical to that of a diode junction.
The diffusion creates a charge imbalance and induces an internal electric field. The electric potential reaches a maximum just inside the n-layer, and it is here that any photo-generated electrons will collect.
All science CCDs have this junction structure, known as a 'Buried Channel'. It has the advantage of keeping the photo-electrons confined away from the surface of the CCD where they could become trapped.
It also reduces the amount of thermally generated noise (dark current).



Cross section through the thickness of the CCD

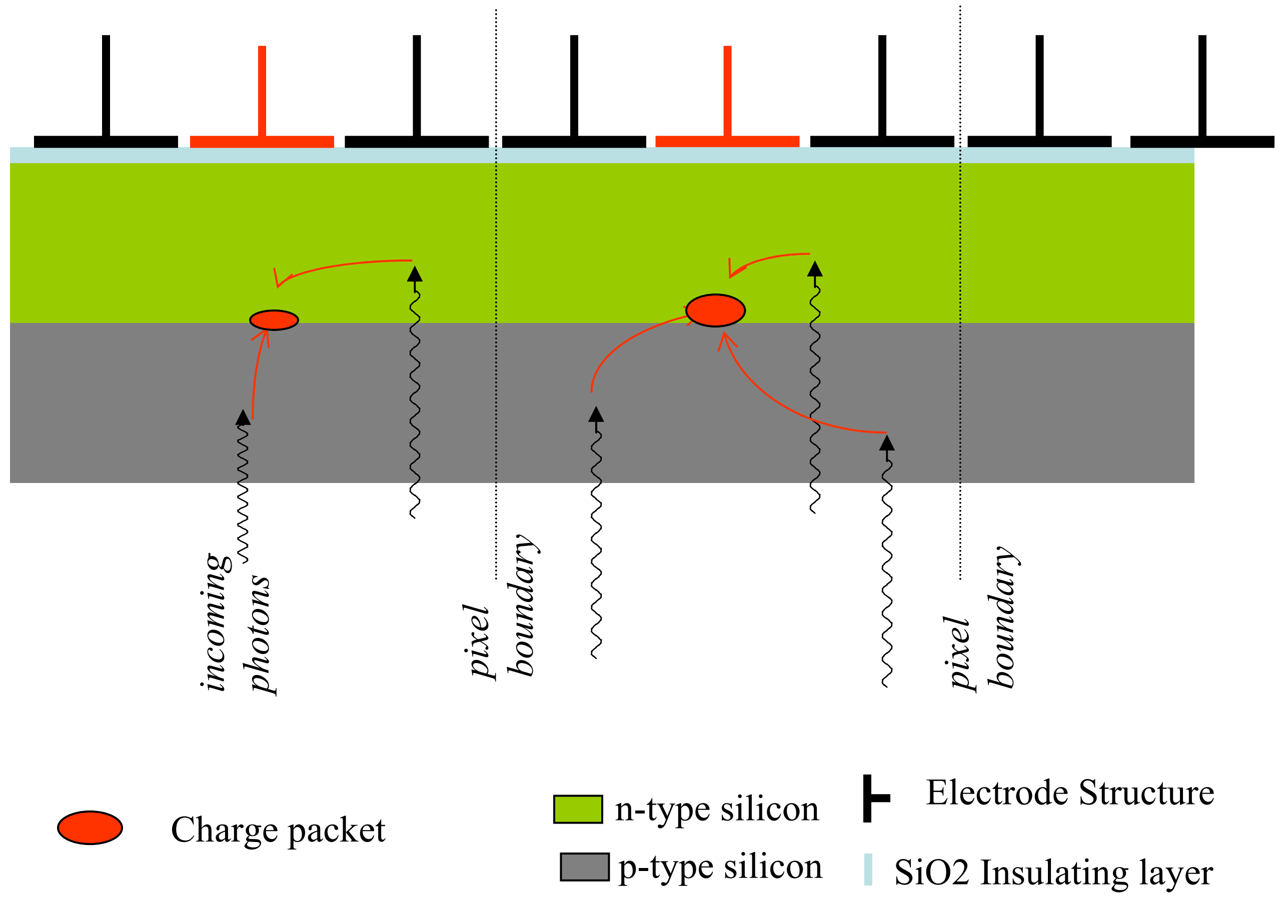
Electric Field in a CCD 2.

During integration of the image, one of the electrodes in each pixel is held at a positive potential. This further increases the potential in the silicon below that electrode and it is here that the photoelectrons are accumulated. The neighboring electrodes, with their lower potentials, act as potential barriers that define the vertical boundaries of the pixel. The horizontal boundaries are defined by the channel stops.



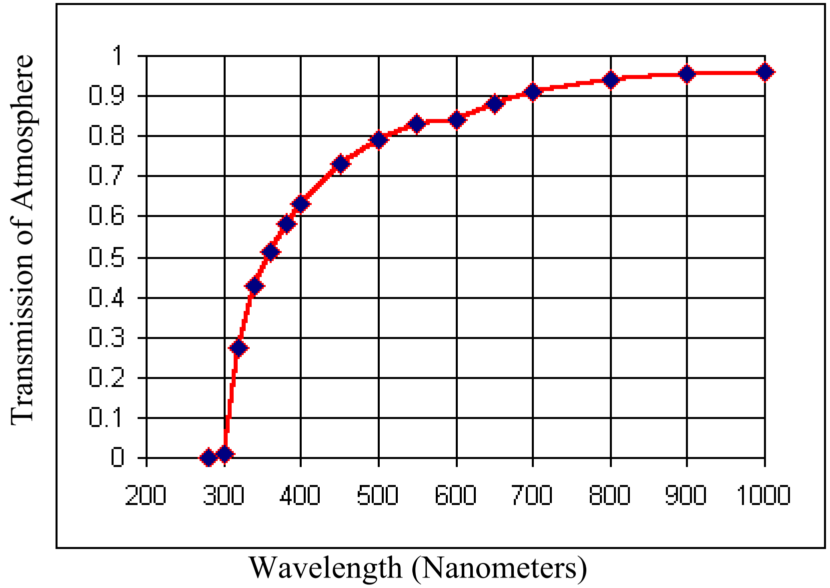
Charge Collection in a CCD.

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



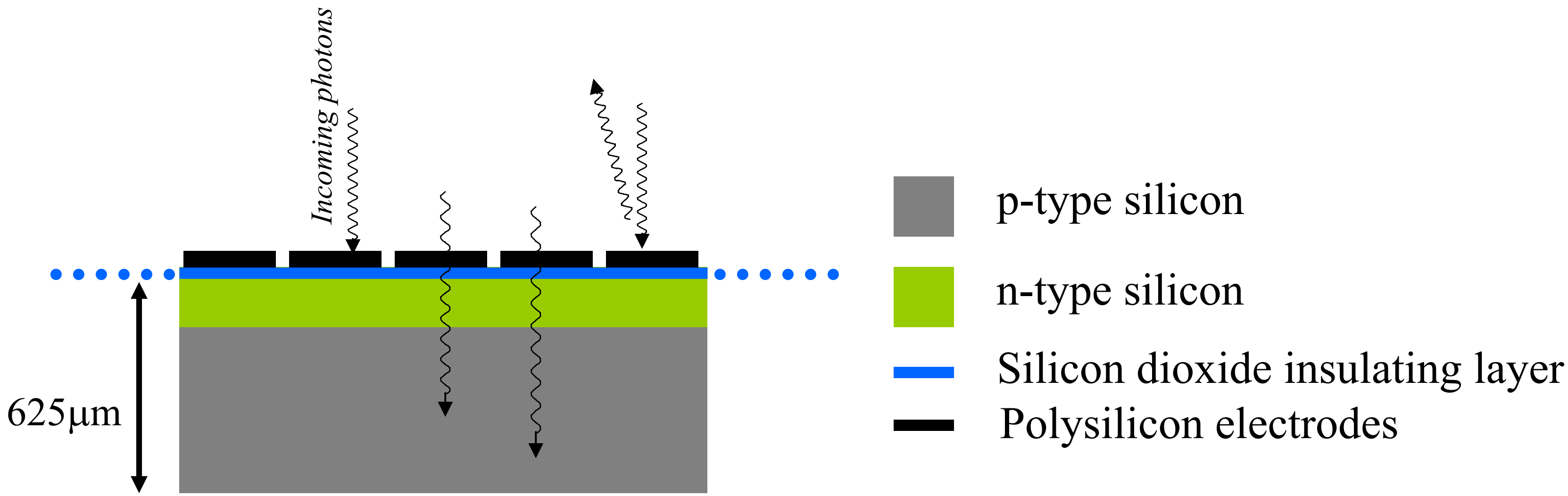
Spectral Sensitivity of CCDs

The graph below shows the transmission of the atmosphere when looking at objects at the zenith. The atmosphere absorbs strongly below about 330nm, in the near ultraviolet part of the spectrum. An ideal CCD should have a good sensitivity from 330nm to approximately 1000nm, at which point silicon, from which CCDs are manufactured, becomes transparent and therefore insensitive.



Over the last 25 years of development, the sensitivity of CCDs has improved enormously, to the point where almost all of the incident photons across the visible spectrum are detected. CCD sensitivity has been improved using two main techniques : ‘thinning’ and the use of anti-reflection coatings. These are now explained in more detail.

Thick Front-side Illuminated CCD



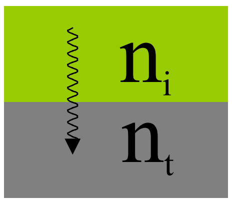
These are cheap to produce using conventional wafer fabrication techniques. They are used in consumer imaging applications. Even though not all the photons are detected, these devices are still more sensitive than photographic film.

They have a low Quantum Efficiency due to the reflection and absorption of light in the surface electrodes. Very poor blue response. The electrode structure prevents the use of an Anti-reflective coating that would otherwise boost performance.

The amateur astronomer on a limited budget might consider using thick CCDs. For professional observatories, the economies of running a large facility demand that the detectors be as sensitive as possible; thick front-side illuminated chips are seldom if ever used.

Anti-Reflection Coatings 1

Silicon has a very high Refractive Index (denoted by **n)**. This means that photons are strongly reflected from its surface.



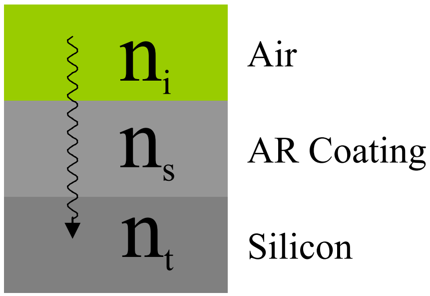
Fraction of photons reflected at the interface between two mediums of differing refractive indices $= \left[\dfrac{n_t - n_i}{n_t + n_i}\right]^2$

n of air or vacuum is 1.0, glass is 1.46, water is 1.33, Silicon is 3.6. Using the above equation we can show that window glass in air reflects 3.5% and silicon in air reflects 32%. Unless we take steps to eliminate this reflected portion, then a silicon CCD will at best only detect 2 out of every 3 photons.

The solution is to deposit a thin layer of a transparent dielectric material on the surface of the CCD. The refractive index of this material should be between that of silicon and air, and it should have an optical thickness = 1/4 wavelength of light. The question now is what wavelength should we choose, since we are interested in a wide range of colours. Typically 550nm is chosen, which is close to the middle of the optical spectrum.

Anti-Reflection Coatings 2

With an Anti-reflective coating we now have three mediums to consider :



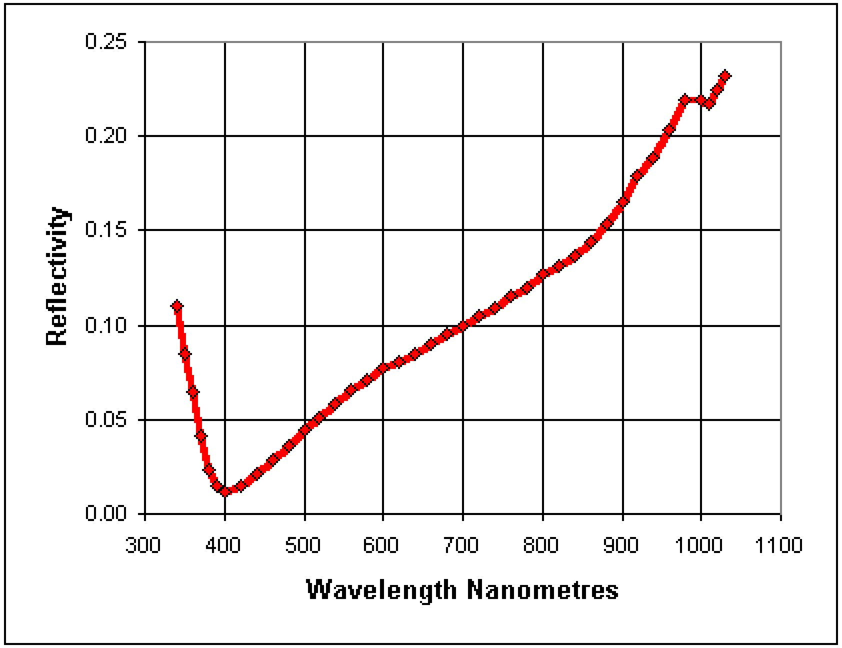
The reflected portion is now reduced to :

$$\left[\frac{n_t \times n_i - n_s^2}{n_t \times n_i + n_s^2}\right]^2$$

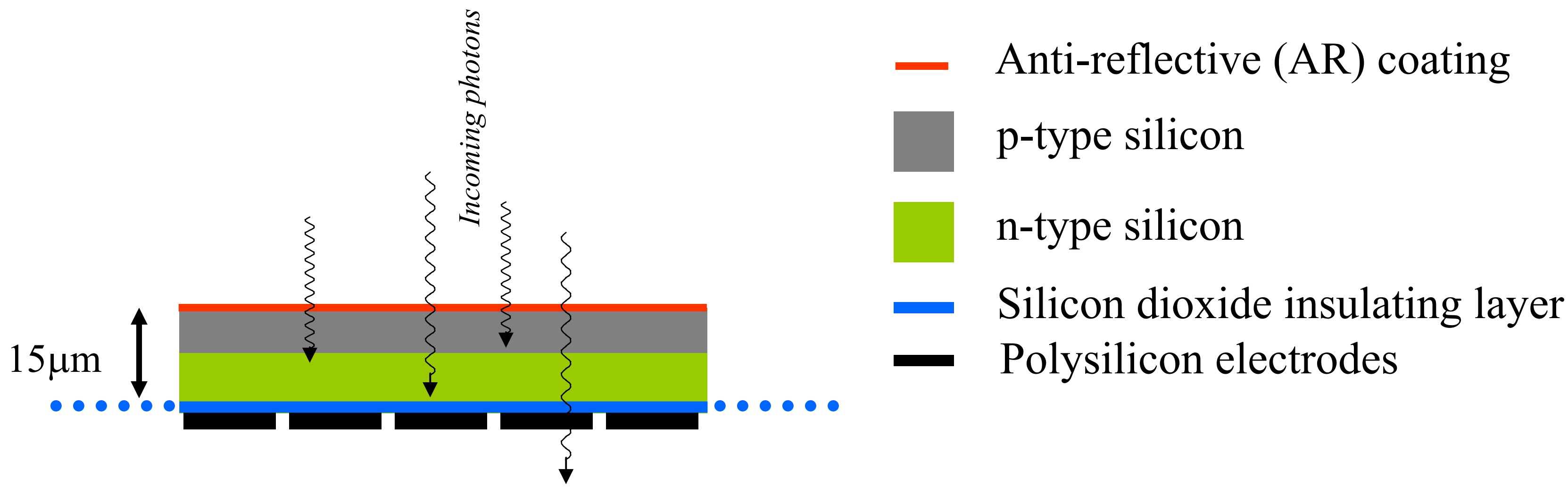
In the case where $n_s^2 = n_t$ the reflectivity actually falls to zero! For silicon we require a material with $\mathbf{n}$ = 1.9, fortunately such a material exists, it is Hafnium Dioxide. It is regularly used to coat astronomical CCDs.

Anti-Reflection Coatings 3

The graph below shows the reflectivity of an EEV 42-80 CCD. These thinned CCDs were designed for a maximum blue response and it has an anti-reflective coating optimised to work at 400nm. At this wavelength the reflectivity falls to approximately 1%.



Thinned Back-side Illuminated CCD



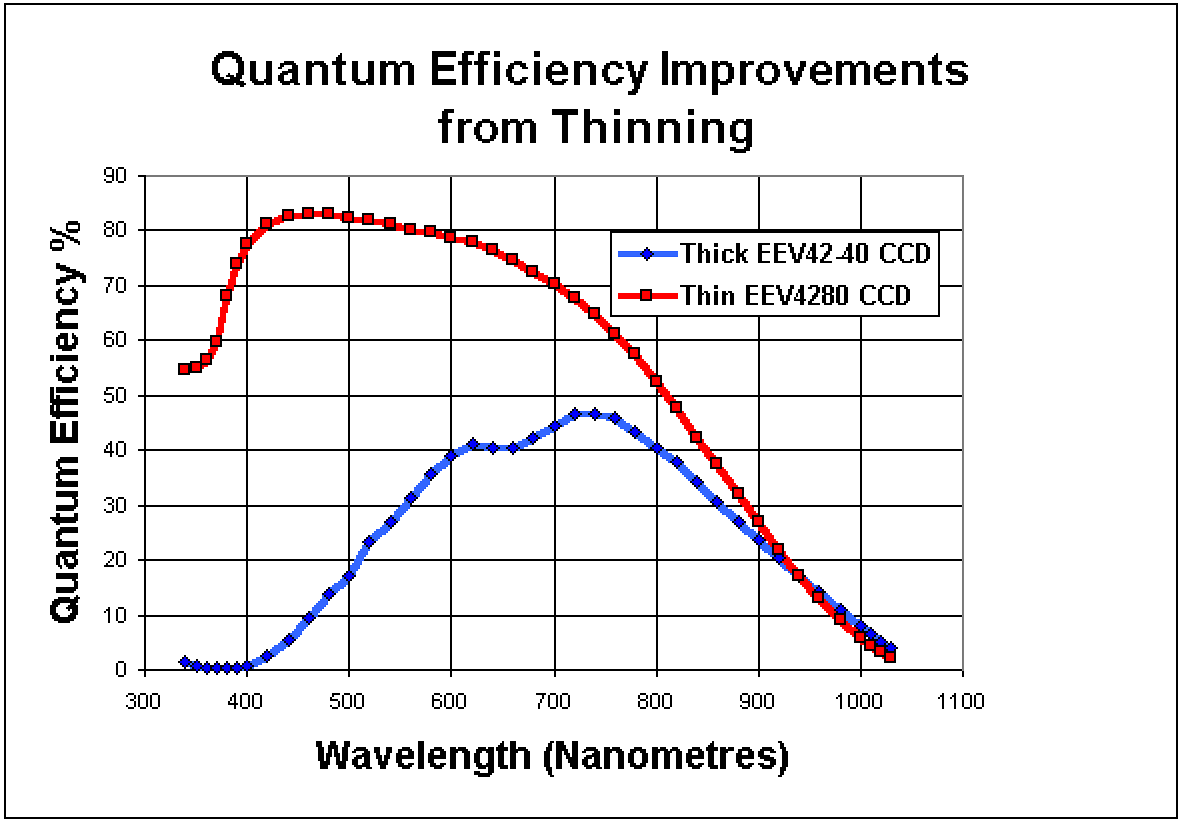
The silicon is chemically etched and polished down to a thickness of about 15microns. Light enters from the rear and so the electrodes do not obstruct the photons. The QE can approach 100% .

These are very expensive to produce since the thinning is a non-standard process that reduces the chip yield. These thinned CCDs become transparent to near infra-red light and the red response is poor. Response can be boosted by the application of an anti-reflective coating on the thinned rear-side. These coatings do not work so well for thick CCDs due to the surface bumps created by the surface electrodes.

Almost all Astronomical CCDs are Thinned and Backside Illuminated.

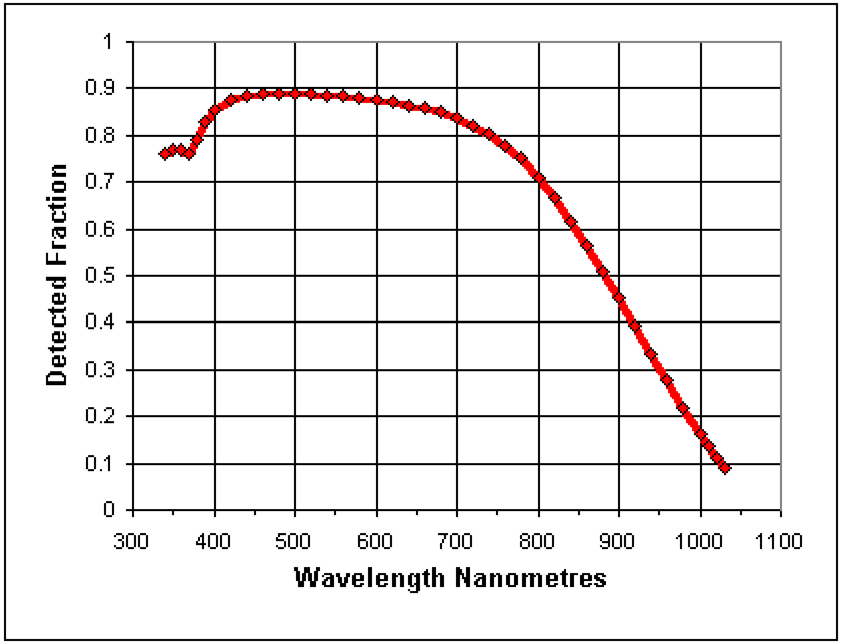
Quantum Efficiency Comparison

The graph below compares the quantum of efficiency of a thick frontside illuminated CCD and a thin backside illuminated CCD.



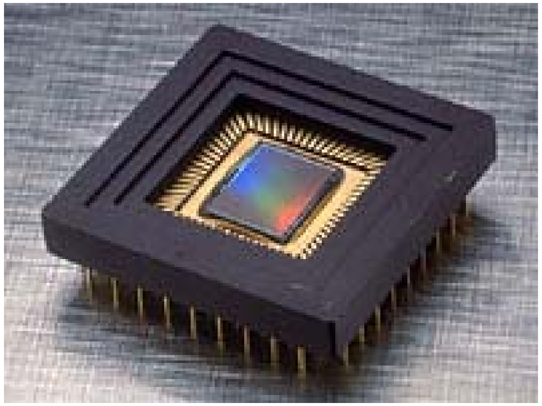
'Internal' Quantum Efficiency

If we take into account the reflectivity losses at the surface of a CCD we can produce a graph showing the 'internal QE' : the fraction of the photons that enter the CCDs bulk that actually produce a detected photo-electron. This fraction is remarkably high for a thinned CCD. For the EEV 42-80 CCD, shown below, it is greater than 85% across the full visible spectrum. Todays CCDs are very close to being ideal visible light detectors!

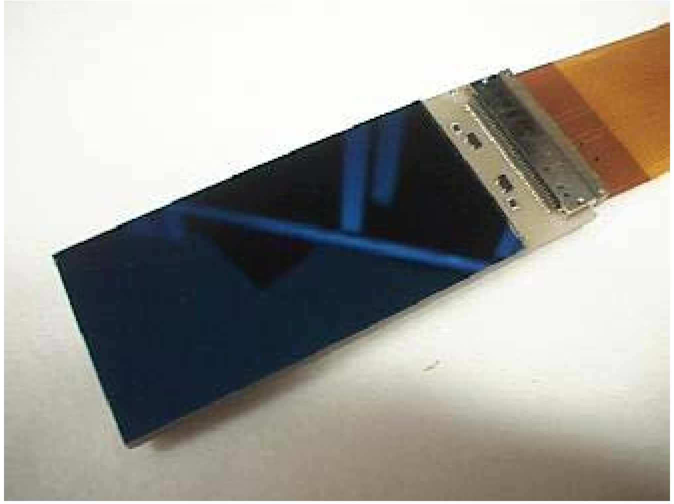


Appearance of CCDs

The fine surface electrode structure of a thick CCD is clearly visible as a multi-coloured interference pattern. Thinned Backside Illuminated CCDs have a much planer surface appearance. The other notable distinction is the two-fold (at least) price difference.



Kodak Kaf1401 Thick CCD



MIT/LL CC1D20 Thinned CCD

Computer Requirements 1.

Computers are required firstly to coordinate the sequence of clock signals that need to be sent to a CCD and its signal processing electronics during the readout phase, but also for data collection and the subsequent processing of the images.

The CCD Controller

In this first application, the computer is an embedded system running in a ‘CCD controller’. This controller will typically contain a low noise analogue section for amplification and filtering of the CCD video waveform, an analogue to digital converter, a high speed processor for clock waveform generation and a fibre optic transceiver for receipt of commands and transmission of pixel data.
An astronomical system might require clock signals to be generated with time resolutions of a few tens of nanoseconds. This is typically done using Digital Signal Processing (DSP) chips running at 50Mhz. Clock sequences are generated in software and output from the DSP by way of on-chip parallel ports. The most basic CCD design requires a minimum of 7 clock signals. Perhaps 5 more are required to coordinate the operation of the signal processing electronics. DSPs also contain several on-chip serial ports which can be used to transmit pixel data at very high rates. DSPs come with a small on-chip memory for the storage of waveform generation tables and software. Less time critical code , such as routines to initialise the camera and interpret commands can be stored in a few KB of external RAM. The computer running in the CCD controller is thus fast and of relatively simple design. A poorly performing processor here could result in slow read out times and poor use of telescope resources. Remember that when a CCD is reading out the telescope shutter is closed and no observations are possible. For an amateur observer using a small CCD with a fast readout time, a slow CCD controller may not be such a disadvantage; there are not so many pixels to process.

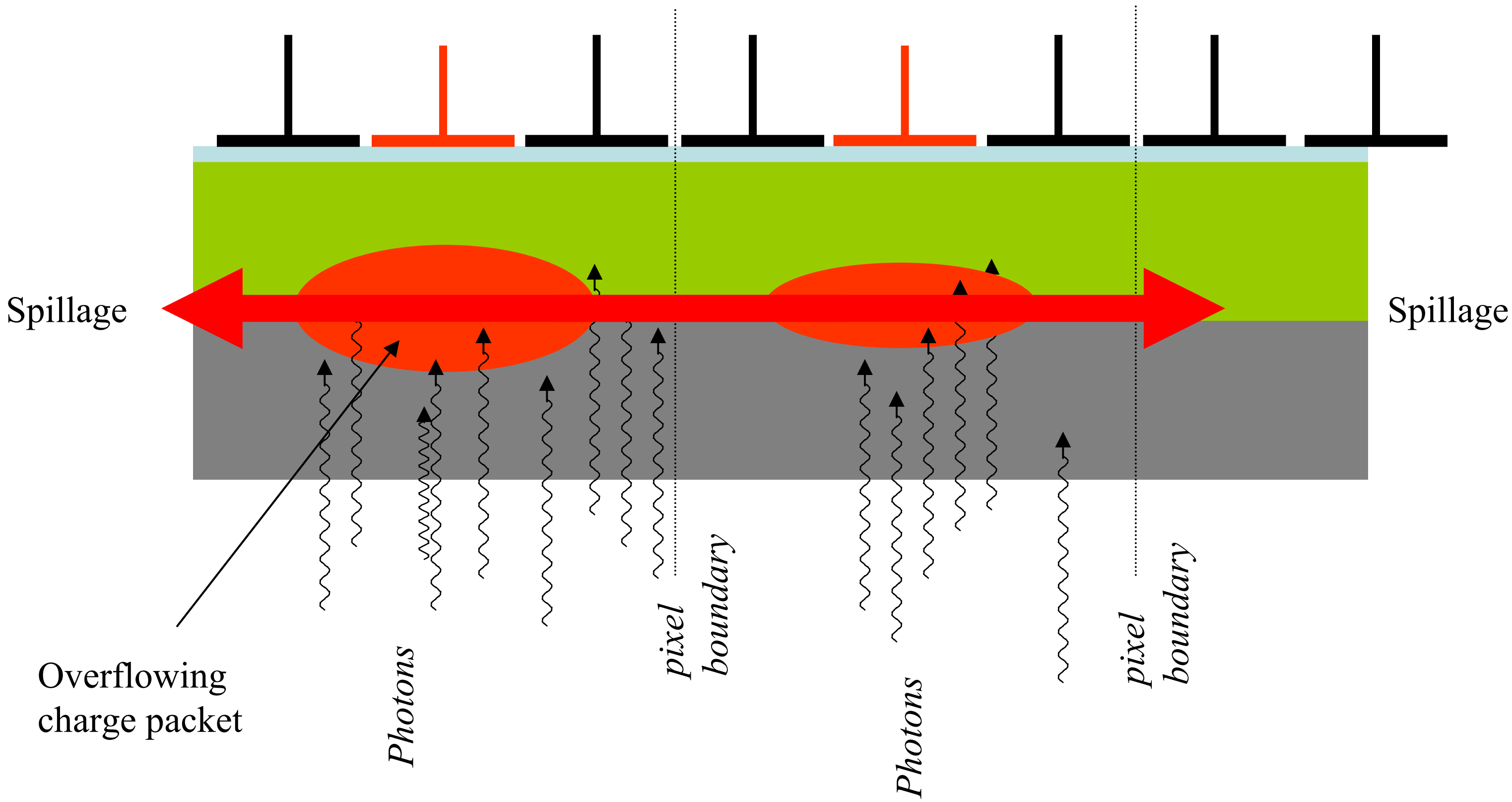
Computer Requirements 2.

The Data Acquisition System(DAS)

This will be typically based around a SUN SPARC workstation which is a high-end desktop computer. Pixel data will be received from the CCD controller by way of a fibre optic. The hardware in such a system will be cheap and ‘off-the shelf’, the only speciality item being the high speed fibre optic transceiver card.
The hardware may typically consist of a Sparc Ultra 6 workstation, 500Mb of RAM, a 9GB hard-drive and a DAT drive. There will also be a high speed Ethernet card for connection to the observatory Local Area Network.The software required to carry out the data acquisition task is typically developed in-house by each observatory and represents the major cost of such a system. It will provide an easy-to-use interface (typically graphics based) between observer and instrument. Its complexity will be further increased by the need to talk to other telescope systems such as the Telescope Control System. This will allow information on the pointing of the telescope to be stored alongside the pixel data as a ‘file header’.

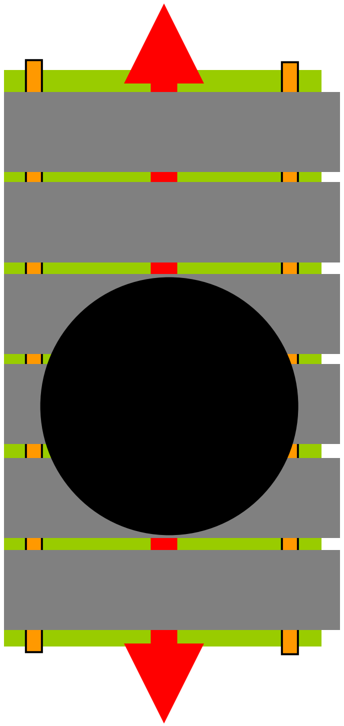
Blooming in a CCD 1.

The charge capacity of a CCD pixel is limited, when a pixel is full the charge starts to leak into adjacent pixels. This process is known as 'Blooming'.



Blooming in a CCD 2.

The diagram shows one column of a CCD with an over-exposed stellar image focused on one pixel.



Flow of bloomed charge

The channel stops shown in orange prevent the charge spreading sideways. The charge confinement provided by the electrodes is less so the charge spreads vertically up and down a column.

The capacity of a CCD pixel is known as the ‘Full Well’. It is dependent on the physical area of the pixel. For Tektronix CCDs, with pixels measuring 24µm x 24µm it can be as much as 300,000 electrons. Bloomed images will be seen particularly on nights of good seeing where stellar images are more compact .

In reality, blooming is not a big problem for professional astronomy. For those interested in pictorial work, however, it can be a nuisance.

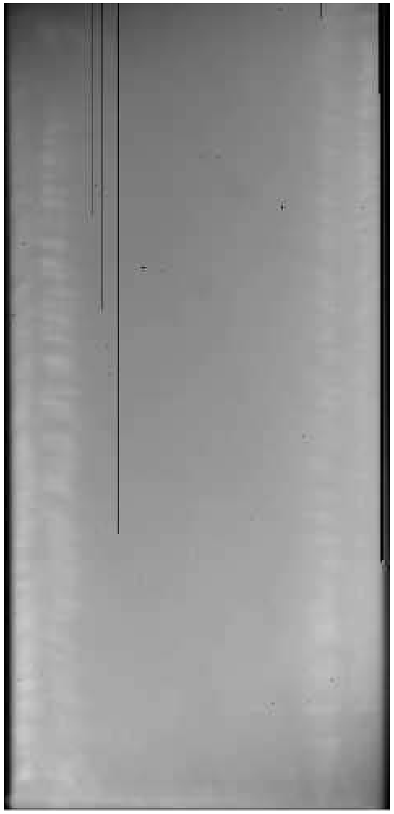
Blooming in a CCD 3.

The image below shows an extended source with bright embedded stars. Due to the long exposure required to bring out the nebulosity, the stellar images are highly overexposed and create bloomed images.

(The image is from a CCD mosaic and the black strip down the center is the space between adjacent detectors)

Image Defects in a CCD 1.

Unless one pays a huge amount it is generally difficult to obtain a CCD free of image defects. The first kind of defect is a 'dark column'. Their locations are identified from flat field exposures.



Flat field exposure of an EEV42-80 CCD

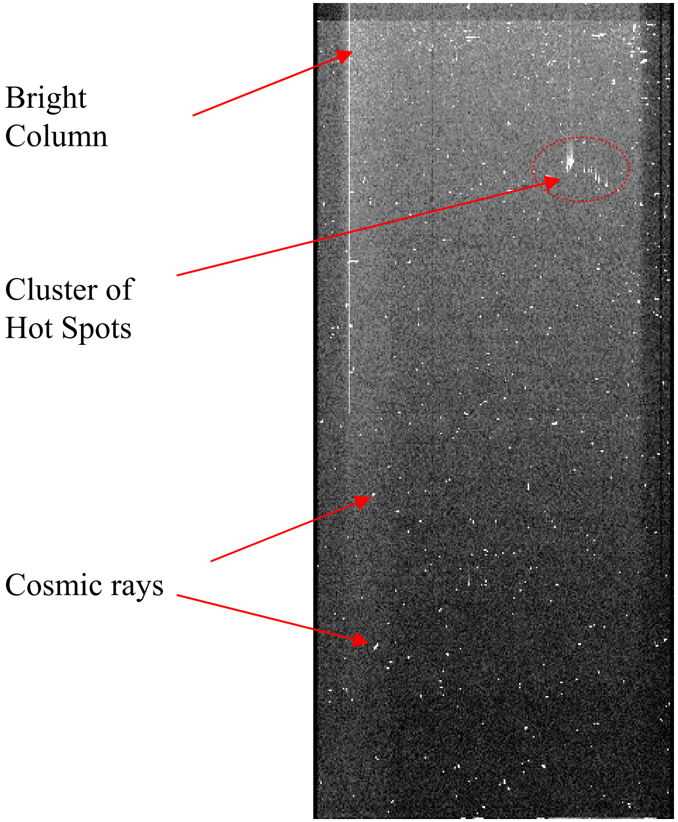
Dark columns are caused by 'traps' that block the vertical transfer of charge during image readout. The CCD shown at left has at least 7 dark columns, some grouped together in adjacent clusters.

Traps can be caused by crystal boundaries in the silicon of the CCD or by manufacturing defects.

Although they spoil the chip cosmetically, dark columns are not a big problem for astronomers. This chip has 2048 image columns so 7 bad columns represents a tiny loss of data.

Image Defects in a CCD 2.

There are three other common image defect types : Cosmic rays, Bright columns and Hot Spots.
Their locations are shown in the image below which is a lengthy exposure taken in the dark (a ‘Dark Frame’)



900s dark exposure of an EEV42-80 CCD

Bright columns are also caused by traps . Electrons contained in such traps can leak out during readout causing a vertical streak.

Hot Spots are pixels with higher than normal dark current. Their brightness increases linearly with exposure times

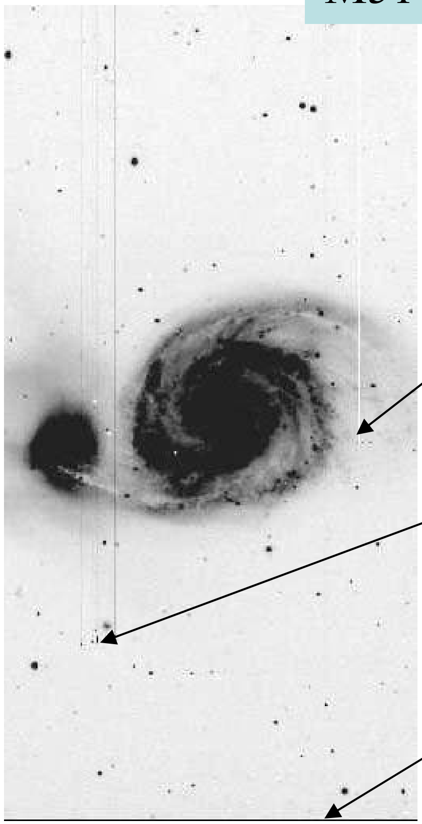
Cosmic rays are unavoidable. Charged particles from space or from radioactive traces in the material of the camera can cause ionisation in the silicon. The electrons produced are indistinguishable from photo-generated electrons. Approximately 2 cosmic rays per cm^2 per minute will be seen. A typical event will be spread over a few adjacent pixels and contain several thousand electrons.

Somewhat rarer are light-emitting defects which are hot spots that act as tiny LEDS and cause a halo of light on the chip.

Image Defects in a CCD 3.

Some defects can arise from the processing electronics. This negative image has a bright line in the first image row.

M51



Dark column

Hot spots and bright columns

Bright first image row caused by incorrect operation of signal processing electronics.

Biases, Flat Fields and Dark Frames 1.

These are three types of calibration exposures that must be taken with a scientific CCD camera, generally before and after each observing session. They are stored alongside the science images and combined with them during image processing. These calibration exposures allow us to compensate for certain imperfections in the CCD. As much care needs to be exercised in obtaining these images as for the actual scientific exposures. Applying low quality flat fields and bias frames to scientific data can degrade rather than improve its quality.

Bias Frames

A bias frame is an exposure of zero duration taken with the camera shutter closed. It represents the zero point or base-line signal from the CCD. Rather than being completely flat and featureless the bias frame may contain some structure. Any bright image defects in the CCD will of course show up, there may be also slight gradients in the image caused by limitations in the signal processing electronics of the camera.
It is normal to take about 5 bias frames before a night's observing. These are then combined using an image processing algorithm that averages the images, pixel by pixel, rejecting any pixel values that are appreciably different from the other 4. This can happen if a pixel in one bias frame is affected by a cosmic ray event. It is unlikely that the same pixel in the other 4 frames would be similarly affected so the resultant 'master bias', should be uncontaminated by cosmic rays. Taking a number of biases and then averaging them also reduces the amount of noise in the bias images. Averaging 5 frames will reduce the amount of read noise (electronic noise from the CCD amplifier) in the image by the square-root of 5.

Biases, Flat Fields and Dark Frames 2.

Flat Fields

Some pixels in a CCD will be more sensitive than others. In addition there may be dust spots on the surface of either the chip, the window of the camera or the coloured filters mounted in front of the camera. A star focused onto one part of a chip may therefore produce a lower signal than it might do elsewhere. These variations in sensitivity across the surface of the CCD must be calibrated out or they will add noise to the image. The way to do this is to take a 'flat-field ' image : an image in which the CCD is evenly illuminated with light. Dividing the science image , pixel by pixel , by a flat field image will remove these sensitivity variations very effectively.

Since some of these variations are caused by shadowing from dust spots, it is important that the flat fields are taken shortly before or after the science exposures; the dust may move around! As with biases, it is normal to take several flat field frames and average them to produce a 'Master'.

A flat field is taken by pointing the telescope at an extended , evenly illuminated source. The twilight sky or the inside of the telescope dome are the usual choices. An exposure time is chosen that gives pixel values about halfway to their saturation level i.e. a medium level exposure.

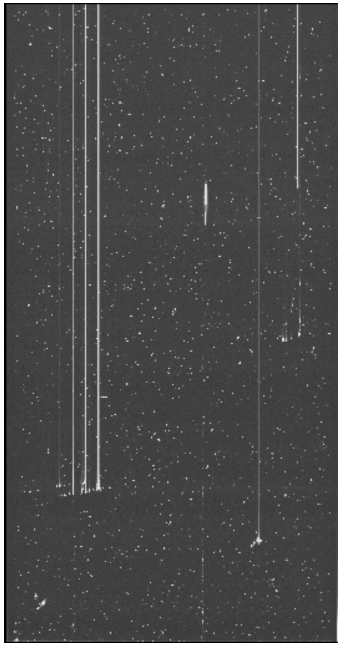
Dark Frames.

Dark current is generally absent from professional cameras since they are operated cold using liquid nitrogen as a coolant. Amateur systems running at higher temperatures will have some dark current and its effect must be minimised by obtaining 'dark frames' at the beginning of the observing run. These are exposures with the same duration as the science frames but taken with the camera shutter closed. These are later subtracted from the science frames. Again, it is normal to take several dark frames and combine them to form a Master, using a technique that rejects cosmic ray features.

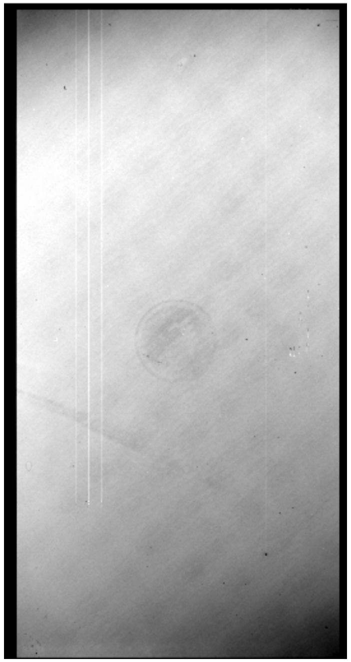
Biases, Flat Fields and Dark Frames 3.

A dark frame and a flat field from the same EEV42-80 CCD are shown below. The dark frame shows a number of bright defects on the chip. The flat field shows a criss-cross patterning on the chip created during manufacture and a slight loss of sensitivity in two corners of the image. Some dust spots are also visible.

Dark Frame

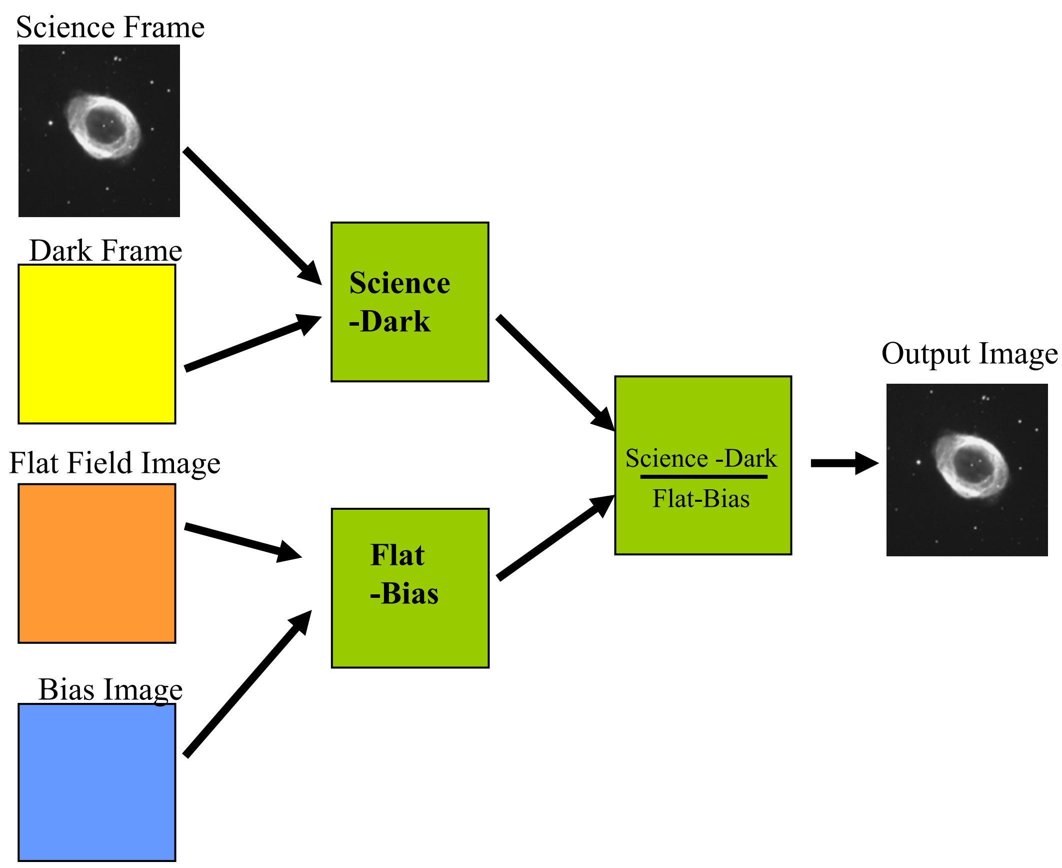


Flat Field



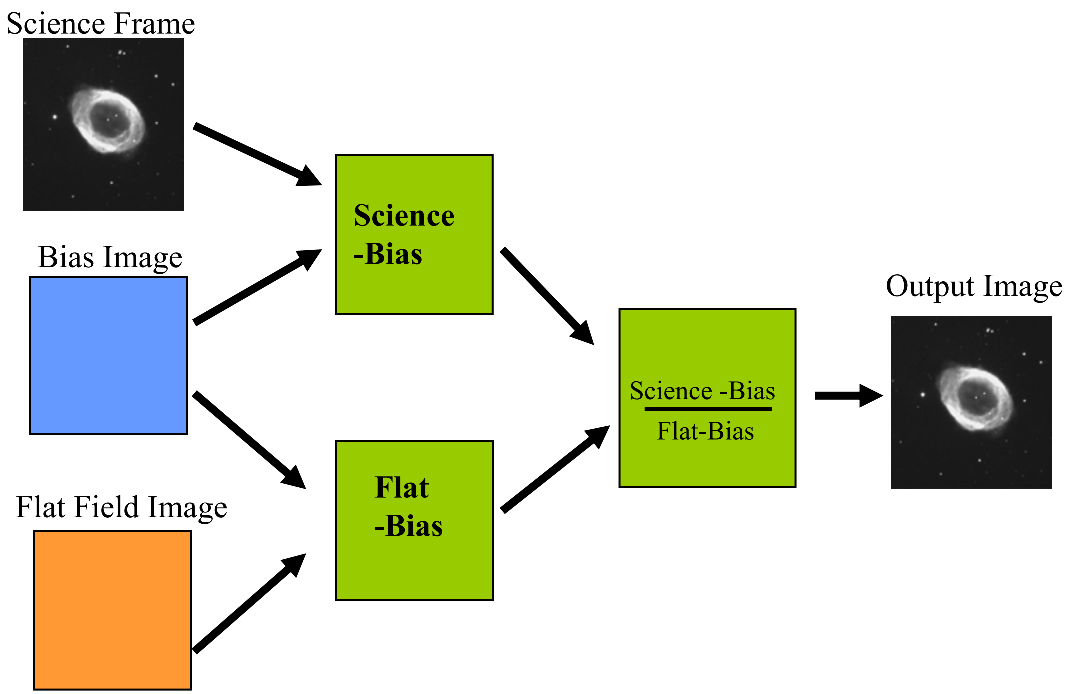
Biases, Flat Fields and Dark Frames 4.

If there is significant dark current present, the various calibration and science frames are combined by the following series of subtractions and divisions :



Dark Frames and Flat Fields 5.

In the absence of dark current, the process is slightly simpler :



Pixel Size and Binning 1.

Nyquist Sampling

It is important to match the size of a CCD pixel to the focal length of the telescope. Atmospheric seeing places a limit on the sharpness of an astronomical image for telescope apertures above 15cm. Below this aperture, the images will be limited by diffraction effects in the optics. In excellent seeing conditions, a large telescope can produce stellar images with a diameter of 0.6 arc-seconds. In order to record all the information present in such an image, two pixels must fit across the stellar image; the pixels must subtend at most 0.3 arc-seconds on the sky. This is the 'Nyquist criterium'. If the pixels are larger than 0.3 arc-seconds the Nyquist criteria is not met, the image is under-sampled and information is lost. The Nyquist criterium also applies to the digitisation of audio waveforms. The audio bandwidth extends up to 20KHz , so the Analogue to Digital Conversion rate needs to exceed 40KHz for full reproduction of the waveform. Exceeding the Nyquist criterium leads to 'over-sampling'.This has the disadvantage of wasting silicon area ; with improved matching of detector and optics a larger area of sky could be imaged.

Under-sampling an image can produce some interesting effects. One of these is the introduction of features that are not actually present. This is occasionally seen in TV broadcasts when, for example, the fine-patterned shirt of an interviewee breaks up into psychedelic bands and ripples. In this example, the TV camera pixels are too big to record the fine detail present in the shirt.
This effect is known as 'aliasing'.

Pixel Size and Binning 2.

Matching the Pixels to the telescope

Example 1.
The William Herschel Telescope, with a 4.2m diameter primary mirror and a focal ratio of 3 is to be used for prime focus imaging. What is the optimum pixel size assuming that the best seeing at the telescope site is 0.7 arc-seconds ?
First we calculate the 'plate-scale' in arc-seconds per millimeter at the focal plane of the telescope.

$$\text{Plate Scale (arc-seconds per mm)} = \frac{206265}{\text{Aperture in mm } \mathbf{X} \text{ f-number}} = 16.4 \text{ arc-sec per mm}$$

(Here the factor 206265 is the number of arc-seconds in a Radian)

Next we calculate the linear size at the telescope focal plane of a stellar image (in best seeing conditions)

Linear size of stellar image = 0.7 / Plate Scale = 0.7/ 16.4 = 42 microns.

To satisfy the Nyquist criterium, the maximum pixel size is therefore 21microns. In practice, the nearest pixel size available is 13.5 microns which leads to a small degree of over-sampling.

Pixel Size and Binning 3.

Example 2.
An Amateur telescope with a 20cm aperture and a focal ratio of 10 is to be used for imaging. The best seeing conditions at the observing site will be 1 arc-second. What is the largest pixel size that can be used?

$$\text{Plate Scale (arc-seconds per mm)} = \frac{206265}{\text{Aperture in mm } \mathbf{X} \text{ f-number}} = 103 \text{ arc-sec per mm}$$

Linear size of stellar image = 1 / Plate Scale = 1/ 103 = 9.7 microns.

To satisfy the Nyquist criterium, the maximum pixel size is therefore 5 microns. This is about the lower limit of available pixel sizes.

Pixel Size and Binning 4.

Binning

In the first example we showed that with 13.5micron pixels the system exceeded the Nyquist Criterium even on nights with exceptionally good sub-arcsecond seeing. If we now suppose that the seeing is 2 arc-seconds, the size of a stellar image will increase to 120microns on the detector. The image will now be grossly over-sampled. (One way to think of this is that the image is less sharp and therefore requires fewer pixels to record it). It would be more efficient now for the astronomer to switch to a detector with larger pixels since the resultant image files would be smaller, quicker to read out and would occupy less disc space.

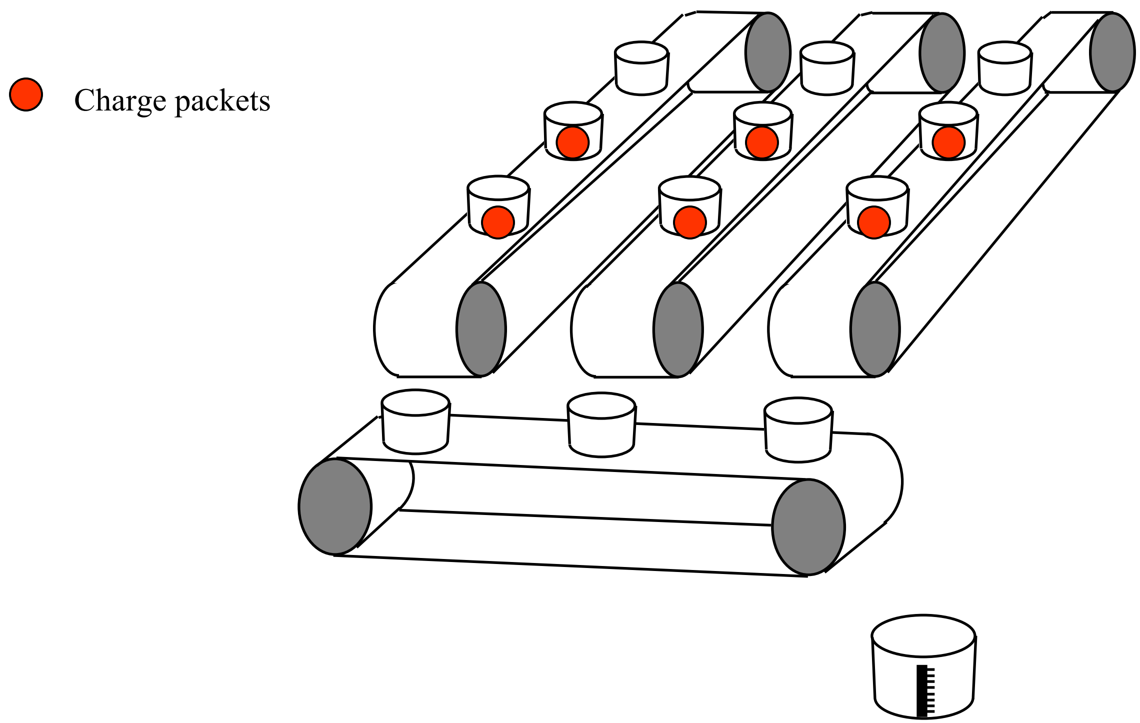
There is a way to read out a CCD so as to increase the effective pixel size, this is known as ‘Binning’. With binning we can increase pixel size arbitrarily. In the limit we could even read out the CCD as a single large pixel. Astronomers will more commonly use 2 x 2 binning which means that the charge in each 2 x 2 square of adjacent pixels is summed on the chip prior to delivery to the output amplifier. One important advantage of ‘on-chip binning’ is that it is a noise free process.

Binning is done in two distinct stages : vertical binning and horizontal binning. Each may be done without the other to yield rectangular pixels.

Pixel Size and Binning 5.

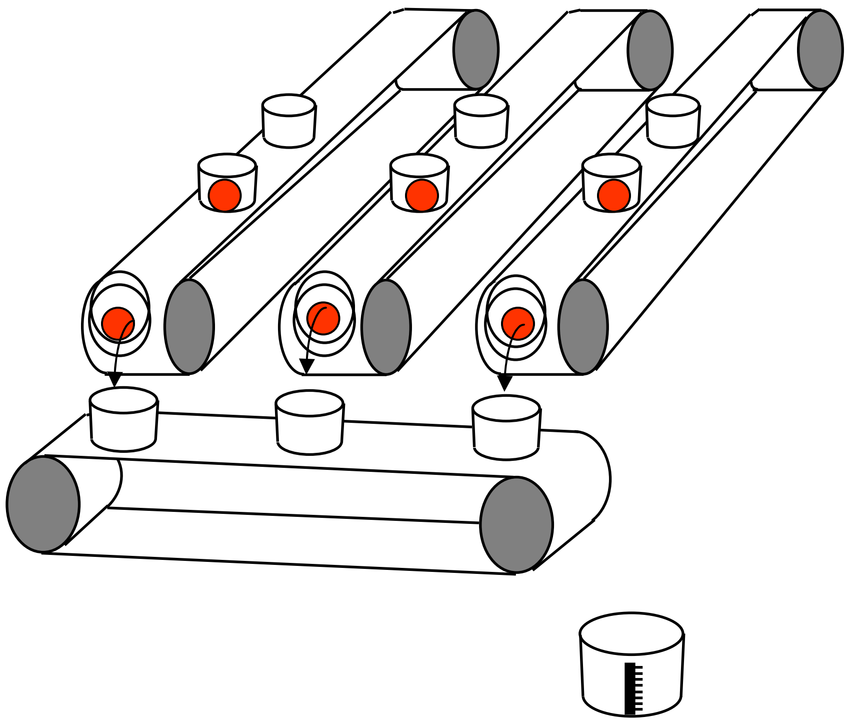
Stage 1 :Vertical Binning

This is done by summing the charge in consecutive rows .The summing is done in the serial register. In the case of 2 x 2 binning, two image rows will be clocked consecutively into the serial register prior to the serial register being read out. We now go back to the conveyor belt analogy of a CCD. In the following animation we see the bottom two image rows being binned.



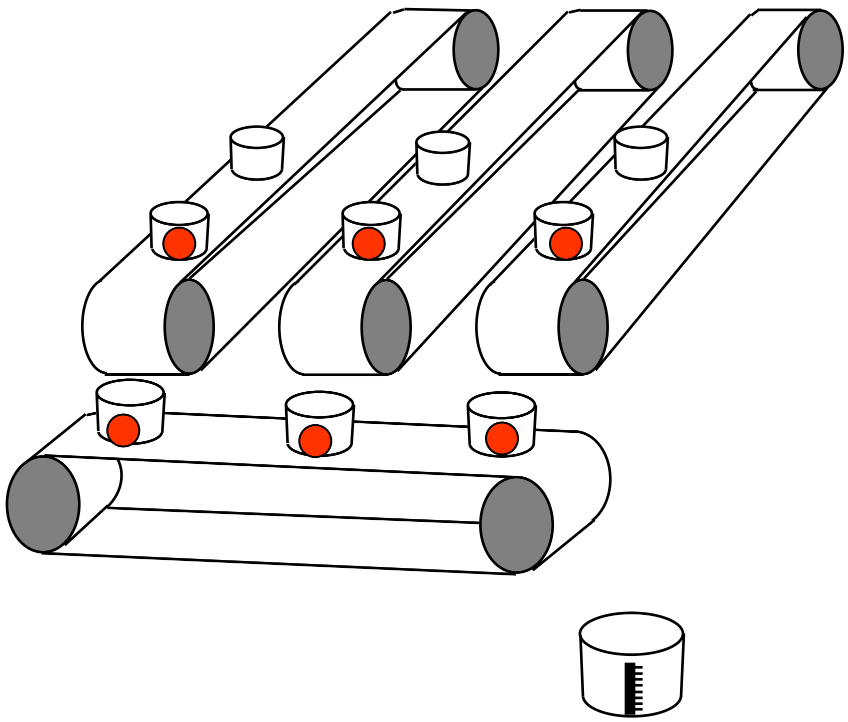
Pixel Size and Binning 6.

The first row is transferred into the serial register



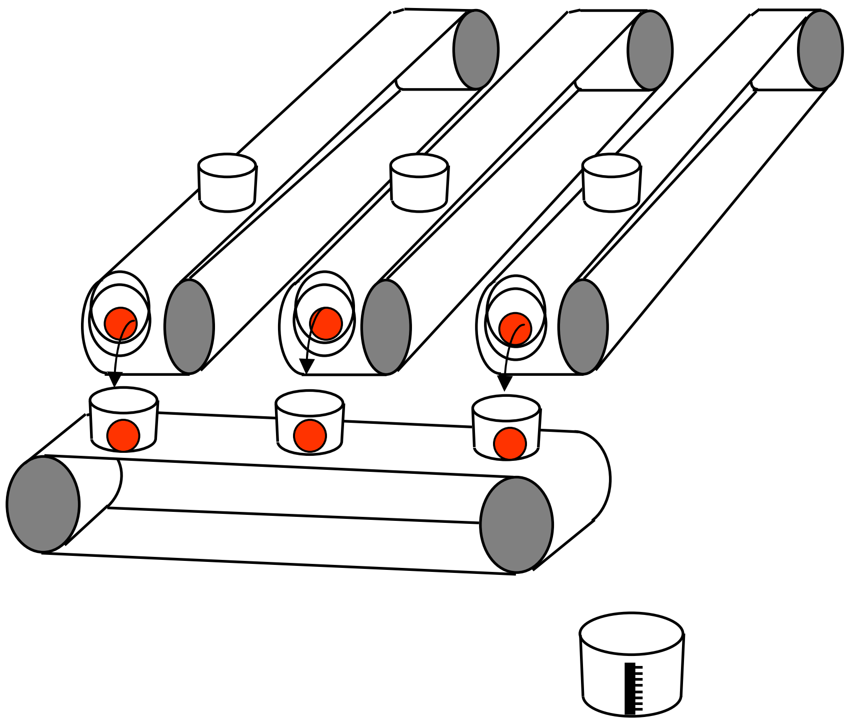
Pixel Size and Binning 7.

The serial register is kept stationary ready for the next row to be transferred.



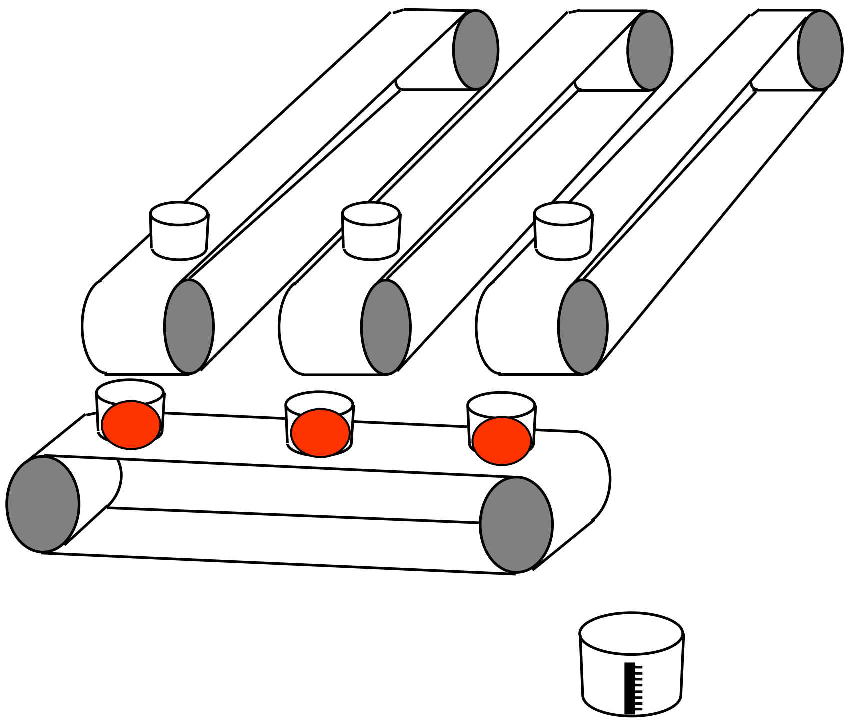
Pixel Size and Binning 8.

The second row is now transferred into the serial register.



Pixel Size and Binning 9.

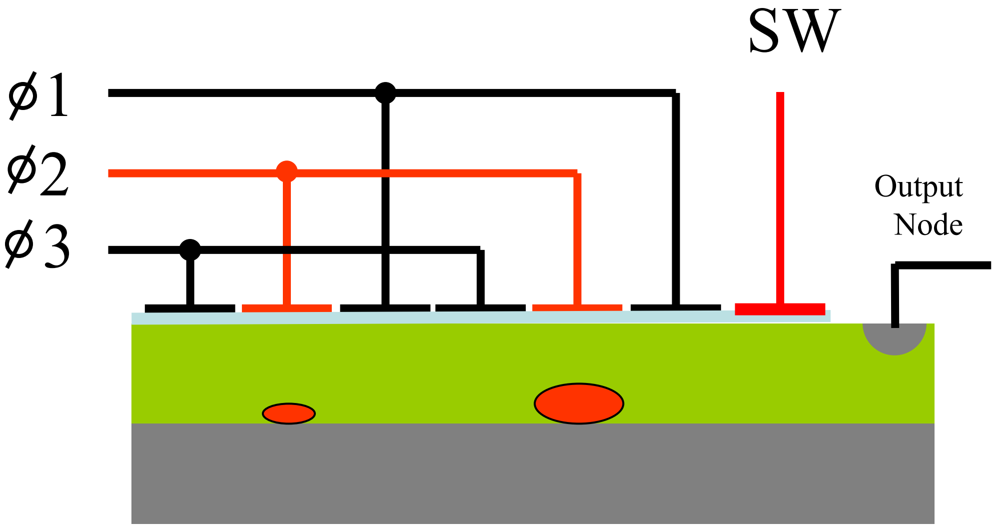
Each pixel in the serial register now contains the charge from two pixels in the image area. It is thus important that the serial register pixels have a higher charge capacity. This is achieved by giving them a larger physical size.



Pixel Size and Binning 10.

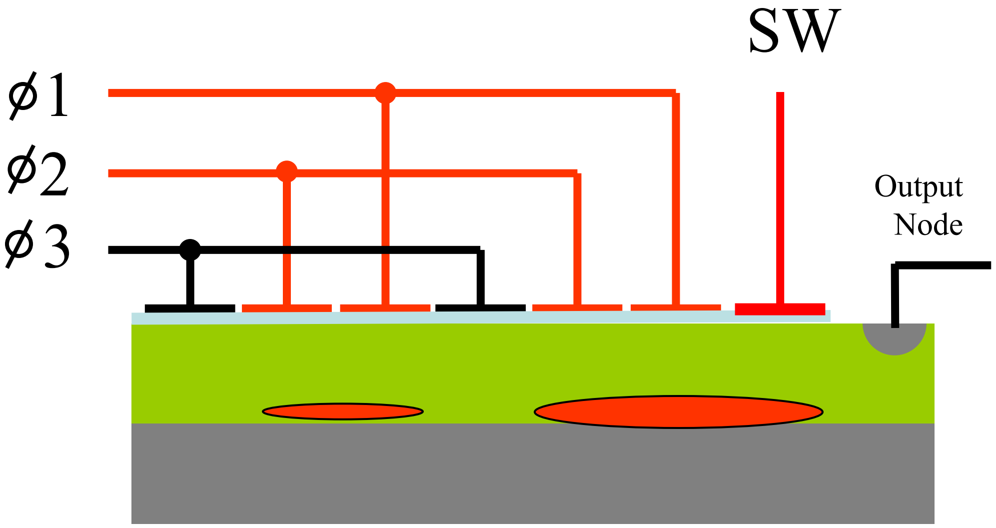
Stage 2 :Horizontal Binning

This is done by combining charge from consecutive pixels in the serial register on a special electrode positioned between serial register and the readout amplifier called the Summing Well (SW).
The animation below shows the last two pixels in the serial register being binned :

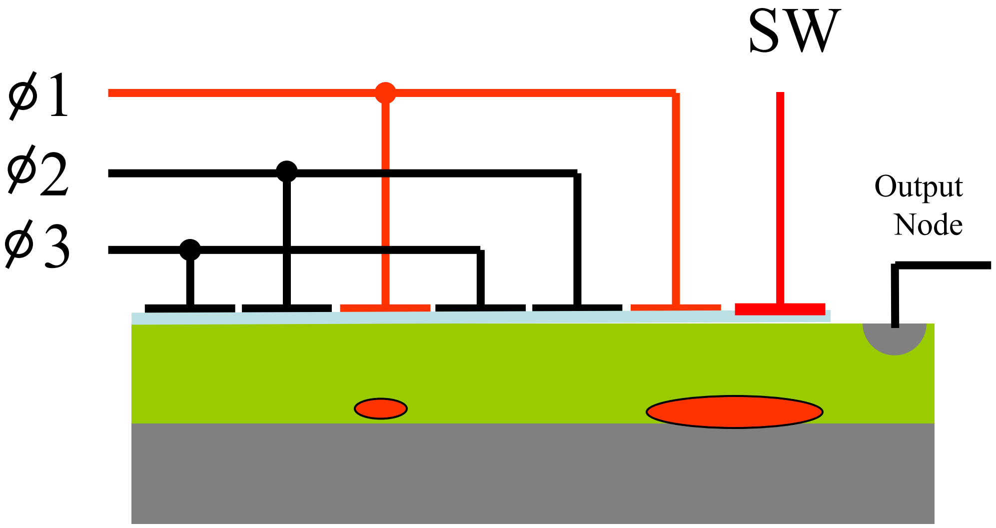


Pixel Size and Binning 11.

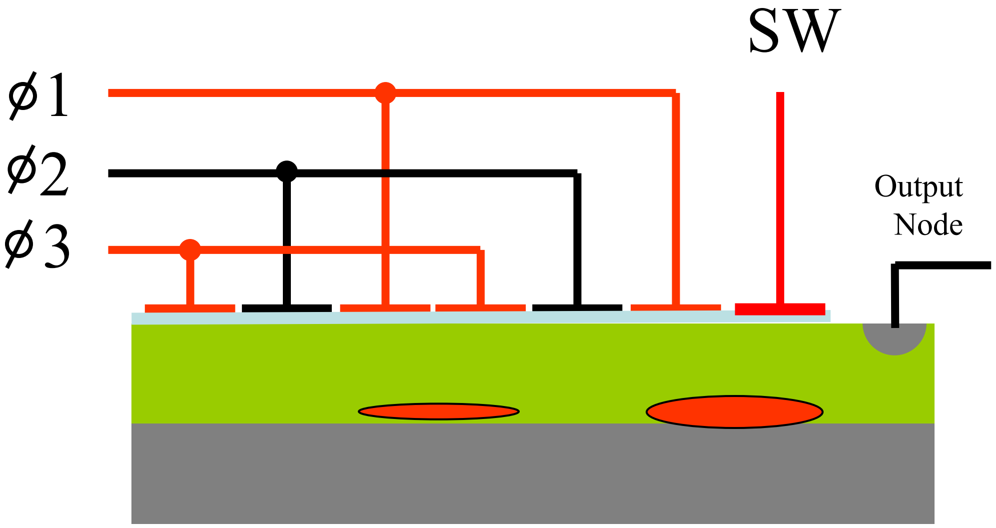
Charge is clocked horizontally with the SW held at a positive potential.



Pixel Size and Binning 12.

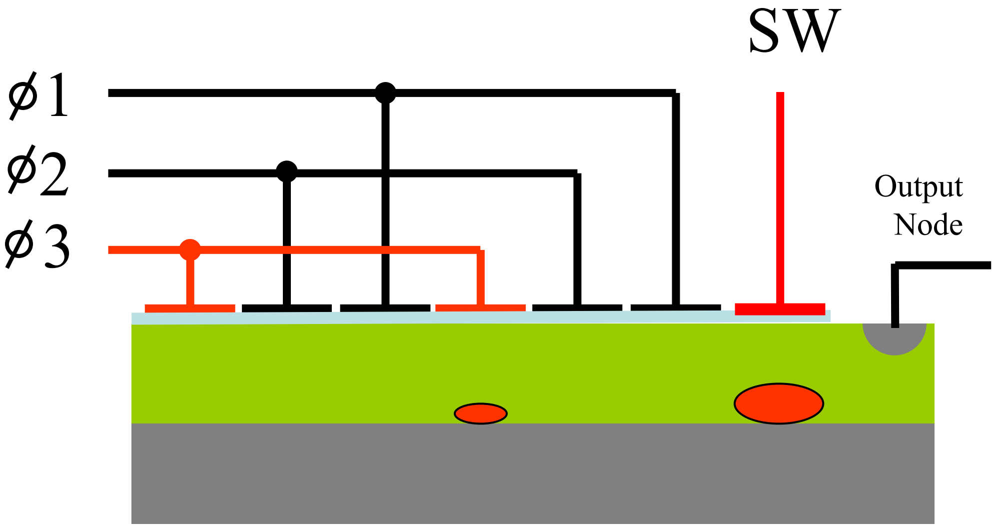


Pixel Size and Binning 13.



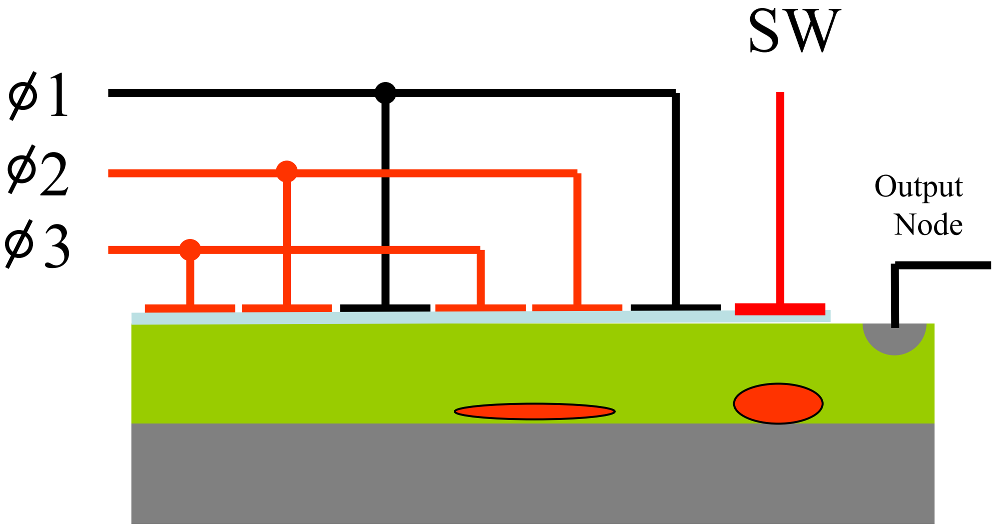
Pixel Size and Binning 14.

The charge from the first pixel is now stored on the summing well.

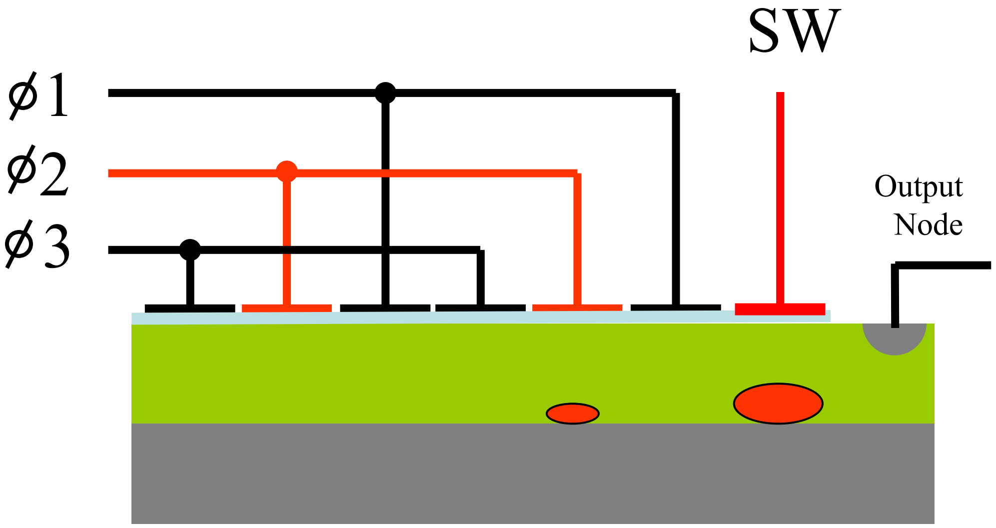


Pixel Size and Binning 15.

The serial register continues clocking.

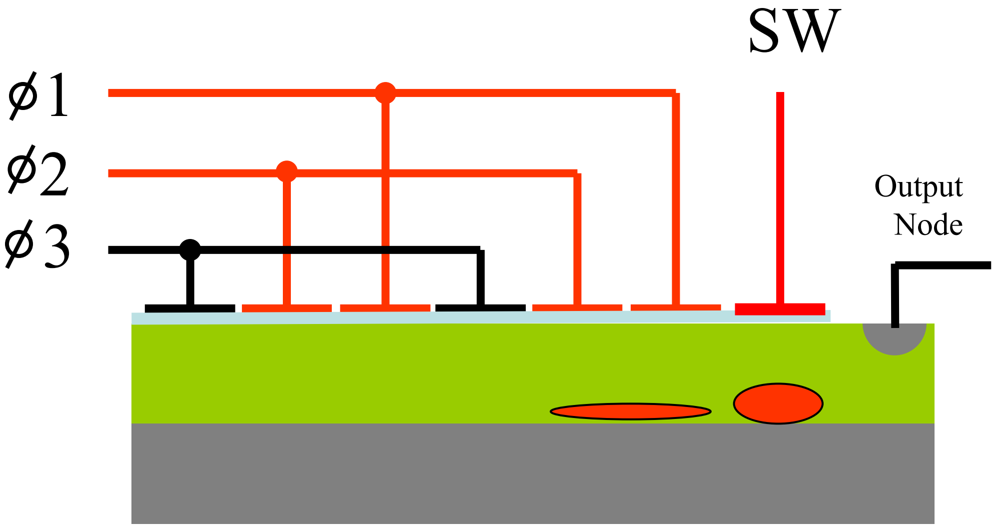


Pixel Size and Binning 16.

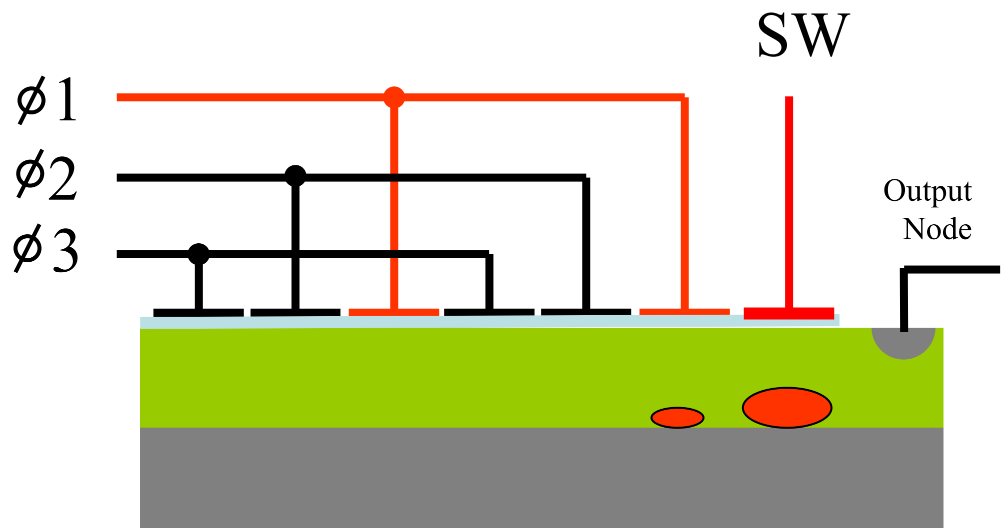


Pixel Size and Binning 17.

The SW potential is set slightly higher than the serial register electrodes.



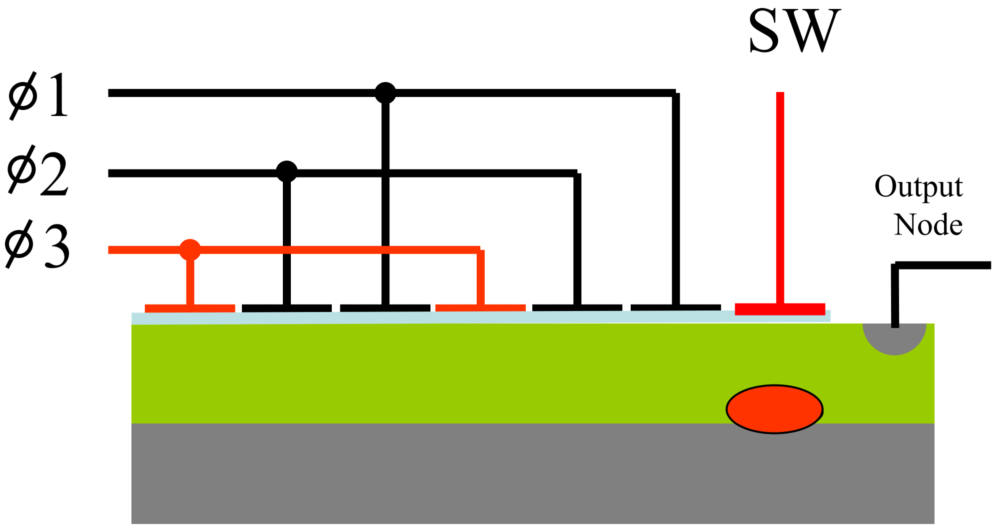
Pixel Size and Binning 18.



Pixel Size and Binning 19.

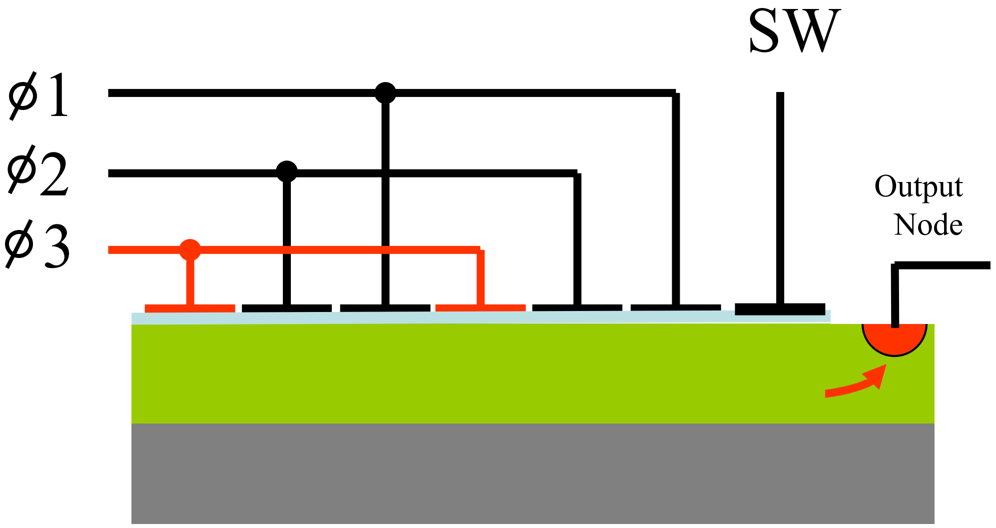
The charge from the second pixel is now transferred onto the SW. The binning is now complete and the combined charge packet can now be dumped onto the output node (by pulsing the voltage on SW low for a microsecond) for measurement.

Horizontal binning can also be done directly onto the output node if a SW is not present but this can increase the read noise.



Pixel Size and Binning 20.

Finally the charge is dumped onto the output node for measurement



Noise Sources in a CCD Image 1.

The main noise sources found in a CCD are :

1. READ NOISE.

Caused by electronic noise in the CCD output transistor and possibly also in the external circuitry. Read noise places a fundamental limit on the performance of a CCD. It can be reduced at the expense of increased read out time. Scientific CCDs have a readout noise of 2-3 electrons RMS.

2. DARK CURRENT.

Caused by thermally generated electrons in the CCD. Eliminated by cooling the CCD.

3. PHOTON NOISE.

Also called ‘Shot Noise’. It is due to the fact that the CCD detects photons. Photons arrive in an unpredictable fashion described by Poissonian statistics. This unpredictability causes noise.

4. PIXEL RESPONSE NON-UNIFORMITY.

Defects in the silicon and small manufacturing defects can cause some pixels to have a higher sensitivity than their neighbours. This noise source can be removed by ‘Flat Fielding’; an image processing technique.

Noise Sources in a CCD Image 2.

Before these noise sources are explained further some new terms need to be introduced.

FLAT FIELDING

This involves exposing the CCD to a very uniform light source that produces a featureless and even exposure across the full area of the chip. A flat field image can be obtained by exposing on a twilight sky or on an illuminated white surface held close to the telescope aperture (for example the inside of the dome). Flat field exposures are essential for the reduction of astronomical data.

BIAS REGIONS

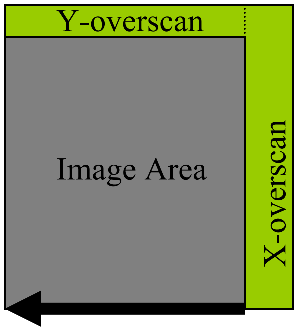
A bias region is an area of a CCD that is not sensitive to light. The value of pixels in a bias region is determined by the signal processing electronics. It constitutes the zero-signal level of the CCD. The bias region pixels are subject only to readout noise. Bias regions can be produced by ‘over-scanning’ a CCD, i.e. reading out more pixels than are actually present. Designing a CCD with a serial register longer than the width of the image area will also create vertical bias strips at the left and right sides of the image. These strips are known as the ‘x-underscan’ and ‘x-overscan’ regions

A flat field image containing bias regions can yield valuable information not only on the various noise sources present in the CCD but also about the gain of the signal processing electronics i.e. the number of photoelectrons represented by each digital unit (ADU) output by the camera’s Analogue to Digital Converter.

Noise Sources in a CCD Image 3.

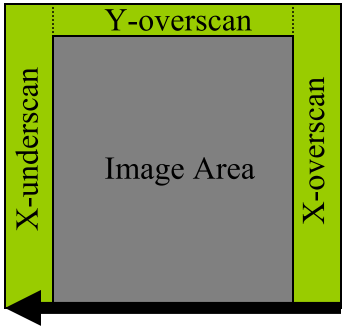
Flat field images obtained from two CCD geometries are represented below. The arrows represent the position of the readout amplifier and the thick black line at the bottom of each image represents the serial register.

CCD With Serial Register equal in length to the image area width.



Here, the CCD is over-scanned in X and Y

CCD With Serial Register greater in length than the image area width.



Here, the CCD is over-scanned in Y to produce the Y-overscan bias area. The X-underscan and X-overscan are created by extensions to the serial register on either side of the image area. When charge is transferred from the image area into the serial register, these extensions do not receive any photo-charge.

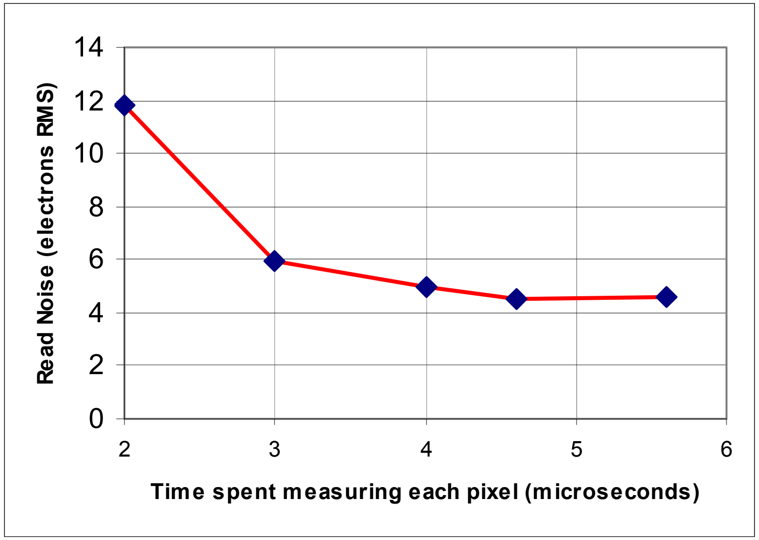
Noise Sources in a CCD Image 4.

These four noise sources are now explained in more detail:

READ NOISE.

This is mainly caused by thermally induced motions of electrons in the output amplifier. These cause small noise voltages to appear on the output. This noise source, known as Johnson Noise, can be reduced by cooling the output amplifier or by decreasing its electronic bandwidth. Decreasing the bandwidth means that we must take longer to measure the charge in each pixel, so there is always a trade-off between low noise performance and speed of readout. Mains pickup and interference from circuitry in the observatory can also contribute to Read Noise but can be eliminated by careful design. Johnson noise is more fundamental and is always present to some degree.

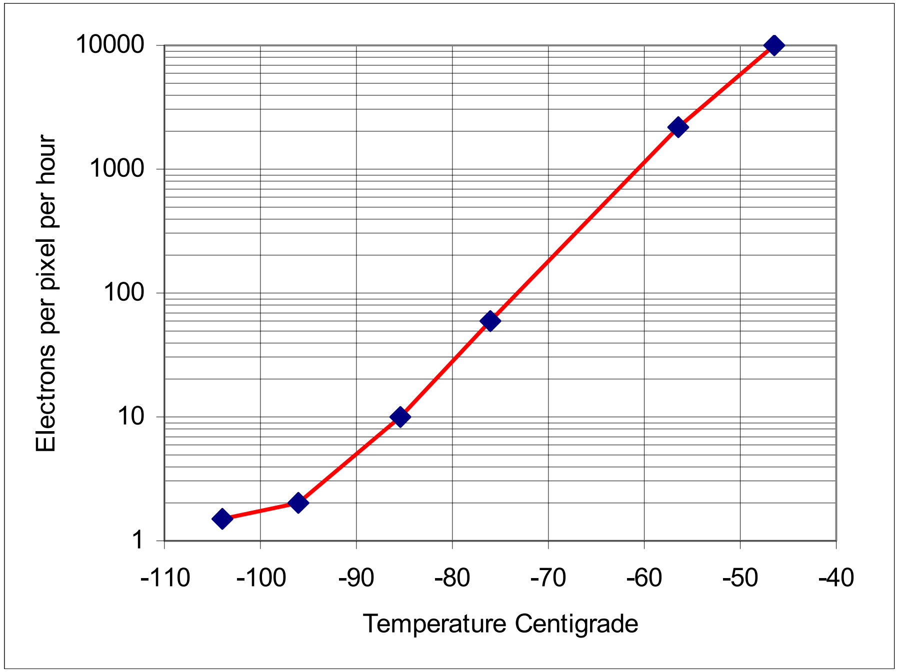
The graph below shows the trade-off between noise and readout speed for an EEV4280 CCD.



Noise Sources in a CCD Image 5.

DARK CURRENT.

Electrons can be generated in a pixel either by thermal motion of the silicon atoms or by the absorption of photons. Electrons produced by these two effects are indistinguishable. Dark current is analogous to the fogging that can occur with photographic emulsion if the camera leaks light. Dark current can be reduced or eliminated entirely by cooling the CCD. Science cameras are typically cooled with liquid nitrogen to the point where the dark current falls to below 1 electron per pixel per hour where it is essentially un-measurable. Amateur cameras cooled thermoelectrically may still have substantial dark current. The graph below shows how the dark current of a TEK1024 CCD can be reduced by cooling.



Noise Sources in a CCD Image 6.

PHOTON NOISE.

This can be understood more easily if we go back to the analogy of rain drops falling onto an array of buckets; the buckets being pixels and the rain drops photons. Both rain drops and photons arrive discretely, independently and randomly and are described by Poissonian statistics. If the buckets are very small and the rain fall is very sparse, some buckets may collect one or two drops, others may collect none at all. If we let the rain fall long enough all the buckets will measure the same value , but for short measurement times the spread in measured values is large. This latter scenario is essentially that of CCD astronomy where small pixels are collecting very low fluxes of photons.

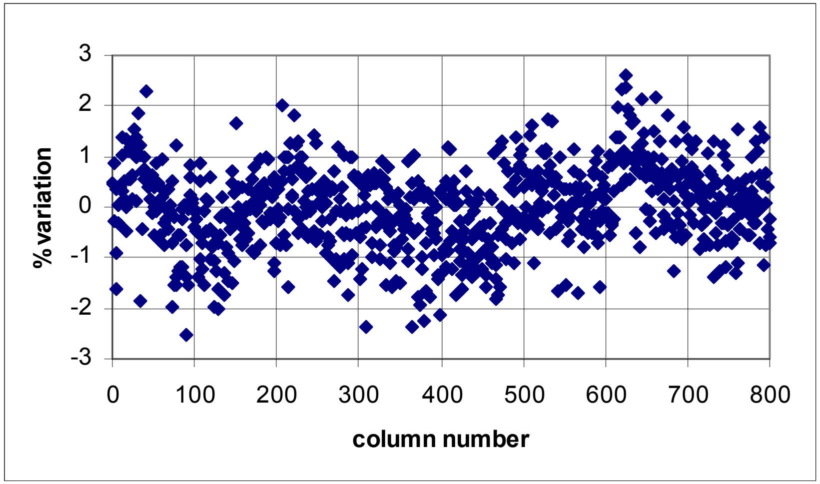
Poissonian statistics tells us that the Root Mean square uncertainty (RMS noise) in the number of photons per second detected by a pixel is equal to the square root of the mean photon flux (the average number of photons detected per second).
For example, if a star is imaged onto a pixel and it produces on average 10 photo-electrons per second and we observe the star for 1 second, then the uncertainty of our measurement of its brightness will be the square root of 10 i.e. 3.2 electrons. This value is the ‘Photon Noise’.
Increasing exposure time to 100 seconds will increase the photon noise to 10 electrons (the square root of 100) but at the same time will increase the ‘Signal to Noise ratio’ (SNR). In the absence of other noise sources the SNR will increase as the square root of the exposure time. Astronomy is all about maximising the SNR.

{ Dark current, described earlier, is also governed by Poissonian statistics. If the mean dark current contribution to an image is 900 electrons per pixel, the noise introduced into the measurement of any pixels photo-charge would be 30 electrons }

Noise Sources in a CCD Image 7.

PIXEL RESPONSE NON-UNIFORMITY (PRNU).

If we take a very deep (at least 50,000 electrons of photo-generated charge per pixel) flat field exposure , the contribution of photon noise and read noise become very small. If we then plot the pixel values along a row of the image we see a variation in the signal caused by the slight variations in sensitivity between the pixels. The graph below shows the PRNU of an EEV4280 CCD illuminated by blue light. The variations are as much as +/-2%. Fortunately these variations are constant and are easily removed by dividing a science image, pixel by pixel, by a flat field image.



Noise Sources in a CCD Image 8.

HOW THE VARIOUS NOISE SOURCES COMBINE

Assuming that the PRNU has been removed by flat fielding, the three remaining noise sources combine in the following equation:

$$\mathrm{NOISE}_{\mathrm{total}} = \sqrt{(\text{READ NOISE})^2 + (\text{PHOTON NOISE})^2 + (\text{DARK CURRENT})^2}$$

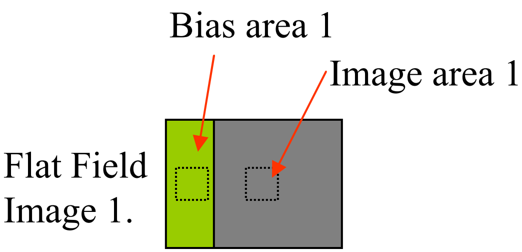
In professional systems the dark current tends to zero and this term of the equation can be ignored. The equation then shows that read noise is only significant in low signal level applications such as Spectroscopy. At higher signal levels, such as those found in direct imaging, the photon noise becomes increasingly dominant and the read noise becomes insignificant. For example , a CCD with read noise of 5 electrons RMS will become photon noise dominated once the signal level exceeds 25 electrons per pixel. If the exposure is continued to a level of 100 electrons per pixel, the read noise contributes only 11% of the total noise.

Photon Transfer Method 1.

Using two identical flat field exposures it is possible to measure the read noise
of a CCD with the Photon Transfer method. Two exposures are required to remove
the contribution of the PRNU and of small imperfections in the flat fields caused by uneven
illumination.
The method actually measures the conversion gain of the CCD camera; the number of electrons
represented by each digital interval (ADU) of the analogue to digital converter, however, once
the gain is known the read noise follows straightforwardly.

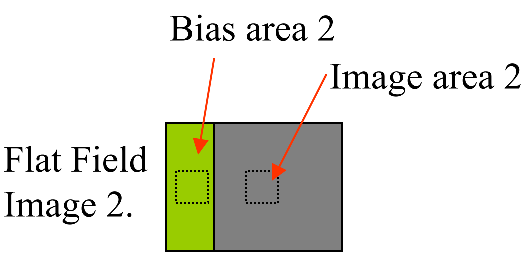
This method exploits the Poissonian statistics of photon arrival. To use it, one requires an image
analysis program capable of doing statistical analysis on selected areas of the input images.

Photon Transfer Method 2.



STEP 1

Measure the Standard Deviation in the two bias areas and average the two values.
result= $\text{Noise}_{\text{ADU}}$ the Root Mean Square readout noise in ADU.



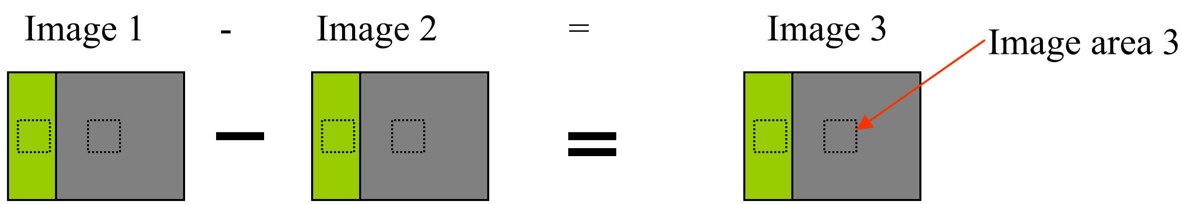
STEP 2

Measure the mean pixel value in the two bias areas and the two image areas. Then subtract $\text{Mean}_{\text{Bias area 1}}$ from $\text{Mean}_{\text{Image area 1}}$
result= Mean_{ADU} ,the Mean Signal in ADU.

As an extra check repeat this for the second image, the Mean should be very similar. If it is more than a few percent different it may be best to take the two flat field exposures again.

Photon Transfer Method 3.

STEP 3 The two images are then subtracted pixel by pixel to yield a third image



STEP 4

Measure the Standard Deviation in image area 3
result= $StdDev_{ADU}$.
The statistical spread in the pixel values in this subtracted image area will be due to a combination of readout noise and photon noise.

STEP 5

Now apply the following equation.

$$\text{Gain} = \frac{2 \text{ x } Mean_{ADU}}{(StdDev_{ADU})^2 - (2 \text{ x } Noise_{ADU}{}^2)}.$$

The units will be electrons per ADU, which will be inversely proportional to the *voltage* gain of the system.

Photon Transfer Method 4.

STEP 6 The Readout noise is then calculated using this gain value :

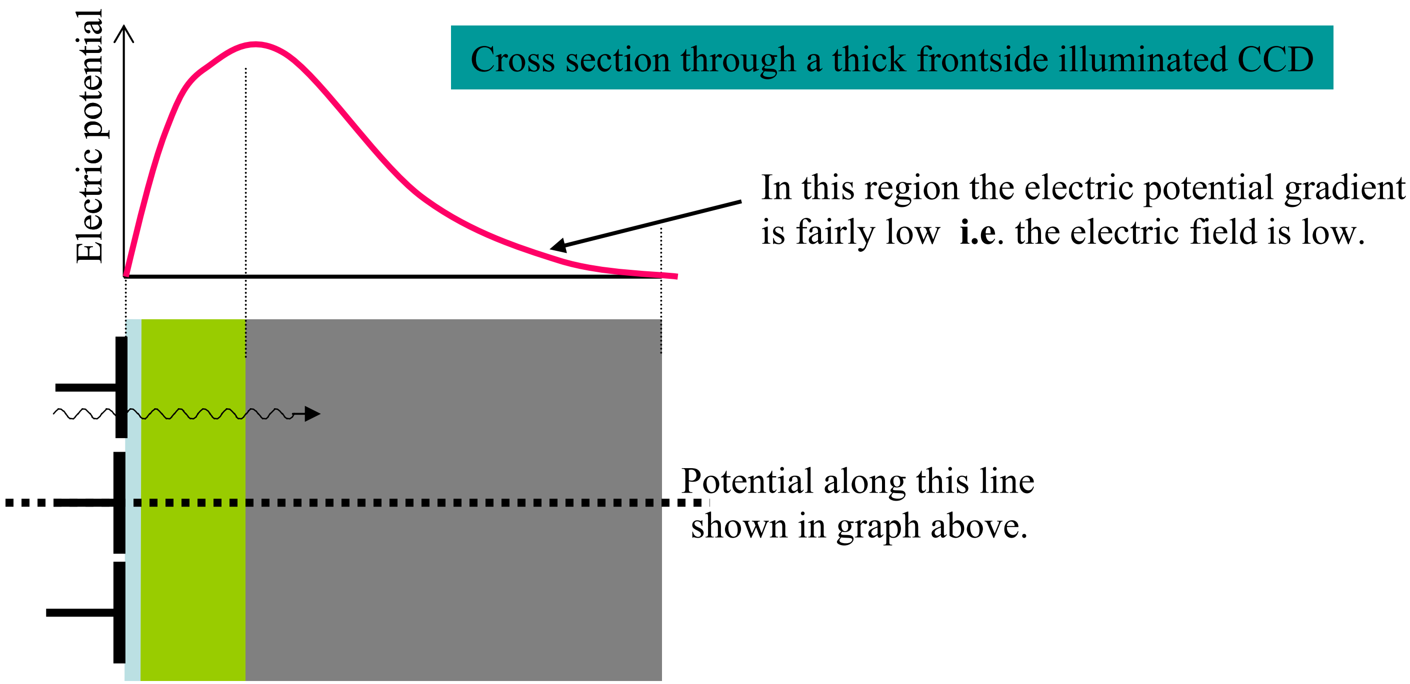
$$\text{Readout Noise}_{\text{electrons}} = \text{Gain} \times \text{Noise}_{\text{ADU}}$$

Precautions when using this method

The exposure level in the two flat fields should be at least several thousand ADU but not so high that the chip or the processing electronics is saturated. 10,000 ADU would be ideal. It is best to average the gain values obtained from several pairs of flat fields. Alternatively the calculations can be calculated on several sub-regions of a single image pair. If the illumination of the flat fields is not particularly flat and the signal level varies appreciable across the sub-region on which the statistics are performed, this method can fail. If good flat fields are unavailable, as will be the case if the camera is connected to a spectrograph, then the sub-regions should be kept small.

Deep Depletion CCDs 1.

The electric field structure in a CCD defines to a large degree its Quantum Efficiency (QE). Consider first a thick frontside illuminated CCD, which has a poor QE.



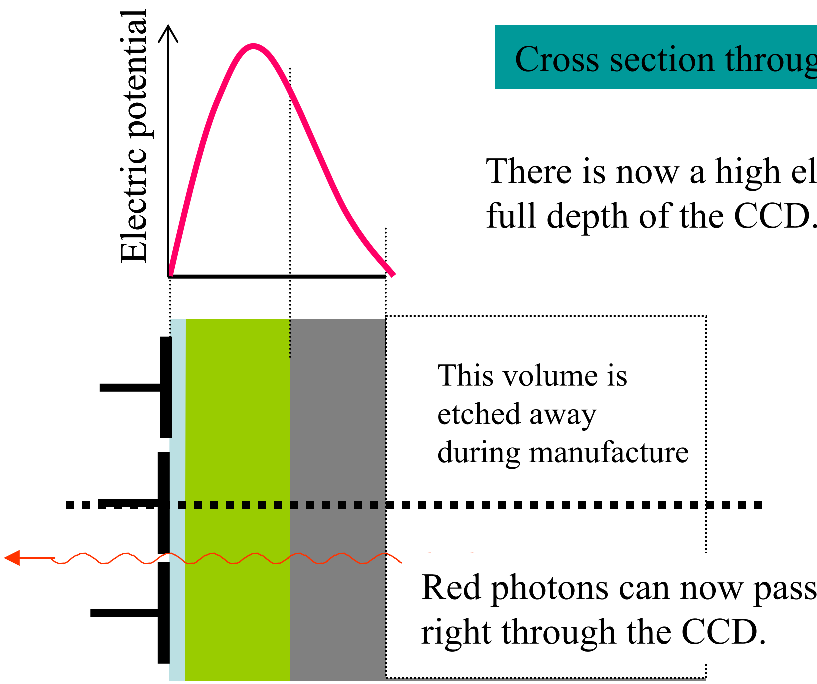
Any photo-electrons created in the region of low electric field stand a much higher chance of recombination and loss. There is only a weak external field to sweep apart the photo-electron and the hole it leaves behind.

Deep Depletion CCDs 2.

In a thinned CCD , the field free region is simply etched away.

Cross section through a thinned CCD

There is now a high electric field throughout the full depth of the CCD.



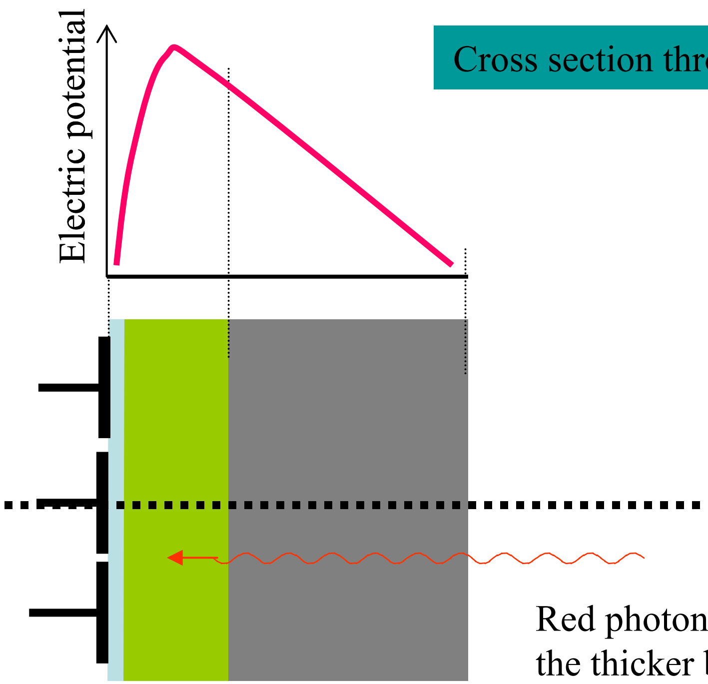
Problem : Thinned CCDs may have good blue response but they become transparent at longer wavelengths; the red response suffers.

Photo-electrons created anywhere throughout the depth of the device will now be detected. Thinning is normally essential with backside illuminated CCDs if good blue response is required. Most blue photo-electrons are created within a few nanometers of the surface and if this region is field free, there will be no blue response.

Deep Depletion CCDs 3.

Ideally we require all the benefits of a thinned CCD plus an improved red response. The solution is to use a CCD with an intermediate thickness of about 40μm constructed from Hi-Resistivity silicon. The increased thickness makes the device opaque to red photons. The use of Hi-Resistivity silicon means that there are no field free regions despite the greater thickness.

Cross section through a Deep Depletion CCD



Red photons are now absorbed in the thicker bulk of the device.

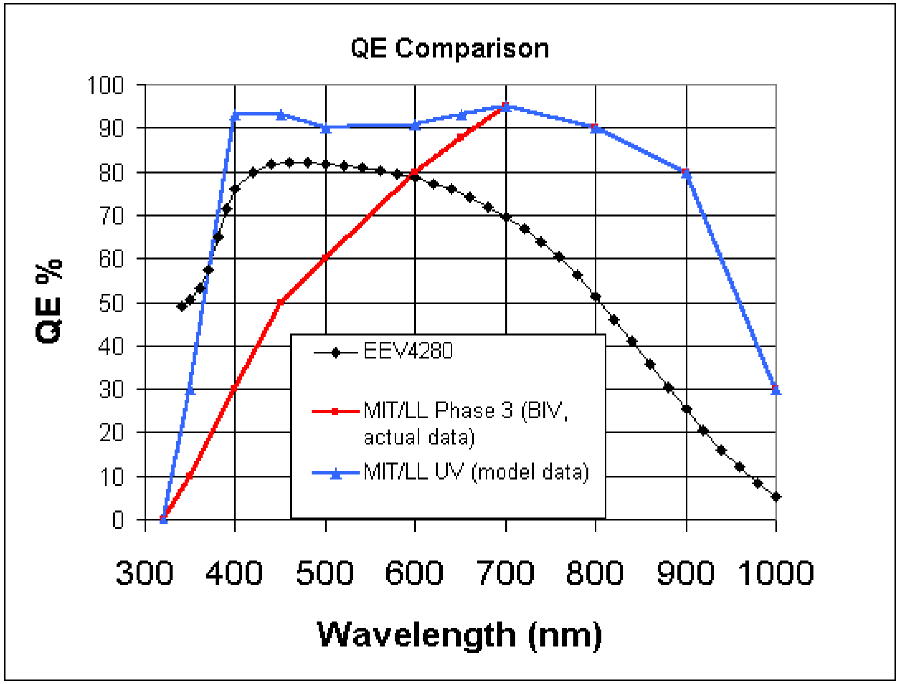
Problem :

Hi resistivity silicon contains much lower impurity levels than normal. Very few wafer fabrication factories commonly use this material and deep depletion CCDs have to be designed and made to order.

There is now a high electric field throughout the full depth of the CCD. CCDs manufactured in this way are known as Deep depletion CCDs. The name implies that the region of high electric field, also known as the ‘depletion zone’ extends deeply into the device.

Deep Depletion CCDs 4.

The graph below shows the improved QE response available from a deep depletion CCD.

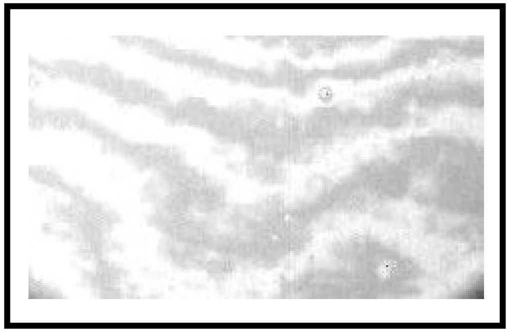


The black curve represents a normal thinned backside illuminated CCD. The Red curve is actual data from a deep depletion chip manufactured by MIT Lincoln Labs. This latter chip is still under development.The blue curve suggests what QE improvements could eventually be realised in the blue end of the spectrum once the process has been perfected.

Deep Depletion CCDs 5.

Another problem commonly encountered with thinned CCDs is ‘fringing’.which is greatly reduced in deep depletion CCDs. Fringing is caused by multiple reflections inside the CCD. At longer wavelengths, where thinned chips start to become transparent, light can penetrate through and be reflected from the rear surface. It then interferes with light entering for the first time. This can give rise to constructive and destructive interference and a series of fringes where there are minor differences in the chip thickness.

The image below shows some fringes from an EEV42-80 thinned CCD



For spectroscopic applications, fringing can render some thinned CCDs unusable, even those that have quite respectable QEs in the red. Thicker deep depletion CCDs , which have a much lower degree of internal reflection and much lower fringing are preferred by astronomers for spectroscopy.

Mosaic Cameras 1.

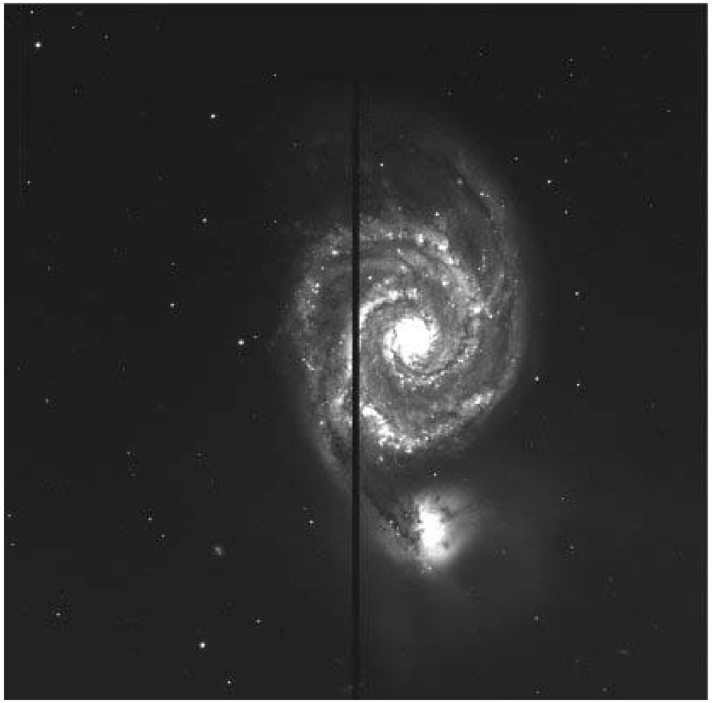
When CCDs were first introduced into astronomy, a major drawback, compared to photographic plate detectors was their small size. CCDs are still restricted in size by the silicon wafers that are used in their production. Most factories can only handle 6” diameter wafers. The largest photographic plates are about 30 x 30cms and when used with wide angle telescopes can simultaneously image a region of sky 6^0 x 6^0 in size. To cover this same area of sky with a smaller CCD would require hundreds of images and would be an extremely inefficient use of the telescope’s valuable time. It is unlikely that CCDs will ever reach the same size as photographic detectors, so for applications requiring large fields of view, mosaic CCD cameras are the only answer. These are cameras containing a number of CCDs mounted in the same plane with only small gaps between adjacent devices.

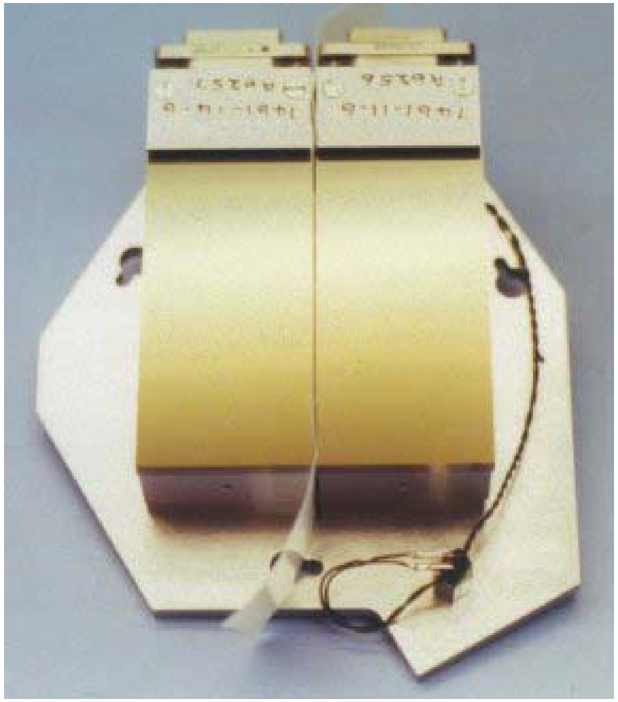
Mosaic CCD cameras containing up to 30 CCD chips are in common use today, with even larger mosaics planned for large survey telescopes in the near future. One interesting technical challenge associated with their design is in keeping all the chips in the same plane (i.e. the focal plane of the telescope) to an accuracy of a few tens of microns. If there are steps between adjacent chips then star images will be in focus on one chip but not necessarily on its neighbors.

Most new CCD are designed for close butting and the construction of mosaics. This is achieved by using packages with electrical connections along one side only leaving the other three sides free for butting. The next challenge is to build CCDs which have the connections on the rear of the package and are buttable on 4 sides! This would allow full unbroken tiling of a telescopes focal plane and the best possible use of its light gathering power.

Mosaic Cameras 2.

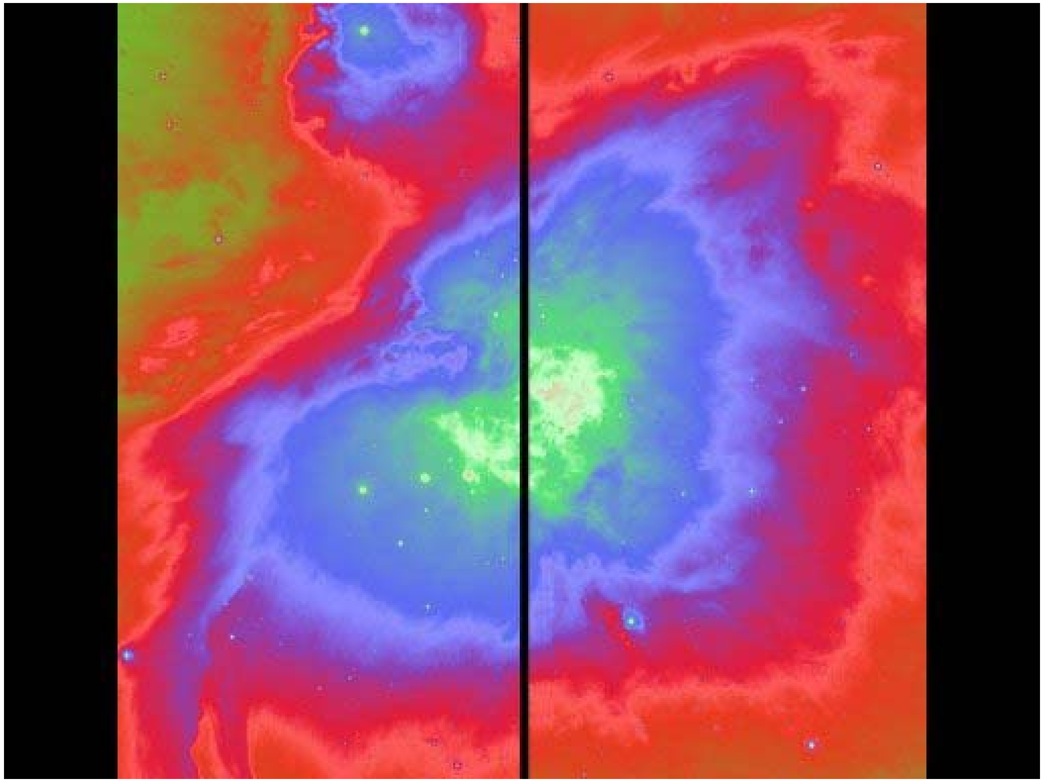
The pictures below show the galaxy M51 and the CCD mosaic that produced the image. Two EEV42-80 CCDs are screwed down onto a very flat Invar plate with a 50 micron gap between them. Light falling down this gap is obviously lost and causes the black strip down the centre of the image. This loss is not of great concern to astronomers, since it represents only 1% of the total data in the image.





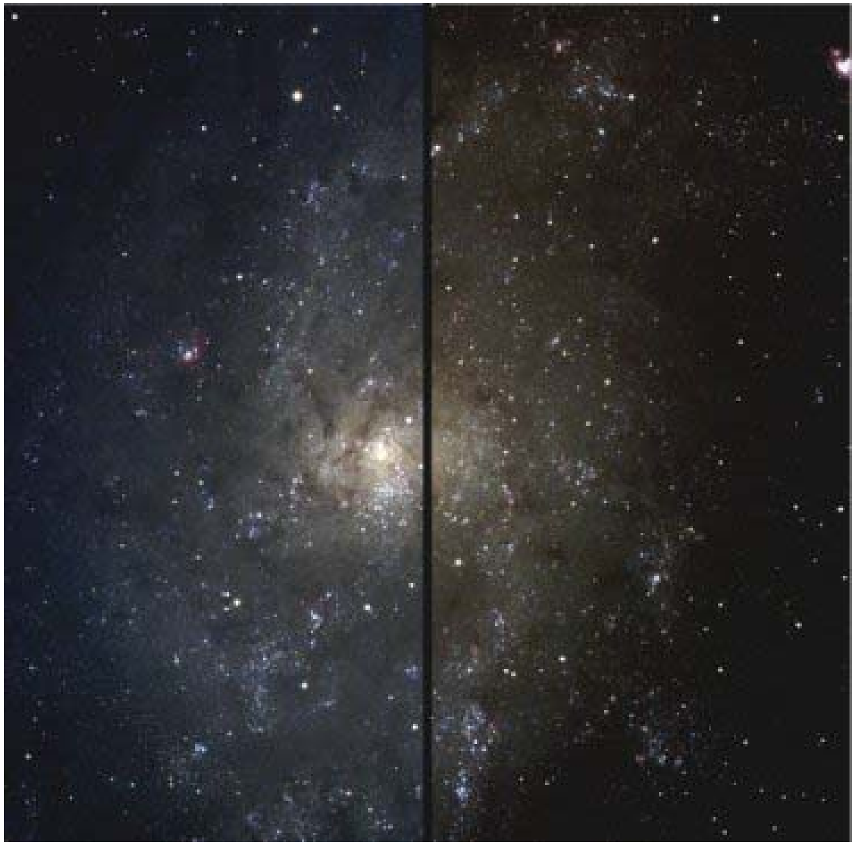
Mosaic Cameras 3.

Another image from this camera is shown below. The object is M42 in Orion. This false colour image covers an area of sky measuring 16’ x 16’. The image was obtained on the William Herschel Telescope in La Palma.



Mosaic Cameras 4.

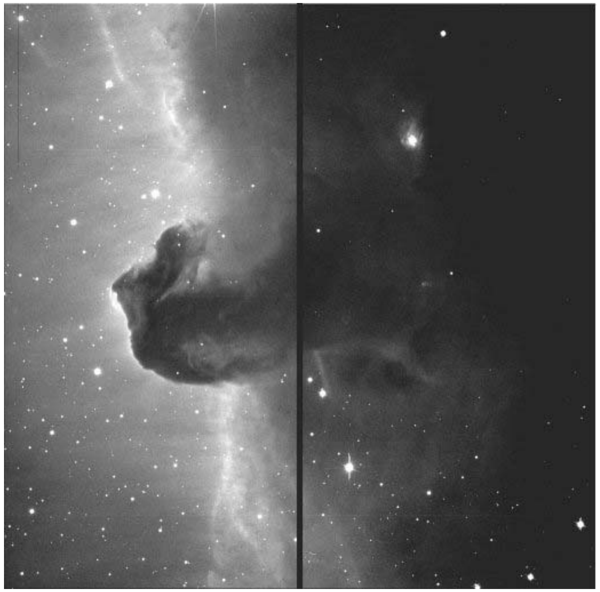
A further image is shown below, of the galaxy M33 in Triangulum. Images from this camera are enormous; each of the two chips measures 2048 x 4100 pixels. The original images occupy 32MB each.



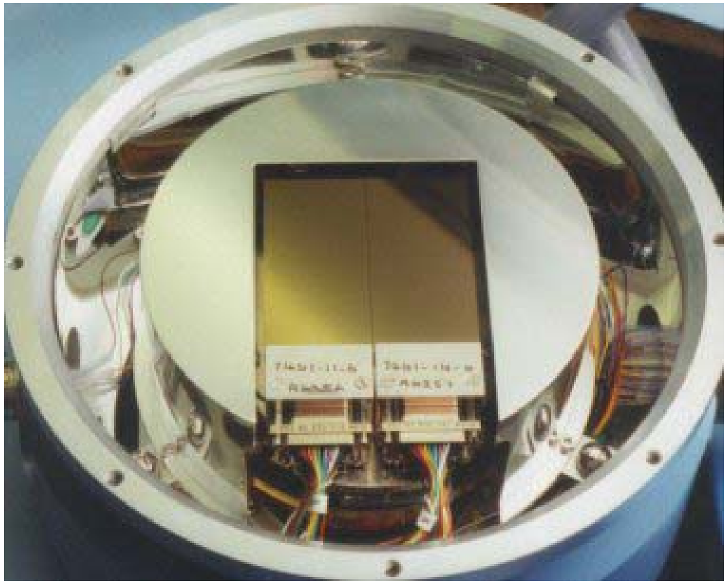
Nik Szymanek

Mosaic Cameras 5.

The Horsehead Nebula in Orion.

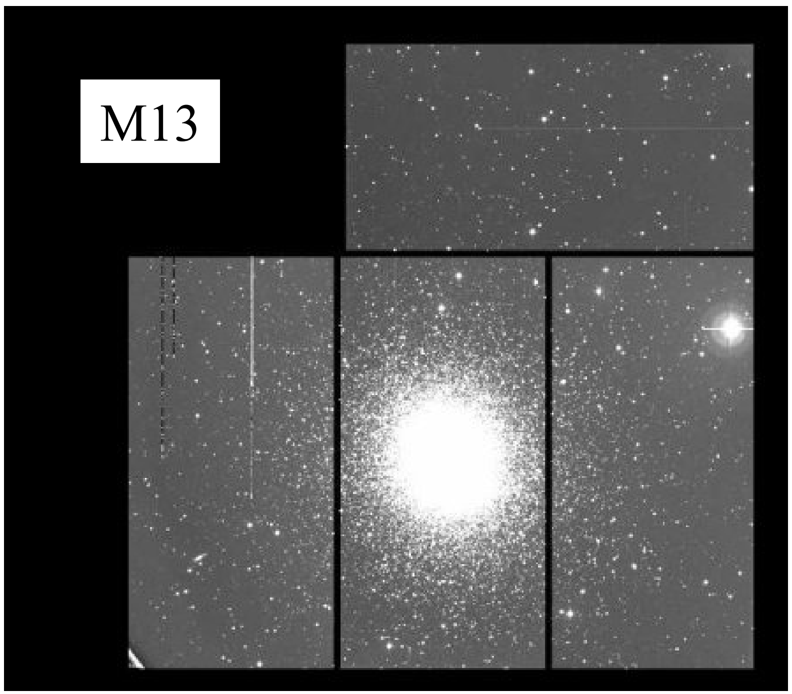


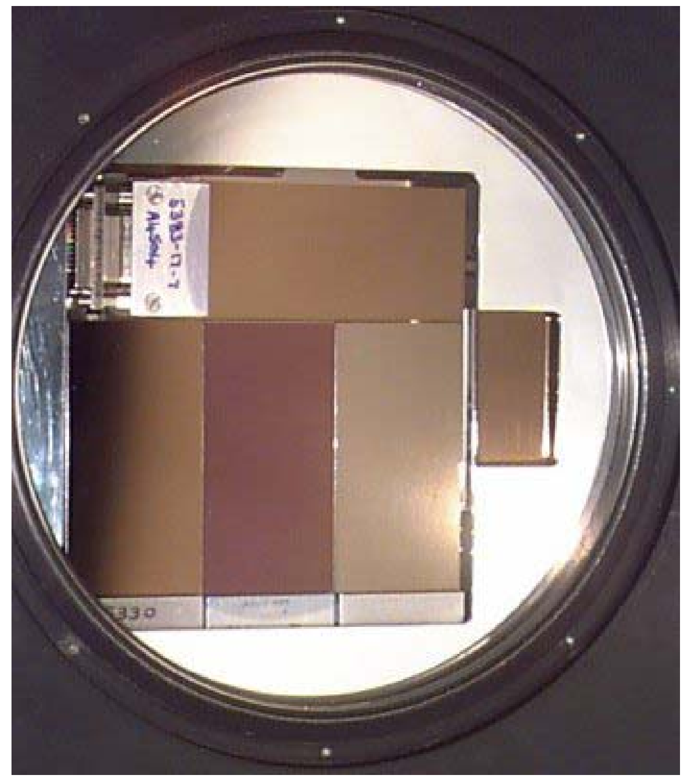
The mosaic mounted in its camera.



Mosaic Cameras 7.

This mosaic of 4 science CCDs was built at the Royal Greenwich Observatory. The positioning of the CCDs is somewhat unusual but ultimately all that matters is the total area covered . A smaller fifth CCD on the right hand side is used for auto-guiding the telescope. An example of this camera’s output is shown on the left.





Low Light Level CCDs (LLLCCD)

A new idea from Marconi (EEV) to reduce or eliminate CCD read-out noise.