Image Sensors

Learners' Space Astronomy

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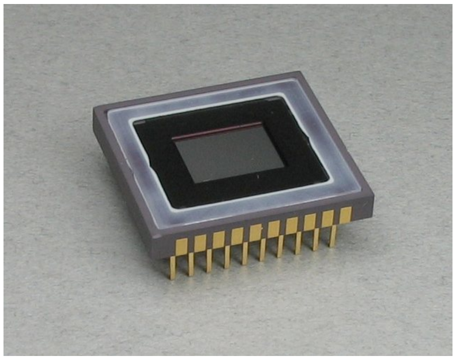
Image Sensors

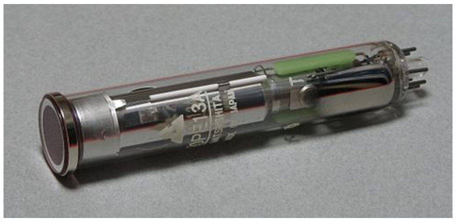
As we know that many objects in the sky are not visible to the naked eye, but we still want to be able to capture these objects and study them.

For this, we use image sensors.There are multiple different types of image sensors like digital image sensors, electronic image sensors and analog image sensors.

The two main types of electronic image sensors are the charge-coupled device (CCD) and the active-pixel sensor (CMOS sensor). Both CCD and CMOS sensors are based on metal–oxide–semiconductor (MOS) technology, with CCDs based on MOS capacitors and CMOS sensors based on MOSFET (MOS field-effect transistor) amplifiers. Analog sensors for invisible radiation tend to involve vacuum tubes of various kinds, while digital sensors include flat-panel detectors.



(a) A ccd sensor



(b) vidicon(analog image sensor)

There are many parameters that can be used to evaluate the performance of an image sensor, including dynamic range (a camera's dynamic range refers to how many increments the image sensor can detect between pure black and pure white – plus the tones in between.), signal-to-noise ratio, and low-light sensitivity. For sensors of comparable types, the signal-to-noise ratio and dynamic range improve as the size increases. It is because in a given integration (exposure) time, more photons hit the pixel with larger area.
The amount of time the sensor is shown to the source is called as the exposure time, and is controlled by a shutter which is usually electronic. This shuttering can be

- **Global** : which means that the entire image area's accumulation of photoelectrons is read at once. Aka, the whole image is read in one go.

- **Rolling** : which means that the accumulation of photoelectrons are read pixel line by line

To see the effect in action check this and more on how the rolling shutter works.

CCD

What is a CCD Sensor?

A charge-coupled device (CCD) is a light-sensitive integrated circuit that captures images by converting photons to electrons. A CCD sensor breaks the image elements into pixels. Each pixel is converted into an electrical charge whose intensity is related to the intensity of light captured by that pixel.

They are semiconductor devices invented by Williard Boyle and George Smith at the AT&T Bell Laboratories in 1970.

Structure and Working principle of CCD

A CCD imager consists of a large number of light-sensing elements arranged in a two-dimensional array on a thin silicon substrate. The semiconductor properties of silicon allow the CCD chip to trap and hold photon-induced charge carriers under appropriate electrical bias conditions. Individual picture elements, or pixels, are defined in the silicon matrix by an orthogonal grid of narrow transparent current-carrying electrode strips, or gates, deposited on the chip. The fundamental light-sensing unit of the CCD is a metal oxide semiconductor (MOS) capacitor operated as a photodiode and storage device. A single MOS device of this type is illustrated in figure below, with reverse bias operation causing negatively charged electrons to migrate to an area underneath the positively charged gate electrode.

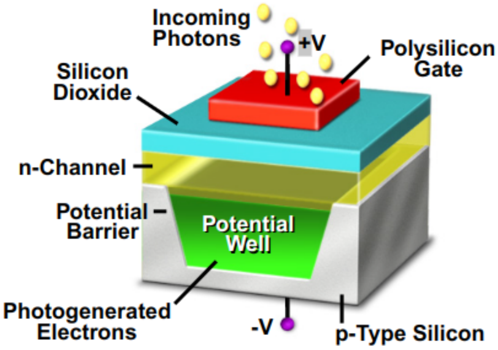


Figure 2.1: a single MOS unit

Electrons liberated by photon interaction are stored in the depletion region up to the full well reservoir capacity. When multiple detector structures are assembled into a complete CCD, individual sensing elements in the array are segregated in one dimension by voltages applied to the surface electrodes and are electrically isolated from their neighbors in the other direction by insulating barriers, or channel stops, within the silicon substrate.

Image generation with a CCD camera can be divided into four primary stages or functions: charge generation through photon interaction with the device's photosensitive region, collection and storage of the liberated charge, charge transfer, and charge measurement.
During the first stage, electrons and holes are generated in response to incident photons in the depletion region of the MOS capacitor structure, and liberated electrons migrate into a potential well formed beneath an adjacent positively-biased gate electrode.
During readout, the collected charge is subsequently shifted along the transfer channels under the influence of voltages applied to the gate structure.
In general, the stored charge is linearly proportional to the light flux incident on a sensor pixel up to the capacity of the well; consequently this **full-well capacity** (FWC) determines the maximum signal that can be sensed in the pixel, and is a primary factor affecting the CCD's dynamic range.
The stored charge accumulated within each CCD photodiode during a specified time interval, referred to as the integration time or **exposure time**, must be measured to determine the photon flux on that diode.

The electrode network, or gate structure, built onto the CCD in a layer adjoining the sensor elements, constitutes the shift register for charge transfer. The basic charge transfer concept that enables serial readout from a two-dimensional diode array initially requires the entire array of individual charge packets from the imager surface, constituting the parallel register, to be simultaneously transferred by a single-row incremental shift. The charge-coupled shift of the entire parallel register moves the row of pixel charges nearest the register edge into a specialized single row of pixels along one edge of the chip referred to as the serial register. It is from this row that the charge packets are moved in sequence to an on-chip amplifier for measurement. After the serial register is emptied, it is refilled by another row-shift of the parallel register, and the cycle of parallel and serial shifts is repeated until the entire parallel register is emptied.

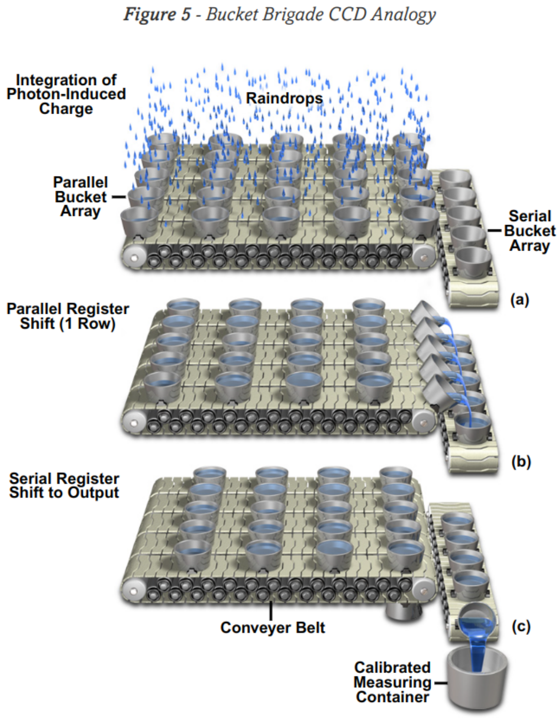


Figure 2.2: Bucket analogy

A widely used analogy to aid in visualizing the concept of serial readout of a CCD is the bucket brigade for rainfall measurement, in which rain intensity falling on an array of buckets may vary from place to place in similarity to incident photons on an imaging sensor (see Figure 5 (a)). The parallel register is represented by an array of buckets, which have collected various amounts of signal (water) during an integration period. The buckets are transported on a conveyor belt in stepwise fashion toward a row of empty buckets that represent the serial register, and which move on a second conveyor oriented perpendicularly to the first. In Figure 5(b), an entire row of buckets is being shifted in parallel into the reservoirs of the serial register. The serial shift and readout operations are illustrated in Figure 5(c), which depicts the accumulated rainwater in each bucket being transferred sequentially into a calibrated measuring container, analogous to the CCD output amplifier. When the contents of all containers on the serial conveyor have been measured in sequence, another parallel shift transfers contents of the next row of collecting buckets into the serial register containers, and the process repeats until the contents of every bucket (pixel) have been measured.
To understand a bit more on how it works , Check this out.

CMOS

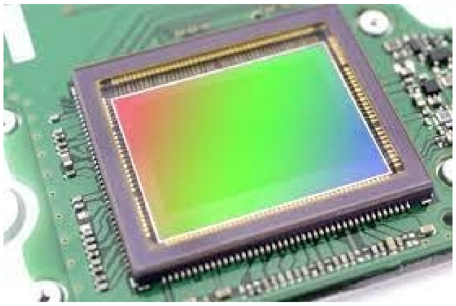
What are CMOS Sensors?

CMOS (Complementary Metal-Oxide-Semiconductor) sensors are semiconductor devices used to convert light into electronic signals.Because CMOS image sensors are constructed with standard semiconductor manufacturing technology, the chips usually include signal processing, analog-to-digital converter, and digital logic on-chip. This results in a full camera on a chip. This technology has enabled many imaging applications, including tiny digital cameras on smartphones, high-definition, high-speed professional video cameras, and Earth observation sensors on satellites.

Types of CMOS Sensors:

- **Active Pixel Sensors (APS):** The most common type of CMOS sensor. Each pixel has its own photodiode and active amplifier, allowing for the direct conversion of light to voltage. This enables faster readout and processing.
- **Passive Pixel Sensors (PPS):** An older technology where the charge collected by each pixel is transferred to a common output amplifier. This type has largely been replaced by APS due to its lower performance and slower speed.

(a) Active Pixel Sensor



(b) Passive Pixel Sensor

How Does a CMOS Sensor Work?

CMOS sensors operate by converting light into electrical signals through a series of processes:

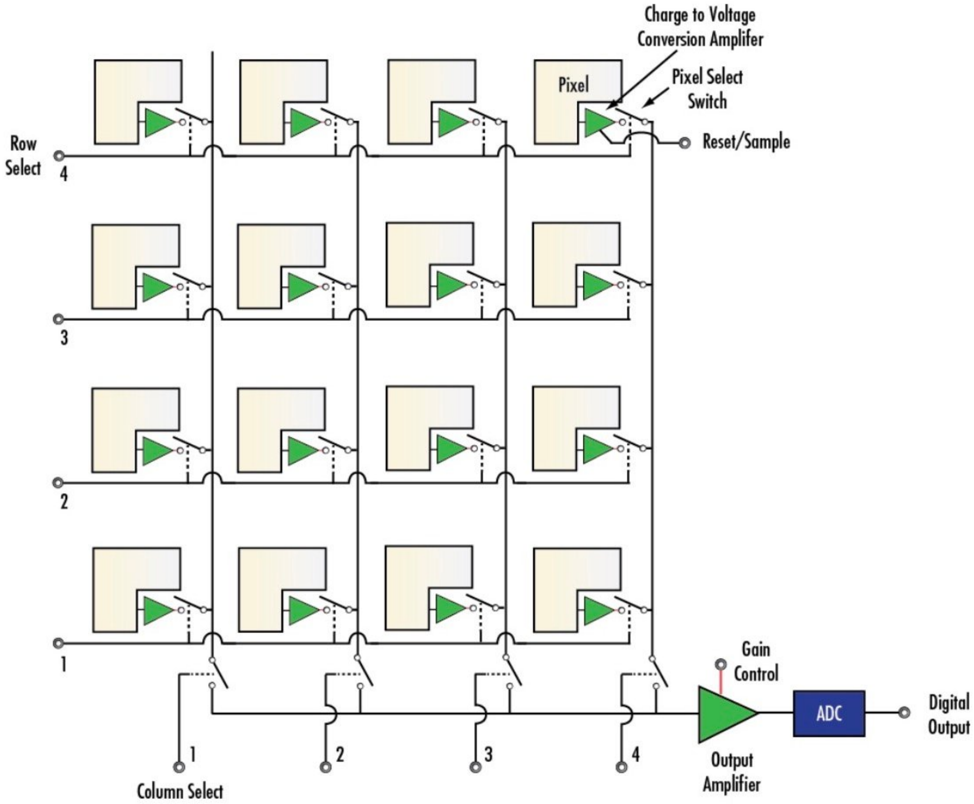


Figure 3.2: CMOS Sensor Design (Block Diagram)

- **Photon Detection:** When light enters the camera, it passes through the lens and strikes the sensor. Each pixel on the sensor contains a photodiode, which absorbs photons and converts them into electron-hole pairs, generating an electrical charge proportional to the light intensity.
- **Charge Conversion:** In Active Pixel Sensors (APS), each pixel's photodiode is connected to an amplifier. The accumulated charge is converted into a voltage by this amplifier. This voltage signal represents the intensity of the light that hit the pixel.
- **Signal Readout:** The voltages from each pixel are read out by row and column addressing circuitry. This readout process can happen very quickly, allowing for high frame rates and fast image capture.
- **Analog-to-Digital Conversion (ADC):** The analog voltage signals are then converted into digital signals by an ADC. This digital data represents the image and can be processed, stored, or displayed.
- **Image Processing:** Additional on-chip processing functions, such as noise reduction, color correction, and compression, can be integrated into CMOS sensors. This integration simplifies the overall system design and enhances performance.

CCD VS CMOS

CMOS Sensor	CCD Sensor
CMOS sensor is a metal oxide semiconductor chip, used to change light into an electrical signal.	It is a charge-coupled device, used to transmit electrically charged signals.
CMOS sensors are available in two types active pixel and passive pixel.	CCD sensors are available in three types like Full-Frame, Frame-Transfer and Interline-Transfer.
Low power consumption	Moderate to high power consumption
Low uniformity	High uniformity
These sensors are not expensive to design because these sensors are designed on most typical Si production lines.	These are expensive to generate.
more noisy images, lesser quality images	less noisy and higher quality images
CMOS sensors are used from automation in industries to traffic control-based applications.	CCD sensors are used in hand-held, surveillance, video cameras of desktop computers, etc.

In the last decade or so, CMOS has been evolving much faster than CCD as a result of investments in the cell phone camera market/consumer market.

The change over in the industrial camera market from CCD to CMOS is now.

There are global shutter CMOS image sensors available with image quality that is now comparable to CCD. The latest CMOS image sensors even perform better than CCD on key image quality parameters, such as sensitivity in low light.

Flux Units in Optical Astronomy

Light is the main signal we get from space. It is therefore important to be able to measure the brightness of stars and galaxies. If we can quantify how bright an object is, we can compare it with other objects. It also lets us work out whether the brightness of an object changes over time.

The Magnitude Scale

When you hear the word magnitude in astronomy, you're usually hearing a number describing how bright a star – or other space object – looks.At optical wavelengths, it the most common unit used.The magnitude scale was invented by an Ancient Greek astronomer named Hipparchus. He gave the brightest stars a value of 1 and the dimmest stars he could see a value of 6.
Thus,**Large number = faint source !!!**

So, a 2nd-magnitude star is modestly bright. But it's fainter than a 1st-magnitude star.

And a 5th-magnitude star is still pretty faint. But it's brighter than a 6th-magnitude star.

Since the invention of better and better telescopes, the magnitude scale has had to be extended. We now know of objects much fainter than the naked eye limit of 6. We also include bright objects that have magnitudes less than 1. For example, the star Vega is given the value of zero.

Also, the scale is logarithmic, not linear. For example, a magnitude 1 star is not 2 times as bright as a magnitude 2 star. The difference in brightness between each magnitude is actually almost 2.512 times. This means that a star with a magnitude of 1 is 100 times brighter than a star with a magnitude of 6 (2.512 x 2.512 x 2.512 x 2.512 x 2.512 =100).

The maths of magnitude can be summed up in the equation:

$$m1 - m2 = -2.5log(f1/f2)$$

$m1$ and $m2$ represent the magnitude of two stars and $f1$ and $f2$ represent their relative fluxes. Flux is the brightness divided by the area used to collect the light (usually the telescope aperture).

For example, imagine 2 stars visible in the night sky. One star is 100 times brighter than the other. This value of 100 represents the ratio of the fluxes ($f1/f2$). Since the log of 100 is 2, we can say that $m1 - m2 = -2.5 \times 2 = -5$. This tells us that star 1 is 5 magnitudes brighter than

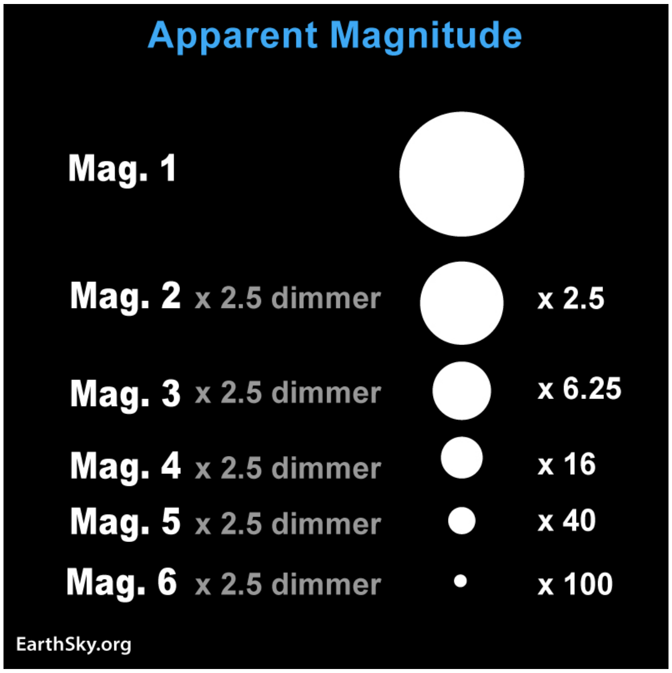


Figure 5.1: The Magnitude Scale Visualization

star 2 (remember that the magnitude scale is inverse).

Types of Magnitude

There are 2 types of stellar magnitude: absolute and apparent.

- The **absolute magnitude** (M) is how bright the object would be if it was a set distance from the Earth. A distance of 10 parsecs is used. A parsec is a distance unit used in astronomy. It is the same as 3.26 light years, or 31,000 billion kilometres (19,000 billion miles)! Absolute magnitudes let us compare the brightness of different objects.
- The **apparent magnitude** (m) is how bright the object appears to be from Earth. When objects get further away from Earth they appear fainter. A star more than 10 parsecs away from Earth will look fainter than its absolute magnitude. A star which is closer will be brighter than its absolute magnitude.

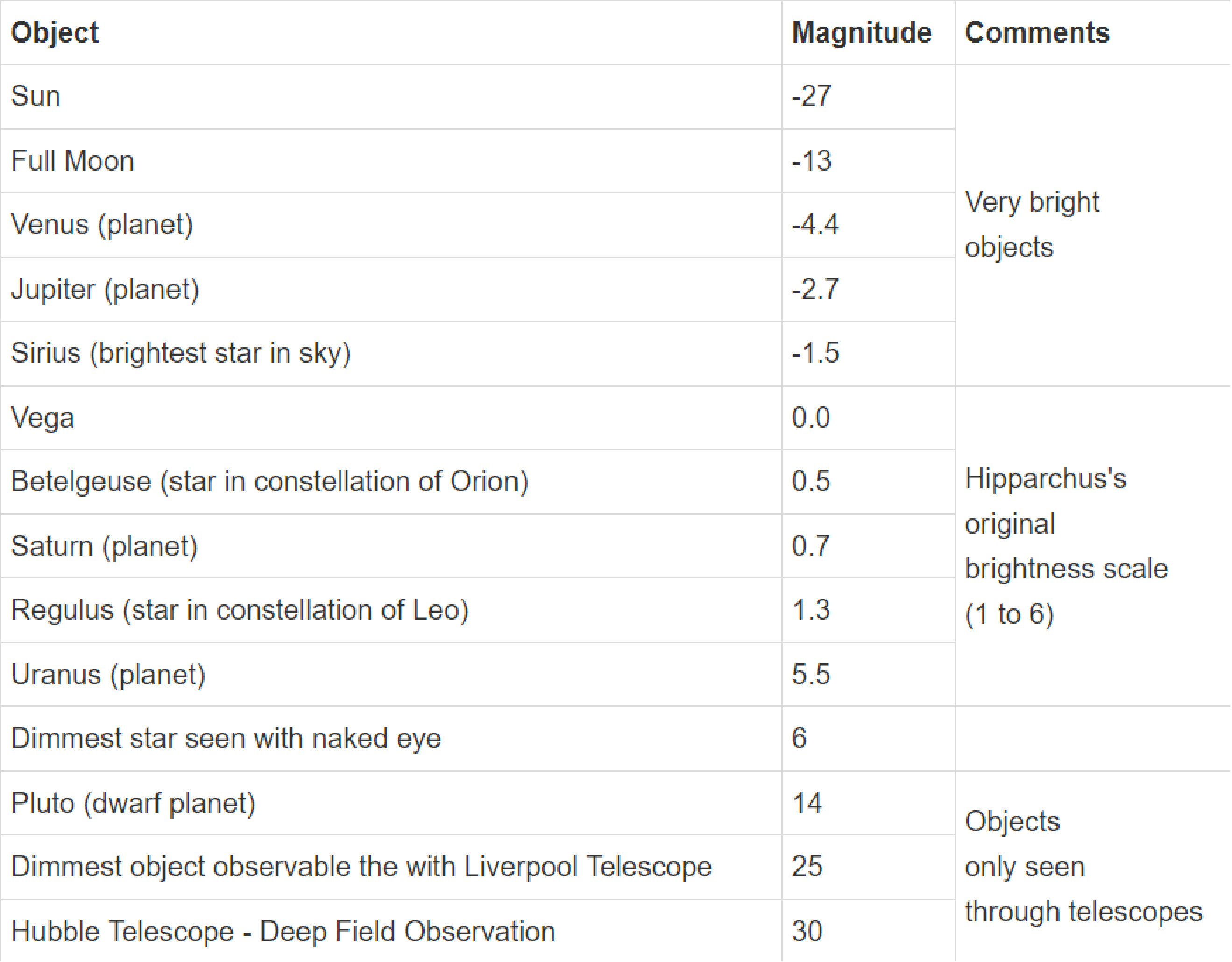
Astronomers use the difference between apparent and absolute magnitude, the **distance modulus**, as a way of determining the distance to a star.

- Distance Modulus $= m - M$.
- Distance modulus is negative for stars closer than 10 parsecs.
- Distance modulus is positive for stars further away than 10 parsecs.

The distance modulus can be used to determine the distance to a star using the equation:

$$m - M = 5log(d/10)$$

where d is in parsecs. Note that if $d = 10$ pc then m and M are the same. (For those interested, a formal derivation of this equation is given on this page).



Object	Magnitude	Comments
Sun	-27	Very bright objects
Full Moon	-13	
Venus (planet)	-4.4	
Jupiter (planet)	-2.7	
Sirius (brightest star in sky)	-1.5	
Vega	0.0	Hipparchus's original brightness scale (1 to 6)
Betelgeuse (star in constellation of Orion)	0.5	
Saturn (planet)	0.7	
Regulus (star in constellation of Leo)	1.3	
Uranus (planet)	5.5	
Dimmest star seen with naked eye	6	
Pluto (dwarf planet)	14	Objects only seen through telescopes
Dimmest object observable the with Liverpool Telescope	25	
Hubble Telescope - Deep Field Observation	30	

Figure 5.2: Some Examples of Magnitude Scale