What's In An Astro-Video Camera?

by

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October 2012

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Acknowledgements

Sony Corporation (www.sony.net) for their CCD data sheets.

Edmund Optics (www.edmundoptics.com) for their online tutorial “Imaging Electronics 101”.

Special thanks to Rock Mallin (mallincam.tripod.com) for sharing his knowledge and insight into astro-video camera design.

1.0 Introduction

The field of Video Astronomy grows day by day, with new cameras coming on to the market at an ever increasing rate. The growing list of astro-video camera manufacturers and models is providing amateur astronomers with more choices, but it is also making it more difficult to choose the right camera for one's particular application. An important component in an astro-video camera is the sensor, which in most cases is a Charge-Coupled Device (CCD). In an effort to help with the camera selection process, I have compiled this whitepaper that provides some background on imaging technology for the newbie.

2.0 Sensor Technology

There are two main types of electro-optical sensors used in cameras: the Charge-Coupled Device (CCD) and the Complementary Metal Oxide Semiconductor (CMOS). Each device goes about the business of converting photons into an electrical signal differently. The CCD was invented by Bell Labs in 1969, and consists of a silicon chip with an array of photosensitive sites called "pixels". Figure 1 illustrates a typical cross section of a CCD pixel. Note that later in this report the term "pixel size" refers to the "sensor aperture" shown in Figure 1, and the "chip size" divided by the "resolution" gives the "unit pixel" size which includes both the sensor aperture and the associated read-out circuitry.

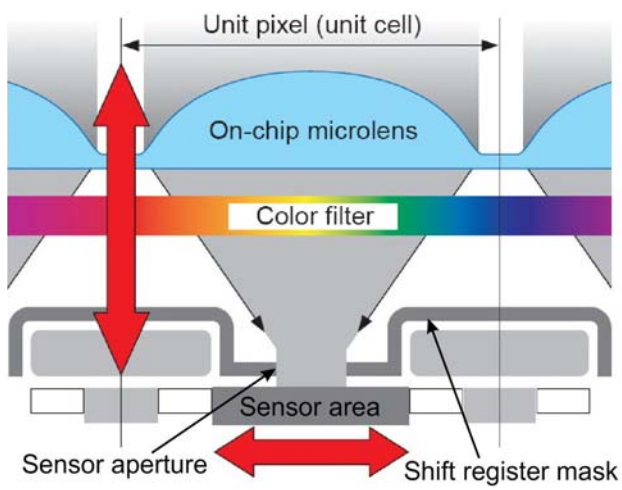

Figure 1 Cross Section of a CCD Pixel (courtesy Sony Corporation)

When a photon strikes a pixel in the array, it is converted to an electron which then accumulates in the pixel over the course of an exposure. At the end of the desired exposure time, the accumulated charge in each pixel is read out by moving the charges along the chip using a clock pulse timed shift register; basically a bucket brigade where each pixel's charge is passed along row by row and column by column until each pixel has been read (see Figure 2). As a result the CCD is an analog device, with its output often converted immediately to digital off-chip before further processing is applied. The disadvantage of the charge-coupled scheme is that CCD's have slower refresh rates than CMOS detectors. The advantage however is that they are more sensitive and have better pixel-to-pixel uniformity than CMOS. CCD's are also prone to blooming, where if the charge capacity of a pixel is exceeded the excess charge can spill over into neighbouring pixels. To improve the sensitivity of CCDs it is very common to use microlenses over each pixel. Sensitivity has been further improved by designing the photoreceptors to respond more efficiently in the red and infrared end of the spectrum, a technology developed by Sony called EXview. Another technological advancement patented by Sony is the Hole Accumulation Diode (HAD), an extra semiconductor layer below the surface of the CCD that accumulates stray charge on the chip, greatly reducing dark current noise.

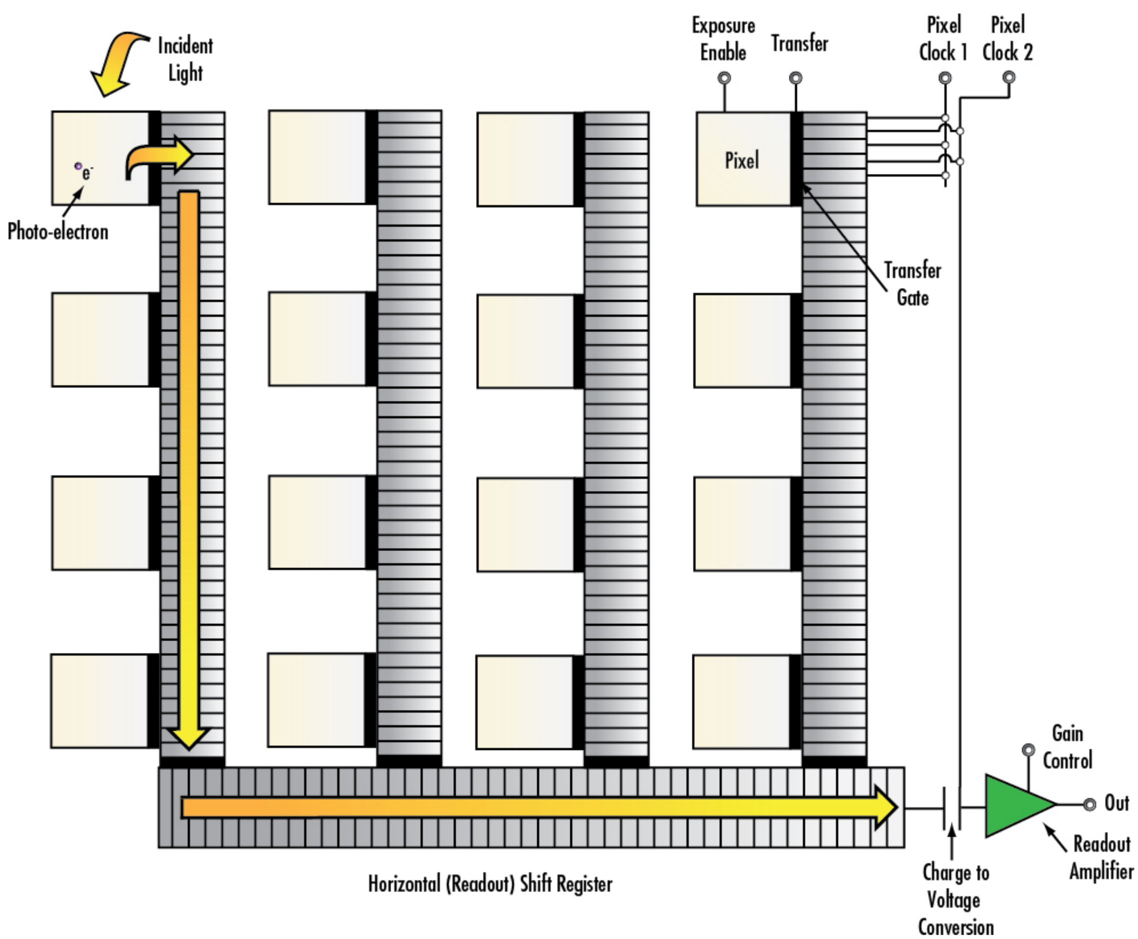

Figure 2 Block Diagram of a CCD (courtesy Edmund Optics)

The CMOS imaging sensor was invented by Frank Wanlass in 1963, but it did not see wide spread use in cameras until the 1990's. In a CMOS sensor the accumulated charge is converted directly to a voltage at the pixel site, and then is multiplexed by row and column to multiple on-chip digital-to-analog converters (DACs). As a result the CMOS sensor is an inherently digital device. Each pixel site on the chip is able to perform the task of resetting the pixel, amplification and charge conversion, and multiplexing, resulting in very high read speeds. The drawback of the design is high fixed-pattern noise due to difficulties manufacturing each of the thousands of voltage conversion circuits exactly the same. The multi-layer MOS fabrication process also does not allow for the addition of microlenses on the chip to improve sensitivity, making CMOS sensors generally much less sensitive than CCDs. CMOS sensors are better able to handle high light levels than CCDs without blooming, making them useful for high dynamic range applications. CMOS based cameras also tend to be smaller in size, and consume less power. Recent advances in CMOS technology, most notably the new Scientific CMOS (sCMOS) sensors, have greatly improved the signal-to-noise ratios that are achievable over earlier CMOS designs. As a result sCMOS sensors are slowly becoming more popular in astro-video cameras.

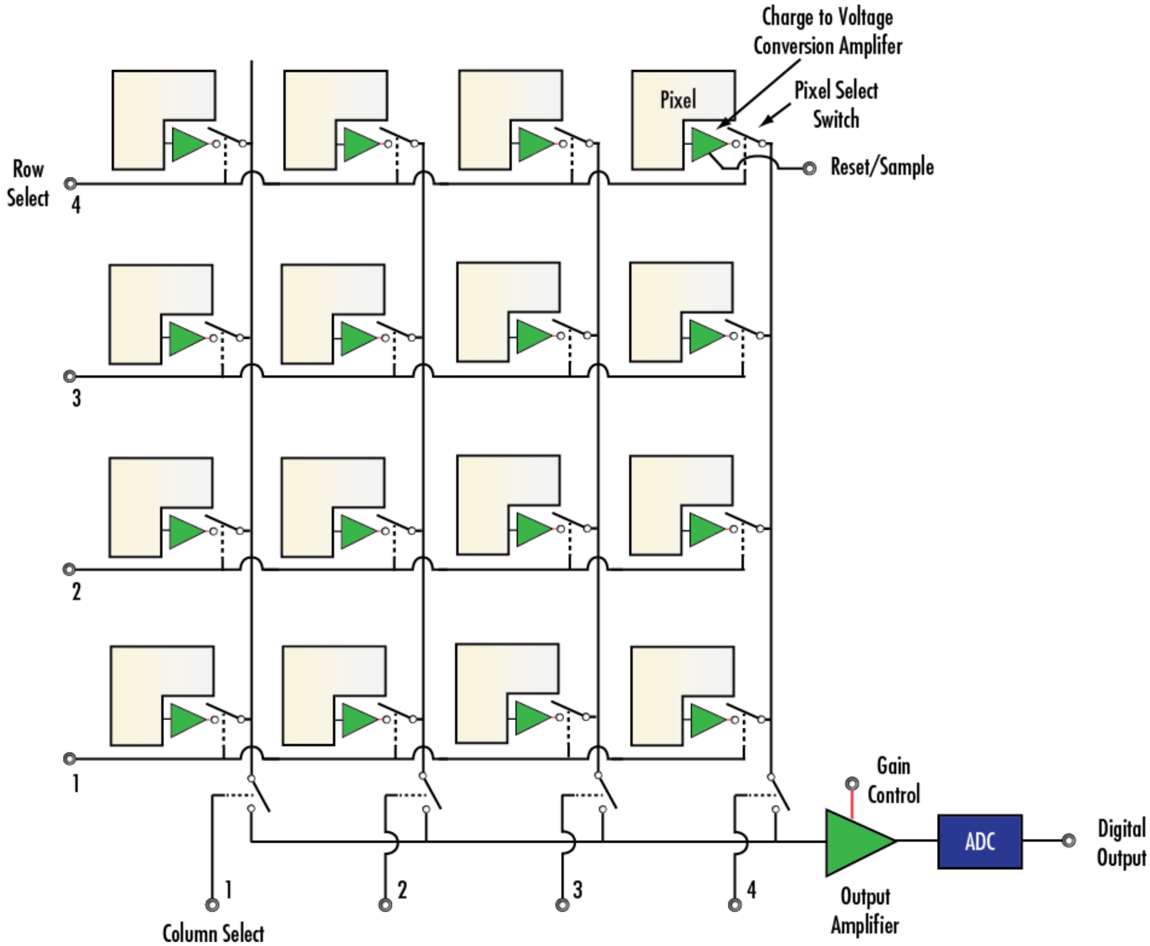

Figure 3 Block Diagram of a CMOS (courtesy Edmund Optics)

3.0 Camera Design

In live video observing of deep-sky objects, sensitivity and low noise are key. As a result CCD based cameras currently dominate the astro-video market. The selection of the best CCD chip to use in a camera for video astronomy is not as simple as picking the one with the highest sensitivity, you also need to consider a number of other parameters:

- *Dark Current Noise*: When the sensor is hidden from all sources of outside light, there still tends to be a small signal detected. This signal is a result of stray electrical charge or heat given off by the rest of the CCD circuitry. The "dark current" rating on a CCD is a measure of this stray "noise", with a lower dark current being better. When CCD's are run continuously and/or at their maximum sensor well capacity, they generate a lot of heat which increases dark current noise. Having a low dark current is very important when trying to view low contrast targets like nebulae or galaxies. To achieve the best low noise signal from the CCD, chip cooling will likely need to be applied.
- *Pixel Size*: The pixel size is analogous to aperture in a telescope. A large pixel size will result in more light being brought in per refresh for that pixel, resulting in a corresponding increase in sensitivity of the sensor. When viewing dim objects the bigger the pixel size the better. If viewing solar system objects like the Sun or Moon however, resolving power is more important than sensitivity, so a small pixel size is better.
- *Resolution*: Within a fixed field of view, a higher resolution of pixels will result in more detail being visible. High resolution is very useful when viewing planets or the Moon where the surface details are numerous and small in size. Associated with a higher resolution is a larger burden on resources since the rate of data flow is higher per frame. As a result, large resolution cameras often have slower refresh rates.
- *Image Size*: The size of the image on the chip is a function of the pixel size and resolution of the CCD. When used with a telescope or lens system, the image size affects the field of view you will achieve. A larger image size will have a larger field of view for the same optics. For reference, the maximum diameter of the fully dilated human pupil is 7mm.

Many astro-video camera manufacturers place a lot of emphasis on sensitivity as a point of comparison, but that really only tells part of the story. Tables and graphs from the CCD manufacturer can only tell us the potential of a particular chip. Once a chip is selected it is up to the camera manufacturer to design and build the supporting circuitry necessary to realize the CCDs full potential.

Figure 4 presents a schematic for a typical CCD astrovideo camera. Each component of the camera (not just the CCD alone) plays a vital role in the overall performance.

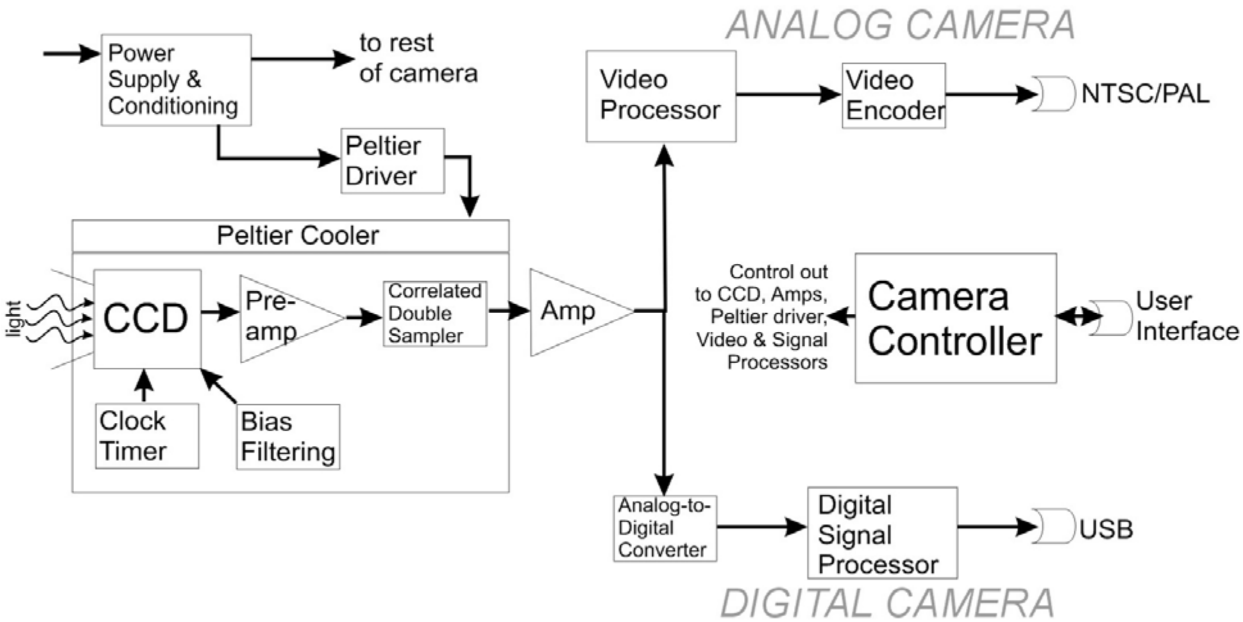

Figure 4 ***Typical Astro-Video Camera Schematic Diagram***

Specific aspects of the camera design requiring careful attention include:

- *Cooling*: In order to reduce dark current noise many cameras use some type of sensor cooling. Inexpensive systems simply allow the CCD to conduct heat away through the circuit board and the limited amount of air inside the camera casing. More sophisticated cameras use custom designed thermal fingers to conduct heat directly from the CCD to the camera casing. The highest performing cameras have active sensor cooling using a Peltier cooler; a simple solid state electrical device that moves heat from a cool reservoir (the CCD) to a warm one (the camera casing) when you apply a DC current in the right direction. The design of the chip cooling system is very important to the performance of the camera. Top grade components must be used to ensure no noise is introduced to the camera signal. The level of cooling must also be carefully controlled in order to achieve the maximum cooling without overcooling and potentially cracking the CCD chip.
- *Duty Cycle*: Most components, whether electrical or mechanical, are designed to function at a rated performance level for some percentage of the time. For example an electric motor may be rated to deliver 1 hp output power, but will also have a percentage duty cycle associated with it. If the motor is used more frequently at full load than it is rated, its performance will gradually decline until eventually the motor

fails entirely. The same is true of an astrovideo camera, which essentially operates at a 100% duty cycle. The constant generation of frame-after-frame, exposure-after-exposure in an astrovideo camera is much more taxing on the camera's components than what a typical imaging camera would see. As a result careful design, component selection and assembly are necessary in order to ensure reliable and consistent performance.

- *Sensor Loading/Gain*: As mentioned earlier, running the CCD at or near its charge capacity generates a lot of heat and thus a lot of dark current noise. Additionally, running the on-chip output amplifier continuously at high gain results in additional heat which shows up in the sensor image as "amp glow". Amp glow and dark current noise is reduced in imaging cameras by reducing the gain and sensor loading, thus trading away sensitivity for a cleaner image. In an astrovideo camera, it is necessary to use all of the available sensor sensitivity in order to see dim objects live, so sensor loading and gain are typically run at maximum. The highest quality and best performing cameras allow the user to tune this balance between high sensitivity and noisy image.
- *Sensor Class*: As you may imagine, the mass production of CCDs is a complicated and expensive task. The cost to produce CCDs is kept reasonable by accepting the fact that there will be a range in the quality of CCDs coming off the assembly line. Statistically a large percentage of the chips produced perform at the average rated level, but the some perform either considerably better or considerably worse. CCD manufacturers categorize the sensors that come off their assembly lines into "classes" and price them accordingly. The class generally identifies how well the chip performs relative to its design specification. Class 0 is the best, and represents chips that exceed the design spec for sensitivity, dark current noise, and other factors such as "hot pixels". Hot pixels are pixels in the array that for some reason or another are not responding correctly and show up generally as a pixel that is always "on". Class 1 sensors are generally considered very good professional grade sensors. Inexpensive commercial cameras tend to have Class 2, 3 or 4 sensors as the class of sensor directly affects its cost. In order to achieve the highest sensitivity and lowest noise, Class 0 or 1 sensors are a must for astrovideo cameras.
- *Component Grade*: There are many other components in an astrovideo camera other than the sensor. There are amps, filters, video processors, voltage regulators, analog-to-digital converters, and much more. The quality and performance rating of these components used in the camera will directly affect its reliability and overall performance. The use of scientific Grade 1 electronic components over commercial grade can reduce electrical noise by as much as 50%. To have a reliable high performance astrovideo camera, it is worth the extra cost to have Grade 1 components.

- *Enhancement Circuitry*: There are numerous opportunities in the design of an astrovideo camera to add special customized circuitry that would not be found in a standard CCD camera, which has the purpose of further improving the performance of the camera. Circuits that boost camera sensitivity (such as the Mallincam Hyper circuit) or that recognize noise and further reduce it may be added to enhance overall camera performance. The designer of these enhancements must have an intimate knowledge of the capabilities of sensor and signal processing technology, as well as a clear understanding of what the video astronomer needs for performance in their astrovideo camera.

All of the above listed things must come together to produce an astrovideo camera.