THE CCD EDGE

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PREFACE

Among professional astronomers, the Charged Coupled Device (CCD) has become the detector of choice for imaging. Technology has advanced such that CCD-based cameras are not only readily available, but also much more affordable for amateur astronomers. The CCD revolution has come about because of the many advantages of using CCD cameras. This report will discuss several of the advantages of CCD cameras over other types. The focus will be on cameras developed for imaging distant, faint, celestial objects.

The report will discuss the following CCD camera advantages:

- efficient operation,
- linear operation,
- cooled operation,
- digital image, and
- instant image.

Together, these advantages account for the ascendancy of CCD cameras over film, other digital, and video cameras.

Since this report has been written for the general reader, overly technical or mathematical explanations will not be included. Explanations of technical terms will be included in the body of the report as they are introduced.

The author greatly appreciates the work of pioneer amateur astronomers who have shared their knowledge through personal contact and by publishing their work on the pages of Astronomy and Sky & Telescope or their own books.

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ABSTRACT

Several advantages of using CCD-based cameras are discussed in this report. Among them are the following:

- CCD-based cameras enable amateurs to compete with professionals for new scientific discoveries, and
- CCD-based cameras produce higher quality images than those taken with standard film, digital, or video cameras.

The Charged Coupled Device has revolutionized the imaging of distant, dim, celestial objects. The CCD-based camera is the tool of choice for imaging by professional astronomers and is now being used by amateur astronomers, as well. This is due to the advantages of CCD-based imaging cameras.

INTRODUCTION

George Smith and Willard Boyle, while working at Bell Labs, invented the Charged Coupled Device (CCD) in 1969. This invention has revolutionized celestial imaging. Today, the CCD based camera is the imaging tool of choice at professional observatories. Because today's CCD cameras are affordable, even amateurs can now purchase and use them. In fact, the amateur today, with modest equipment, can routinely image objects which were once photographed only in professional observatories equipped with huge and expensive telescopes. The CCD camera has enabled the amateur astronomer to capture esthetically-pleasing images of faint galaxies, nebula, star clusters, and other distant celestial objects. More important, amateurs are now making significant scientific contributions with their CCD-based imaging systems. All of this is possible because the CCD detector, which is the core of the CCD camera, has many advantages over other types of light detectors. The CCD detector gives CCD-based cameras the following advantages:

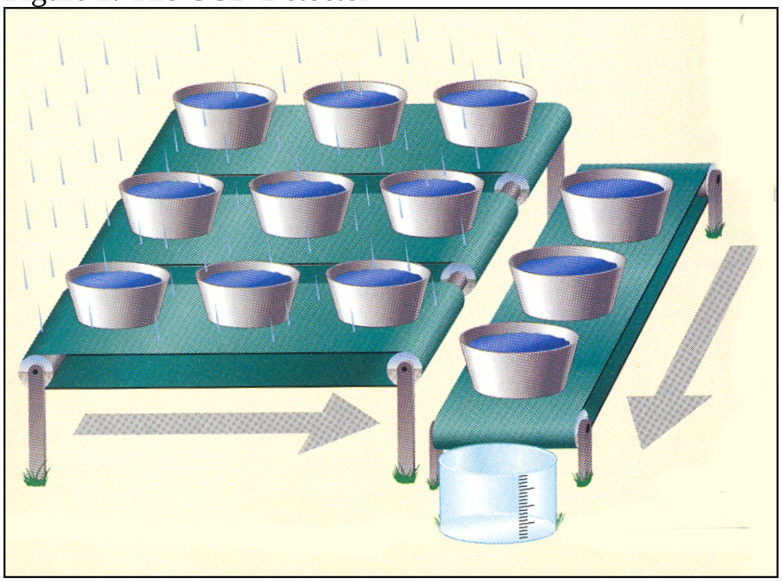
- light-gathering efficiency,
- linear operation,
- cooled operation producing low "noise" images, and
- immediate image availability for viewing or further processing.

This report will discuss these and other CCD advantages. The report begins with a brief description of how a CCD detector works.

THE CCD DETECTOR

Figure 1 depicts, by analogy, how a CCD detector works.

Figure 1: The CCD Detector



Source: James Janesik, "CCDS: The Inside Story," CCD Astronomy Winter 1997: 11.

The CCD detector contains an array of photosensitive sites called pixels or photosites. In the figure, the pixels are represented by buckets. A rainstorm causes rain drops to fall on the buckets. The buckets collect the rain drops that fall on them and accumulate the water drops for the duration of the storm. Each bucket is then shifted to a measuring container where the accumulated water is measured. Similarly, photons "rain" on the CCD pixel array, freeing electrons. The electrons are accumulated in the pixels while the camera's shutter is open. At the end of the exposure, each pixel is shifted out of the CCD array and measured. The measurement is saved as a digital number representing the pixel's accumulated electrons and is proportional to the number of photons that struck the pixel during the exposure. Collectively, the pixel measurements map the luminosity of the objects in that portion of the sky imaged by the camera. After considering this simple model of the CCD detector, the following three important observations can be made:

1) If the buckets are full, no more water can be accumulated and the final measurement will not accurately reflect the rainfall. Likewise, if a pixel is "full" and cannot accumulate more electrons, it will no longer represent the true luminosity of the objects imaged; the pixel is said to be "saturated."

2) The buckets begin to accumulate the rain drops immediately. There is no detection threshold. The same is true with the CCD detector: the pixels begin to accumulate electrons when the first photon strikes the pixel. Other detectors require strikes by multiple photons before accumulation begins. The human eye behaves this way, and so does photographic film. Richard Berry makes this clear with respect to film (12): "When a photon of energy...enters a silver bromide crystal, it creates a defect in the crystal structure. Such defects can migrate through the crystal, and may spontaneously 'heal' after several seconds or minutes." Berry adds that it takes multiple photon strikes to make the defect stable. Together, the stable defects are responsible for creating the photograph when the film is developed. From this, it is apparent that the photograph does not accurately represent the number of photons striking the film because of the detection threshold. Other properties of film degrade the accuracy even further.

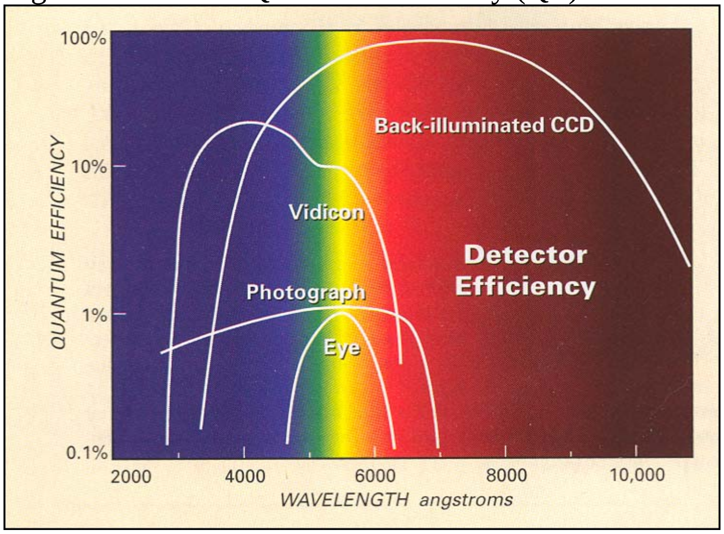
3) Unless there are extraneous sources of either the rain drops or photons, what is accumulated in the buckets and pixels is pure signal, or usable data. In the case of real pixels there are extraneous sources of electrons. However, unlike the film camera, and

because the CCD based camera is a digital device, the extraneous contribution to the signal--called "noise"--can be removed.

QUANTUM EFFICIENCY

Quantum efficiency (QE) is the measure of a detector's efficiency in detecting photons. More specifically, QE is the percentage of photons that are converted into a usable signal (Berry 82). Figure 2 shows the QE of various detectors.

Figure 2: Detector Quantum Efficiency (QE)



Source: James Janesik, "CCDS: The Inside Story,"
<u>CCD Astronomy</u> Winter 1997: 12.

The efficiency of the CCD detector is remarkable. The detector's job is to detect packets of light, called photons, which have been generated by objects so far away that their distance is measured in light years. A light year is the distance traveled by light in one year, the light traveling at about 670 million miles per hour. Arne Henden describes how faint the photon signal is (1). The generated photons are diluted by the immense distance they must travel to reach the earth. A significant part of what is left is lost in passing through the earth's atmosphere. Still more of the photons are lost passing through a telescope's optics on the way to the CCD detector. A light detector must efficiently capture the photons that remain.

Modern CCD cameras typically used by amateurs reach a QE approaching the most expensive back-illuminated detectors. CCD detectors have a much broader spectral sensitivity than other detectors. The high QE of the CCD detector means that it can capture images of faint objects in much less time than other detector types. As Berry states, "With typical quantum efficiencies of 1%, photographic exposure times must be 20 to 60 times longer than comparable exposures with electronic sensors" (13). Being able to image an object in a short period of time has many advantages. For example, there is less chance of an unwanted object, such as an airplane, moving through the picture during exposure. Short exposures can also lessen the impact of system problems, such as a less than optimal telescope tracking. Most important, because the image produced by a CCD camera is a digital image, several short images can be taken and then digitally combined in a computer to enhance the quality of the final image. Surprisingly, another characteristic of the CCD detector makes it possible to take long exposures with better results than conventional emulsion photography.

LINEAR OPERATION

The CCD is a nearly-perfect linear detector (Martinez and Klotz 18). Until saturation is reached, the electrons accumulate in a pixel in proportion to the number of photons striking the pixel. Martinez states, "Exposing 1000 seconds on a CCD generates exactly ten times more electrons than a 100 second exposure would; unfortunately, this is not the case with photographic film, which undergoes an important drop in sensitivity as the exposure time is lengthened, making long integration times almost useless" (18). Thus, the CCD exhibits predictable behavior during exposures. For scientific research, this predictability is important. For example, linearity is critical to the science of photometry.

Photometry is the science of determining an object's brightness. This area of study is of particular interest to CCD-equipped amateur astronomers. Amateurs can make significant scientific contributions in this area. Martinez points out why the CCD is especially suited for photometry. "Since the number of electrons generated is proportional to the quantity of light received, the reading of a CCD array directly leads to a measurement of the luminosity of all of the objects that constitute the image; the application in photometry is immediate and of great precision..." (18-19). Martinez also adds that obtaining photometric data from film "...is more tedious and much less accurate" (19). It is the linear operation of the detector that makes the CCD camera especially useful for photometry.

COOLED OPERATION

As previously mentioned, noise can cause a distorted readout of the signal electrons created by the photon impacts on the pixels. When power is applied to the CCD camera, the camera, including the detector, begins to heat up. In fact, the detector has already been heated to the temperature of the surrounding air. This heat provides enough energy to free additional electrons, designated as thermal electrons. The thermal electrons collectively are known as the "dark current," because they accumulate independent of any light. There is a direct relationship to temperature and the release of thermal electrons. The dark current doubles for each 6 degrees Celsius of temperature rise (Berry 125). This happens even with the camera shutter closed.

Before a new image is initiated, the camera electronics insure that the light buckets, or pixels, are empty. The shutter is then opened and the exposure is begun. Normally, the CCD exposure is termed "integration." This is because signal electrons are essentially being added together, or summed (integrated), in the pixels.

For the duration of the integration, the pixels not only collect photon-generated signal electrons but also accumulate dark current, or noise. The dark current can be reduced dramatically by cooling the CCD detector. When this is done, as it is in CCD cameras designed for astronomical imaging, dark current is dramatically reduced. Even so, the remaining dark current can mask the signal electrons. Fortunately, removal of dark current electrons is possible due to the linear properties of the CCD detector.

For the duration of an integration, and assuming that the temperature does not rise, dark current accumulates at a linear rate. This means that the dark current is the same for integrations with the same duration. Suppose a five-minute integration is taken with the shutter open. An integration taken with the shutter open results in an image called a light frame. The light frame will contain both thermal electrons and photon-generated electrons. Another five-minute integration taken with the shutter closed--and with the camera at the same temperature--will accumulate only thermal electrons, or dark current. The resulting image is called a dark frame. Because of the linear properties of the detector, the dark current will be the same in both the light and dark frames. The rate at which thermal electrons will be generated will be the same for both light and dark frames.

With software generally supplied with the CCD camera or otherwise readily available, the dark frame can be subtracted from the light frame leaving only the photon generated signal. The results can be very dramatic. For example, the image of a faint galaxy will be revealed when the dark current is removed, as if a fog had lifted from before the galaxy. Reduced dark-current noise is a major advantage of the cooled CCD camera over other digital and video cameras.

Cooled operation gives the CCD camera a definite edge when imaging faint objects. Less noise during an integration means that the pixels do not reach saturation as quickly as cameras with no cooling. Image duration can, therefore, be longer. Longer images can be desirable because dark current does not accumulate as quickly as photon-generated electrons. Another way of putting this is that the signal-to-noise ratio is better for a longer image than for a shorter image, when the camera is cooled. The digital advantage of the CCD camera offers another way to achieve a high signal-to-noise ratio.

THE DIGITAL ADVANTAGE

Once an integration is completed by the CCD camera, the signal collected by each pixel, containing both noise and signal components, is measured and quantified. This results in a number for each pixel that represents the collected signal. The number is the pixel value (PV), and when sent to a computer monitor or some other output device will be translated to a light level. Modern CCD cameras are capable of quantifying the signal into one of over 65,000 light values ranging from white to black. Subtle changes in the light intensity of objects, such as faint nebulosity around brighter objects, can be displayed. This is one advantage of the digital CCD camera. There are many others.

In the last section, I suggested that there was another way of achieving a high signal-to-noise ratio. Several short images can be combined. The image sent to the computer is, after all, a collection of numbers. Numbers that can be added, subtracted, divided, or otherwise changed. When the shorter images are combined, the signal levels of the images add together. The signal level increases with respect to the residual image noise, thus increasing the signal-to-noise level of the final image. In this way, shorter images can be combined to have the same signal-to-noise level as does a single image with the same total integration time. Adding short-duration images together can easily be done with available software. Indeed, CCD images are quite at home in the digital age.

Powerful software is available today for the analysis and enhancement of digital images. Software is available that has been tailored for astronomical image processing and analysis. Other software is available for manipulating digital images of all types.

A necessary part of image processing is noise reduction. The removal of dark current has already been discussed. There are other types of noise that can be removed from the CCD image. Noise caused by the camera electronics, for example, can be removed from the image. The effects of dust, fingerprints, and other obstructions in the optical path can also be digitally removed from an image. A finger print or dust particle can reduce the light intensity falling on the CCD detector. A process called flat fielding can correct for this kind of image impairment. In this process, a special image, called the flat field, is taken and digitally applied to the light frame. The result is the removal of the effects of the dust and other obstructions. Amazingly, the effects of sky glow or light pollution can also be removed from a digital CCD image. CCD cameras can, in fact, be used to great advantage in light-polluted areas where photographs with a film camera would be impossible. Removing noise and compensating for problems that could impair the image quality is called image calibration. Image calibration must be done to get the most out of a CCD camera. This is easy to accomplish using today's software. Once the basic image calibration is done, the image is immediately available for analysis, further image processing, or display.

IMMEDIATE IMAGE AVAILABILITY

Being able to display or otherwise utilize the CCD's digital image is an advantage shared by other digital and video cameras, but not by the film camera. Many problems can arise when using a film camera to photograph a faint celestial object. First of all, in order to take a photograph of a faint object, the exposure has to be long. An hour is not atypical. Atmospheric effects, perhaps a thin cloud layer passing overhead, a satellite or airplane passing through the field, a breeze jiggling the camera mount, poor camera mount tracking, cosmic rays passing through the film, less than perfect focus...these are just a few of the problems that can affect the final photograph. Since the results of the photographic session are not immediately available, the photographer cannot detect and correct them.

Compared to the film photographer, the CCD imager has the advantage of being able to immediately see his image when it is done. Short images can be taken and displayed to help find and frame the object. It must be remembered that many objects imaged today are objects so distant and faint that they are not visible even through the imager's telescope. Therefore, being able to point the telescope to the object's probable location in the sky, take an image, and display it immediately to see if the object is there, is a great advantage. Many of the most photographed celestial objects can be imaged in sixty seconds or less with a CCD camera. Once the object is found, using the instant display of multiple short images as feedback can help the astronomer achieve better focus. When the object has been found, framed, and focused using short CCD integrations, the light and calibration frames can then be taken. Whether the imager opts for a series of short images (to be calibrated and combined later) or for single long images, they will still be available for immediate display when completed. If the image is not satisfactory, others can be taken until the desired result is obtained.

Once the desired image has been captured, it can then be calibrated, enhanced, or analyzed. As mentioned earlier, science can be advanced using the calibrated images without any other processing. Image enhancement can also be started without delay in order to create esthetically-pleasing images for printing or display or to bring out or enhance detail in the object's image. Further processing of planet images to bring out the rings of Saturn or the belts on Jupiter, for example, can be done at once. Or--and here is another digital advantage--the image files can be saved for later processing and archived on CD ROMs. Truly, the CCD camera is a device at home in the digital age.

CONCLUSIONS

The CCD detector has many advantages that give the CCD imager an edge when capturing images of distant, faint astronomical objects. The major advantages of CCD-based cameras are their light gathering efficiency, linear behavior, cooled operation, digital images, and immediate image availability.

The CCD detector is a highly-efficient collector of photons. Whereas the naked eye and emulsion film have a QE of about 1%, today's CCD detectors have a QE of 50-85% in the visible spectrum and have a much broader spectral response than other digital or video cameras. The CCD detector's high QE makes it possible to image an object with shorter exposures than required when using a film camera. There is less time for problems with the imaging system to degrade the final image if shorter exposures are used.

The linear characteristic of the CCD detector makes it the tool of choice for scientific imaging. The signal collected is proportional to the luminosity of the imaged objects. The CCD camera is widely used by both professionals and amateurs for photometry. In fact, the availability and affordability of today's CCD cameras have enabled amateurs, with modest equipment, to do serious scientific research and to make their own discoveries. The linear characteristic of the CCD detector also makes it possible to reduce the image noise.

Modern CCD cameras do more than make it possible to remove noise. Their cooled operation directly reduces a major contributor to noise: thermal electrons. Cooling the CCD detector makes it possible to take longer images before the pixels become saturated. When CCD pixels become saturated, the excess electrons can spill into adjacent pixels causing extended bright spots in the image. This is called blooming. Cooling the detector helps eliminate this problem. Since digital and video cameras are not cooled, noise caused by thermal electrons can seriously compromise image quality. They are not, therefore, as desirable for imaging faint objects as is the cooled CCD camera.

We live in the digital age, and the CCD camera is a tool for the times. Coupled with a personal computer, the CCD camera is a natural for celestial imaging. Because the CCD camera produces a digital image, the images are immediately available for display, processing, or analysis. If the image is not of the desired quality, another can be taken at once. Moreover, feedback from short images can aid the imager in finding, framing, and focusing astronomical objects.

In view of all of the advantages of the CCD detector and of the CCD based camera, it is no surprise that the CCD camera has revolutionized imaging the sky. Both professional and amateur astronomers now use this tool at their telescopes. For the amateur, obtaining images of faint and distant objects--without the use of huge and expensive telescopes--is now possible. Discoveries of new objects, such as supernova, comets, and asteroids are not unusual among amateur astronomers, thanks to the CCD camera. Sky & telescope and Astronomy routinely publish spectacular CCD images that would not have been possible a few years ago. The CCD-based camera is not only the professional's edge; it's the amateur's edge, too.

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