PHOTOMETRY WITH CHARGE-COUPLED DEVICES: CHARACTERISTICS AND APPLICATIONS

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Abstract

Charge-Coupled Devices are described together with the observing techniques required to obtain quality data with them.

1. Introduction

The brightness of variable stars has been measured by both visual and photoelectric methods. Imaging devices based on Charge-Coupled Devices (CCDs) have recently become available and provide an attractive alternative to prior means for photoelectric photometry. Indeed, equipment specifically intended for photometry is advertised. The nature of CCDs, their virtues, and their faults must be understood to use these devices effectively.

Whether the magnitude of a variable star is determined by visual or photoelectric means, the approach is similar: identify the variable and compare its brightness to stars of known magnitude. Visually, this is easy, but the accuracy is limited to about a tenth of a magnitude. To achieve the much greater accuracy inherent in photoelectric techniques, it has always been necessary to exercise great care. Specific observing practices are required to circumvent the limitations of CCDs. Further, for maximum usefulness, the measurement process should be calibrated to standard stars so the results are directly comparable to the work of others.

2. What is a CCD?

Charge-Coupled Devices are integrated circuits consisting of a two-dimensional array of photodetectors and a read-out amplifier (Mclean 1989; Buil 1991). Each photodetector may be thought of as a pixel in an image. Many of the photons striking a pixel are converted into an electron. Electrons accumulate in each pixel for the duration of an exposure, established by a mechanical shutter and, after the exposure, the resulting charges are a measure of light intensity. The CCD contains on-chip circuitry to shift the charges from one pixel to the next, as in a bucket brigade. In this manner the charges are passed sequentially to the output amplifier and off the chip. The system integrator provides interface hardware and software to convert the resulting data from analog to digital form and to send it to a computer where it may be stored, imaged, and manipulated.

The pixels in CCD imaging devices are arranged in a rectangular (usually square) matrix containing from <100 to 4096 detectors on a side. Thus a CCD contains tens of thousands to millions of pixels, each about 15 to 30 μm across. Each of these pixels may be measured to 8, 12, or even 16 bit resolution (i.e., one part in 256, 4096, or 65536). Thus the amount of data to be stored from a single image is very great.

Frame transfer technology is used by CCDs suitable for astronomy. In this process the entire image is shifted sequentially to a row where the charges in each column may be moved to the read-out amplifier. A competing technology uses interline transfer in which the charges are first shifted to intervening rows of image transfer pixels that are shielded from direct exposure by a metal overlay. Half the light striking these chips is not recorded.

The quantum efficiency of CCDs is very high. About 40% to 85% of the photons at the wavelength of maximum sensitivity are converted into measurable electrons. Maximum sensitivity for most CCDs is in the 0.5 to 0.75 μm range and the useful spectral range extends from $\approx$0.33 to $>$1.0 μm.

3. Advantages

Convenience, capability, and availability are all attributes of CCD photometry.

CCDs are convenient, since the resulting data are in a computer where they may be readily reduced whenever the user desires. Also, the results are displayed as an image so even extremely faint variables not seen through an eyepiece may be positively identified and measured. This image contains the variable, comparison stars, and sky background all measured at one time and stored in one place.

Many aspects of CCDs make them nearly ideal detectors. They have a very high quantum efficiency; they respond to essentially every photon and can record very faint objects compared to a photomultiplier tube on the same telescope. They are also very linear, producing an electrical output directly proportional to the light falling on them over most of the pixel capacity. They are extremely stable and offer a wide spectral response. Small size, rugged construction, and low power consumption are also advantages.

Several brands of astronomical CCD imaging devices have recently become available to the amateur astronomer and may be used for numerous applications, not just photometry. All are good for imaging and some even act as star-trackers to guide telescopes during photography. Most commercially available CCDs do not come with the filters used in serious photometry.

4. Disadvantages

Unfortunately, CCDs have inherent limitations and deficiencies. For example, commercially available CCD systems cannot be used for high-speed photometry since it takes considerable time to transfer an image from the chip. CCDs must be cooled to minimize dark current (thermal noise), bad pixels (very small in number) must be mapped and avoided, and data can be contaminated by spill-over from a bright object (charge bleed). CCDs are also sensitive to cosmic rays, and have their own internal luminescence, particularly near the read-out amplifier.

There are also practical considerations which place limitations on the use of CCDs. As with other forms of photoelectric photometry, it is appropriate to have a fixed installation, such as an observatory. The telescope should be accurately polar-aligned and the computer should be conveniently located so exposures can be monitored as they are taken. Also, the software and hardware supplied with general purpose CCD imaging systems lack many of the features required for photometry. The measurement process is time-consuming but less so than for aperture photometry since the target star, comparison star, and sky background are recorded simultaneously.

High cost, including the cost of a computer, is another disadvantage. However, equipment prices are comparable to other electronic means for photometry, especially if one considers that the same CCD hardware can be used for general-purpose imaging. Prices are reasonably constant or dropping despite rapid improvements in technology.

5. The Use of CCDs in Photometry

To measure the brightness of a variable star accurately, it is necessary to understand and avoid or correct for potential inaccuracies. To a large degree the process can be simplified by differential photometry, in which it is merely desired to show how the variable changes with respect to several nearby field stars that, over time, are demonstrated to be essentially invariant. In the discussion which follows, a more complete overview is provided, one which permits the determination of magnitude on an absolute basis.

Despite the fact that CCDs are inherently linear, there is an offset or signal even with no exposure. This is called the bias level and is introduced by the chip designer to assure that the analog-to-digital conversion process does not receive a negative input from read-out noise. A "bias frame," that is, an image of zero duration with the shutter closed, can be taken, stored, and then subtracted from every exposed frame. The preferred practice is to use the average of several bias frames.

The random vibration of atoms at temperatures above absolute zero frees electrons which are indistinguishable from those liberated by photons. This is thermal noise and it appears as a dark current. The longer one exposes in the dark, the brighter the "image" becomes. Dark current decreases by 1/3 for every 10° C reduction in temperature. In a single pixel approximately 100,000 electrons/second are liberated at room temperature. By using a multi-stage thermoelectric cooler this may be reduced to 250 electrons/second and, at dry ice temperature, the value is about 50 electrons/*hour*. For comparison, a pixel will saturate with 50,000 to 500,000 electrons depending on the particular CCD chip used. Thus CCDs are cooled to permit exposures of sufficient length to be useful in astronomy.

With a high degree of statistical certainty, the dark current may be measured independently of the observation and subsequently subtracted from it. A "dark frame" is an exposure with the same duration and chip temperature as the observation but is taken with the shutter closed. In practice the median of several recent dark frames are used. Bias current and luminescence in the chip are also included in the dark frame.

The sensitivity of each pixel is unique. This lack of uniformity may be circumvented by taking an image of a uniformly illuminated surface and using the result to normalize the observation. This "flat field" exposure may be of the same duration as the observation, although exposures of some other duration are acceptable. If a filter is used for the observation, the same filter should be used for this "flat field" exposure. Before being used to normalize the sensitivity of the CCD, the dark frame should be subtracted from this flat field frame. The observation image, less the dark frame, should be *divided* by the flat field frame to normalize its sensitivity. To minimize round-off error in division, the image is usually multiplied by the mean of the flat field before division.

The ultimate in nonuniformity is the bad pixel. With the current state of manufacturing technology, several of these may be anticipated on a chip. For photometry it is best to avoid bad pixels by discarding images in which the image of an object of interest falls on one.

Photoelectric photometry is usually done with a defined spectral response. The standard responses are achieved by filtering the light. They are designated U, B, V, R, I, or ultraviolet, blue, visual, red, and infrared. Filters intended for use with photomultiplier tubes may be inadequate for use with CCDs, depending on whether they "leak" in the infrared, a region where the tubes are not sensitive but CCDs are. Filter/CCD combinations should be calibrated by observations of standard stars. The calibration approach is the same as fot other methods of photoelectric photometry.

6. Data Reduction

When an observation is made, it should be examined for imperfections before doing data reduction. Examine the image to see if charge bleed from a bright object has produced a line in the image which intersects the variable or comparison star. Make sure these images do not fall on bad pixels. If the observation is good, then subtract the dark frame and normalize using the flat field.

The resulting image is now suitable for photometric measurement. In examining the image, one notes that the light of each star has fallen on several pixels. These must be integrated to establish the total brightness of the star. This is done with software. Two methods may be used. In the simpler, the intensities of several pixels in a box centered on the star are merely added. In the other, the software produces a best-fit intensity distribution and computes the volume under the resulting "hill".

The brightness of the variable, the comparison stars, and the sky background are all measured from the image. The sky background is then subtracted from the star brightnesses, providing the relative brightnesses of the stars themselves.

Data obtained by this process are good but not of demonstrated quality. It is important to repeat the observation to be assured that the results are consistent to a desired level of accuracy and have not been affected by factors such as instrument errors, mistakes, or obscuration by thin clouds. Then the observation is adequate for studies of a variable star by a single individual or group using the same instrumentation and comparison stars.

If the data are to be directly comparable to observations by others, they must be further reduced to recognized standards. The process is the same as that used for other forms of photoelectric photometry (Henden and Kaitchuck 1982). Calibration constants to bring the observations in line with the standard UBVRI system are applied. Also, the magnitude should be referenced to a standard star which will almost certainly not be in the image, requiring a separate observation and the application of extinction coefficients.

7. Conclusions

The introduction of CCD technology provides a very attractive means for photometry. The devices are sensitive, linear, and stable. Commercial systems permitting data storage, inspection, and reduction by computer also make them relatively convenient. This convenience is also evident when compared to alternate detectors with which the variable, comparison star, and sky background must be measured in separate observations. CCDs are not without their faults, but these may be avoided through understanding and a proper observing technique. As with other forms of photometry, much time and attention to detail is required to achieve the accuracy inherent in the equipment.

References

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