POTENTIAL USEFULNESS OF CCD IMAGERS IN ASTRONOMY

Thomas B. McCord and Jeffrey P. Bosel
Massachusetts Institute of Technology
Cambridge, Massachusetts

Two-dimensional detectors have been important in astronomy since the earliest days of the science. Recently, the requirements for greater photometric accuracy, sensitivity and spectral coverage have driven the search for better imaging devices. Electron-beam readout devices with a variety of target materials and intensification schemes, including the SEC and silicon vidicons, have been used successfully. The CCD as an image detector has several potential advantages over electron-beam readout devices; low noise, simple construction and geometric stability are among them.

Two-dimensional photo-detectors have been used extensively in astronomy since its beginning. The human eye and later the photographic films were used almost exclusively. In the past 10-20 years, a variety of electronic detectors have been tested and a few have been used for actual observations at the telescope. These devices are used for finding, tracking and general field viewing as a substitute for the human eye. More importantly, they are used for quantitative measurement of the direct image as well as of the spectrum of extended objects and point sources.

The charge-coupled device (CCD) is the latest in a series of photon-to-charge-carrier conversion devices and is one that may come closest to being the "perfect" detector. I have been asked to discuss briefly what detector properties are important to the groundbased astronomer and how the CCD might satisfy the astronomer's needs.

The CCD is a silicon wafer onto which a structure of electrodes has been deposited. The silicon wafer is the photo-sensitive material in which photons are converted to charge carriers and the optical properties of the detectors are to first order those of silicon. The charge carriers are collected and stored in potential wells created on the silicon wafer by potentials on the electrodes. At an appropriate time, the stored charge can be shifted across the wafer through a charge-sensitive amplifier and converted to a video signal. Because the potential wells are discrete elements in an array across the wafer, the detector becomes, in effect, an array of discrete abutting photosensors.

Experience with two-dimensional silicon photo-detectors has been gathered through study of the silicon diode array vidicon. This device has recently been put to use in astronomy (Ref. 1). Several at-the-telescope testing programs have been reported (Refs. 2 and 3) and the device is now in routine service for scientific use (Refs. 4 and 5).

Many problems with the silicon vidicon have to do with the electron beam readout and the external preamplifier. The CCD is read out directly and its preamplifier is manufactured on the silicon wafer. Considering the high performance of silicon vidicons, the CCD is potentially quite useful to the astronomer. In fact it is my impression that the center of effort of the image detector development program in astronomy is rapidly shifting to the CCD.

Although I will center my attention on groundbased astronomical needs, I should mention that CCD detectors almost surely will find their way into the new spacecraft-borne telescope programs. The properties which make the CCD useful here on earth will also apply in space. In addition, as I am sure will be discussed elsewhere in this program, the small size and the low power requirement of the CCD will help make it suitable for space.

The variety of observations made by astronomers assures that no one single detector will ever satisfy all requirements. Point source images (stars) and extended sources (planets, nebulae, galaxies) are observed. Spectra of all these objects are imaged like extended sources. The size of the point source is limited by the magnification and diffraction of the telescope optics and by atmospheric turbulence. The spectral range is limited by atmospheric adsorption at short wavelength and by background thermal emission at long wavelength. Table 1 lists the range of conditions under which imaging might be carried out.

The properties and performance for several currently used two-dimensional imaging devices are given in Table 2. These values are often approximate and in some cases there is disagreement among astronomers about the performance. We give our impression of the present state of the art.

The quantum efficiency and spectral range are limited by the photo-cathode for the SEC and SIT and by silicon and its surface coatings for the silicon vidicon and the CCD. Maximum signal is limited by charge storage; capability and minimum signal are equal to preamplifier noise. The range of linearity, the slope of the response curve γ and the photometric precisions are a property of the entire detector-readout system.

The CCD compares favorably with the other detectors. Unless unexpected problems arise, it will be an important device in astronomy. The most important properties to improve, we believe, are the minimum detectable signal and the array size. Spectral coverage and quantum efficiency are also very important.

Table 1. An attempt at defining the range of conditions under which telescope observations may be carried out

Measurement precision	0.1 - 10%
Object size	$\gtrsim$10 μm
Field	1 - 300 mm
Intensity	10 - 10^6 photons/pixel
$\lambda\lambda$	0.3 - 3.0 μm
$\nabla\lambda$	10^{-2} Å - 10^4 Å
Exposure	10^{-2} - 2×10^4 seconds

Table 2. Performance of several two-dimensional detectors as gleaned from personal contact with a variety of astronomers working with experimental systems intended for use in astronomy

Properties	Film	Sec	SI vidicon	SIT	CCD (present)	CCD (future)	Desirable
Q.E. (%)	≤ 1	1 - 15	1 - 70	1 - 15	~1 - 50	≤ 60	100
Spectral coverage (μm)	≤ 0.9	0.4 - 0.85	0.34 - 1.10	0.37 - 0.85	0.4 - 1.0	≤ 1.10	≤ 3
Max. signal (photoevents/pixel)	$\leq 5 \times 10^4$	2000	$\sim 10^6$	$\sim 10^3$	$10^5 - 10^6$	$\sim 10^6$	10^6
Min. det. sig. (photoevents/pixel)	≥ 500	4	300	2	~300	~10	1
Linear range	$10^2 - 10^3$	~500	$\geq 10^3$	$\geq 10^3$	?	$\geq 10^5$	10^6
Gamma	varies	?	1.00 (0)	0.97	?	1.00	1.00000
Photometric prec.	Few percent	1.2 × photon noise	Photon noise limited	Photon noise limited	$\leq 1\%$	Photon noise limited(?)	Photon noise limited
Array size (pixels)	3×10^4 - 3×10^4	$10^3 \times 10^3$	500 × 500	500 × 500	100 × 100	500 × 500	$10^4 \times 10^4$
Pixel size (μm)	10	25	25 - 50	25 - 50	25	25	10
Digital readout	No	Yes	Yes	Yes	Yes	Yes	Yes
Cooling	No	No	Yes	Yes	Yes	Yes	No
Fragility (1 - 3)	3	1	2	2	3	3	3
Cost	Cheap	1000	250	1200	500	≤ 1000	Cheap
Prestorage gain	—	50 - 100	1	1000	1	1	1

ACKNOWLEDGEMENTS

The authors thank P. Crane, J. Westphal and S. Colgate for helpful comments on Table 2. This work was supported by NSF Grant GP31516.

REFERENCES

1. McCord, T. B., and J. A. Westphal. "Two-Dimensional Silicon Vidicon Astronomical Photometer," Applied Optics, 11, 522-526 (1972).

2. Crane, P., and M. Davis. "Characteristics of the Silicon Diode Vidicon," Astron. Soc. Poc., in press (1975).

3. McCord, T. B., and M. Frankston. "Observational Experience with Silicon Diode at the Telescope," Applied Optics, in press (1975).

4. Pieters, C., T. B. McCord, M. Charette, and J. B. Adams. "Dark Mantling Material in the Apollo 17 Soil Samples," Science, 183, 1191-1194 (1974).

5. Schild, R., M. Frankston, and T. B. McCord. "Observation of a Red Nuclear Halo in NGC 4565," Ap. J. Letters, in press (1975).