ASTRONOMY FROM WIDE-FIELD IMAGING

Part Four:

DIGITISED WIDE-FIELD SURVEYS

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DIGITIZATION IN ASTRONOMY

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ABSTRACT. Ground-based wide-field optical astrometry is in a state of technological turmoil. The photographic plate appears to be an endangered species, and the best alternative, the charge coupled device (CCD), is not ready to replace it. This discussion presents various issues related to this inevitable transition from plates to CCDs, and suggests areas where research is needed before the appropriate CCD detectors can be designed.

1. Introduction

As this paper is being written (September 1993), the Eastman Kodak company appears to be changing its photographic plate and spectroscopic emulsion product lines. Since many astronomical telescopes and observing programs have been designed around these products, these changes will have many impacts on observational astronomy. Astrometry will be affected because glass plates provide geometric stability and the emulsion's red cut-off is used to limit the bandpass of many systems. Hardest hit of all will be the wide-field astrometric telescopes that utilize the billions of pixels available on a large photographic plate. Even if Kodak had offered a five year warning that plates would disappear, the astrometric community would have been hard pressed to come up with alternatives. Unfortunately, the time scale is more like one or two years, and this area of astrometric detector development must be given a very high priority. Since Kodak is responding to changes in a very large market, it is unlikely that protestations by the astrometric community will alter Kodak's marketing policy.

2. Technology Issues

To the nearest factor of a few, a modern telescope design has a field size of approximately 10^4 times its spot size, and therefore delivers about 10^8 resolution elements to the focal plane. The traditional suggestion for image sampling is to use 2 pixels per resolution element, so full utilization of the focal plane requires about 4×10^8 pixels, which is about the number contained on an 8 x 10 inch photographic plate. Larger plates and wide-field telescope designs utilize many more pixels. Whereas the best emulsions deliver a detective quantum efficiency of between four and ten percent, the large number of pixels provides a very large overall efficiency for detecting

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stellar photons.

Although CCD technology is still in its infancy, there are several constraints in CCD production that are already clear, and these will not change unless there is a dramatic change in CCD fabrication technology.

1) The cost of a CCD is closely coupled to the fabrication 'yield', which is the number of working devices divided by the total number of devices fabricated. Although yield figures are usually retained as proprietary information by CCD manufacturers, it appears that the yield of physically large devices is substantially smaller than for physically small devices. In summary, you can have as many pixels as you want so long as the CCD is small, perhaps only 25 x 25 millimeters.
2) The full well (quantity of charge) that a pixel can hold is a function of the size of the pixel. Astronomical experience indicates that the dynamic range of CCDs with pixels smaller than about 10 microns is limited by the full well of the pixels, whereas the dynamic range of CCDs with larger pixels is limited by external electronic components. Astrometry requires the largest possible dynamic range so that faint stars can be measured with respect to bright, catalog stars.

These opposing constraints indicate that the size of current CCDs is close to the limit. One can purchase 2048 x 2048 pixel CCDs with 12- and 15-micron pixels (Reticon, Thomson-CSF, Fairchild, Dalsa are known vendors) for modest prices, but the 24-micron devices from Tektronix are expensive and comparatively rare. The common conjecture that CCDs will eventually be quite large and have huge numbers of pixels appears to be only wishful thinking.

A third constraint on CCD technology comes from the desire to have a very high quantum efficiency. CCDs that absorb photons that come through their front surface (the surface on which the various electrodes, etc. have been deposited) are limited to something like 40% peak quantum efficiency due to the reflection arising from the high index of refraction of Silicon. In addition, the CCD gate structure absorbs the blue photons, so the quantum efficiency of these devices drops dramatically below about ~ 4500 Å. This problem is overcome by a process known as backside thinning. Thinned CCDs have had the supporting Silicon removed and are illuminated from what used to be the back side of the substrate. The back side can be treated with anti-reflection coatings, and CCDs with high (≥ 80%) quantum efficiencies and good blue response have been fabricated and used in astronomical applications. There are three known commercial vendors for 2048 x 2048, thin, back side illuminated, anti-reflection coated CCDs for astronomical applications (Tektronix, Reticon and Thomson-CSF), and these devices cost between $40,000 and $125,000 depending on the vendor and the quality required.

Therefore, currently available (but expensive) CCDs offer 4×10^6 pixels and the astrometric application requires about 4×10^8 pixels. Although the CCDs have quantum efficiencies between 8 and 20 times greater than photographic plates, the plates are still more efficient because of their much larger number of pixels. Fortunately, the technology needed to form a mosaic of CCDs is being developed by many investigators, and this technology will provide the detectors that will eventually replace the photographic plate for wide-field astrometry. As this paper is being written, many groups are developing 2 x 2 and 3 x 2 CCD mosaics, and are solving the associated problems of cooling, electronic support systems, filters and shutters. Two groups are developing the larger mosaics that will be the stepping stones to the size of mosaic needed for wide-field astrometry.

1) The Kiso Schmidt telescope has been equipped with a 4 x 2 mosaic of CCDs (Sekiguchi 1994), and they are working on an 8 x 8 mosaic for use on the Subaru telescope.
2) The Sloan Digital Sky Survey (SDSS) is constructing a mosaic of 47 CCDs (Sekiguchi 1994) for use on a 2.4 meter telescope that will do a combined imaging and redshift study of the Northern Galactic Cap.

3. Seeing, Sampling and Scanning

Two subjects that are critical to astrometric detector development require additional research before a wide-field CCD astrometric detector system can be designed. These are seeing and image sampling. Theoretical models of atmospheric seeing (Lindegren 1980) predict that the uncertainty of the measurement of relative position is a function of the exposure time, the angular separation, and other parameters. Because of the relatively low quantum efficiency of plates, the short-exposure, wide-field regime of seeing has not received extensive study, although Han (1989) and Monet & Monet (1992) have reported a few measurements. Because CCDs have a very high quantum efficiency and because stars with known coordinates (HIPPARCOS stars, for example) are relatively bright, the proper strategy for observing these stars may require using a narrow filter so that the exposure time can be lengthened in order to minimize the degradation arising from seeing. Indeed, most astronomical sites have not been examined for the effects of seeing on spatial scales much larger than a few arcseconds.

Image sampling is another area where research is needed. Since CCD pixels are quite expensive, it is appropriate that they be put to the best possible use. Numerical experiments by Monet (unpublished) indicate that oversampling the image does not increase the astrometric accuracy beyond that obtained at critical sampling, and that critical sampling appears to be in the range of 1.2 to 1.5 pixels per full width at half maximum intensity. Reduction of the sampling from 2.0 to 1.2 pixels per arcsecond (assuming 1 arcsecond seeing) makes a tremendous difference for the size of, and observing strategy for, an astrometric mosaic.

Many groups have adopted scan-mode observing in order to map large portions of the sky. For astrometric applications over wide fields, this approach has significant difficulties. A telescope with a scale S (arcsec/pixel) and a CCD with N x N pixels has an angular extent of $A = N\ S$ in each coordinate. For a field center at declination δ_c, the sidereal drift rate is $R_c = 15\cos(\delta_c)$ arcsec/sec and the crossing time is $T_c = N\,S\,/\,R_c = A/(15\cos(\delta_c))$. The declination at the top of the chip is $\delta_t = \delta_c + A/2$, and stars have a drift rate of $R_t = 15\cos(\delta_c + A/2)$. Therefore, the difference in drift rate between center and top is $\varepsilon_{ct} = T_c(R_c - R_t) = A[(\cos(\delta_c) - \cos(\delta_c + A/2))/\cos(\delta_c)]$. Inserting typical numbers $N = 2048$ and $S = 0.67$, we find that $\varepsilon_{ct} < 0.5$ arcsec for $|\delta_c| \leq 3$ degrees. This restriction on declination is unacceptably small. Hence, image smearing due to the trajectory of the stars not on great circles will compromise the astrometric properties of large CCDs operated in scan mode. The cure, scanning on great circles, has been proposed for the SDSS. In most cases, wide-field astrometric observations will be taken using the conventional (stare) observing mode.

4. Conclusions

Currently available CCDs are between a factor of 3 and 10 less efficient for collecting wide-field astrometric data than currently available photographic plates, but the astrometric community is not in control of either technology. Plates appear to be disappearing on a very short time scale, and this renders moot such comparisons of technology. Single CCDs are available, although at a price that many observatories will find unacceptable, but the technology required to put many CCDs into a mosaic is still in its infancy. During this limited time of technology transition, astrometric observatories must place a high priority on understanding issues such as seeing and image sampling, and must design observing programs and strategies that will provide an astrometric bridge between detector technologies.

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