Session 6

Photometry with CCDs

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Abstract

Characteristics of telescopes, photometers, CCDs and data acquisition systems relevant to achieving high quality photometry are discussed.

1. Introduction

In the recent past, the area of the typical CCD available for astronomical use has increased by an order of magnitude. Second generation CCD controllers, essential to efficiently handle large CCDs with multiple readouts, can also provide relatively seamless integration with reduction software and telescope control environments. Computer power has increased greatly, and comprehensive data reduction packages have been written. CCD photometers have become more complex and are often used with auxiliary optics or combined with spectrographs. Active optics and low order adaptive optics, together with attention to telescope collimation and heat management, have been demonstrated to dramatically improve image quality. All these factors have a direct effect on both quality and quantity of CCD photometry.

2. Telescopes

When CCDs first started to be used a decade ago, frequently on relatively moderate sized telescopes, the inadequacies of the guiding, tracking and pointing provided often became painfully obvious. Somewhat more recently it has been generally realized that at good observing sites telescopes and their surroundings frequently limit the image quality by thermal mismatch of telescope and dome with the ambient air, or by the optical quality of the telescope mirrors, or by limitations in mirror support systems. The ESO NTT has demonstrated the dramatic gains possible given the latest advances in telescope and enclosure designs, while the CFHT is an example of how a more traditional telescope and enclosure design can be improved. Since much CCD photometry, independent of telescope size, is done in crowded fields, good image quality is a critical parameter. As an example of a program to improve an already existing telescope, at the CTIO 4m the thermal environment is being improved by moving out of the building all functions not directly concerned with operation of the telescope, by moving the control room to the ground floor, by cooling the oil used in the RA drive bearing, by controlling the temperature of the primary mirror and cell and by drastically venting the dome. At the same time the f/8 secondary mount is to be modified to allow rapid collimation, the secondary itself is to be refigured, and active control of the primary support structure is to be implemented. In addition, a Shack-Hartmann image analyser is to be permanently installed at a side port of the RC focus to allow regular monitoring of the image quality.

Telescopes designed for wide field photography are not always optimal for use with CCDs since they usually require a field flattener in close contact with the plate. For small CCDs the field flattener can generally be left out with negligible effect on the image quality, however CCDs are now approaching the size of small photographic plates, so without the flattener images can be expected to vary as a function of field position. For Cassegrain telescopes coma at field corners can intrude, as an example the CTIO 0.9m f/13.5 telescope provides a 13 arc min square field with a Tektronix 2048 CCD, but even in moderate (1.4 arc sec) seeing the fwhm are 10 percent larger at the corners of the field. Fitting psf functions to stars on such frames requires software which can build a psf which varies with position on the CCD (eg DAOPHOT) and many psf stars. An alternative is to design a suitable corrector, for a 10 cm field at f/10 or slower these can be rather simple, and with sufficient back-focus to allow a normal (plane) window for the CCD dewar. In dedicated dewars the field flattener can serve dual purpose as the dewar window; this is common practice for fast spectrograph cameras.

Difficulties with psf fitting can also arise if the CCD is not flat. TI 800^2 CCDs, which are a floating membrane of silicon supported only at the edges, are notorious for this problem and many are so warped that they cannot be used in fast beams at all. Hopefully, the Reticon 1200J is the last of this genre, but even supposedly flat CCDs are not (eg Tek 2048), and CCDs are not neccessarily aligned in their packages. For prime focus photometers it is a good idea to provide a facility for aligning the CCD with respect to the optic axis, preferably by being able to rotate and tilt the dewar slightly.

In principle, baffling (Young 1967) for the oft-used Cassegrain telescopes should be optimized for the size of CCD. This is often not possible due to the necessity of using an off-axis guider, but in any case the baffles should be well designed with multiple traps in the "chimney" (N. Caldwell, private communication). A related problem is preventing reflections off CCDs and their surroundings returning to the CCD via reflections of filters etc. Dewar windows, filters and any auxiliary optics should be AR coated. It is a good idea to mask the filters with square apertures of a size just large enough not to cause vignetting.

3. Improving the Resolution

We have already mentioned passive and active optical means of improving resolution. Some improvements can be made a posteri (eg maximum entropy sharpening) which are beyond the scope of this review and have in any case received much recent attention in the context of HST images. In most cases it seems that resolution is improved at the expense of photometric integrity (eg in the cases where the resolution improvement is proportional to S/N).

Adaptive Optics methods attempt real time correction or partial correction of wavefront errors. Instruments such as HRCAM, DISCO and MARTINI improve resolution by a combination of removal of star image wander due to seeing inhomogeneities, wind buffeting and telescope drive errors, by closing a fast shutter to exclude the worst seeing, and by using individually corrected sub apertures. Reductions of fwhm by a factor two have been reported (Racine & McClure 1989, Tanvir et al. 1991). Isoplanicity is maintained over a field of a few arc minutes square only (McClure et al. 1991), and even within the corrected field the psf will change with distance from the reference star. As emphasised by Devaney (1992), a reduction code allowing the fitting of variable psfs will be required. Gaussians are a poorer and Lorentzians a better fit than they are to unsharpened images. The above-mentioned instruments are all quite complex. It is possible in principle (T. Ingerson, private communication) to build a very simple instrument on the basis of moving the CCD itself, using one quadrant of a quad-amplifier CCD as the guider. Although such an instrument would not allow the easy use of sub-apertures, the other advantages mentioned above remain. It may be preferable to use a CCD which does not use bond wires in order to avoid mechanical stresses and microphonics.

4. Instruments

CCD photometers, particularly those used at Cassegrain foci, tend in general to be rather simple instruments, often containing no more than one or two filter wheels, an electronic shutter, and an illumination source for providing a preflash exposure. The latter device has become more use to verify correct operation of the CCD since most recent CCDs do not require preflashing. Guiding facilities normally are provided via a guide box to which the photometer is attached.

Photometers used in faster beams, such as at the prime focus of a 4m telescope, tend to be more complex instruments, at least in part due to the restrictive 8-10 cm backfocus behind the final corrector element which decrees that the guider be integrated with the photometer. Correctors in use are often those left over from the days of photography, but newer designs incorporating atmospheric dispersion compensation are feasible. Two such correctors are being built for the CTIO 4m and the La Palma 4.2m telescopes; these will provide 0.25 arcsec images over almost a degree diameter field from 3000-10000Å and correct for dispersion up to 60 deg. from the zenith, and thus will provide high quality imaging even for very large mosaics. Maintaining a sensible pixel scale is the motivation for installing CCDs at the prime foci of large telescopes. The conflicting requirements of obtaining a reasonable sized field and at the same time sufficiently sampling star images in the best seeing have been relaxed with the availability of larger CCDs. Some reduction programs (eg DOPHOT) work optimally with fwhm $\sim$ 2 pixels, however better sampling is required for work in crowded fields. Focal reducers (eg Aldering & Bothun 1991) can alter the pixel scale and are particularly useful where well sampled stellar images are not required. Similar motivation has led to the popularity of CCDs on Schmidt telescopes.

We mention only briefly integrated instruments, those that can do both spectroscopy and photometry. Given that these instruments are of necessity optimized

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for spectroscopy there are some trade-offs for photometry. UV throughput is normally poor (although new glasses and coatings have improved matters), field size is limited preventing use of the largest CCDs, while it is difficult to prevent low level ghost images. The major advantage is the ease of changing from spectroscopy to photometry, and since these instruments have a parallel beam many modes of operation are possible. Although EMMI (d'Odorico 1990) is a recent example of such an instrument which has few of the mentioned disadvantages, its complexity and high cost suggests that for pure imaging applications the simple instruments are generally to be preferred.

5. CCDs

Within the last 2-3 years, after several years of relative paucity, a number of excellent devices have become available. It has become de rigueur to use a CCD with 1024^2 pixels for photometry while 2048^2 CCDs are desirable for many programs. At the time of writing, the most popular CCDs for photometry are the Tektronix 512^2, 1024^2, 2048^2 family of back-illuminated CCDs. Also common are the Thomson 1024^2, EEV (eg 1242x1152) and the Loral (ex Ford Aerospace) 512^2, 1024^2, 2048^2, all of which are front-illuminated, and are often laser-dye or phosphor coated to improve blue and UV QE. Even larger devices (4096^2 in both 7.5 micron and 15 micron pixels sizes) have been fabricated by Loral, while Thomson, EEV and Reticon all have R&D programs for thinning large CCDs. Thinning of foundry (usually Loral) CCDs has also been accomplished by SAIC and M. Lesser (University of Arizona). In addition, Kodak produces small-pixel CCDs up to 2048^2, while older devices (TI 800^2, RCA, EEV) still see much use. Long term commitment to producing scientific grade CCDs by at least some of these companies seems assured. Janesick & Elliott (1991) have provided a fascinating in-depth look at the history of CCD evolution including recent developments. Table 1 summarizes the most popular mega-pixel CCDs.

These latest devices are not only larger than their predecessors but are improved in several important respects. The number of amplifiers provided is often two or four per CCD, offering the possibility of reducing readout time for the mega-pixel devices to that of the smaller CCDs. Unfortunately, if you want extra working amplifiers, there is often a price premium. Cosmetics for the top grade devices can be perfect or nearly so, charge transfer efficiency has improved with the incorporation of sculptured channels ("minichannels") which expose small charge packets to less silicon, read noise is now just a few electrons, while full-well per given pixel area has increased. Quantum efficiencies have generally improved with the perfection of thinned, anti-reflection coated CCDs chiefly by Tektronix (although RCA successfully pioneered this technology more than a decade ago). We shall now consider some of these properties in more detail.

Process improvements have led to a general increase in yield which has resulted in the virtual elimination of hot columns and fully blocked columns from grade one devices. Even image area charge traps, which if not too numerous are more of a nuisance to be avoided rather than a catastrophe, are now not common. Achieving

Table 1: Some Megapixel CCDs useful for Photometry

Manufacturer	Type	Size	Pixel size	Amps	Comments
Tektronix	thinned	1024^2	24	4	AR coated, implant
Tektronix	thinned	2048^2	24	4	AR coated, implant
Thomson	thick	1024^2	19	4	
Loral	thick	2048^2	15	2,4	foundry
Loral	thick	4096^2	15	4	foundry
Reticon	thinned	1024^2	13.5	4	1992?
Reticon	thinned	2048^2	13.5	4	1992?
EEV	thinned	1242x1152	22.5	2	
EEV	thick	2186x1152	22.5	2	1992?

Table 2: Examples of UBVRI filter transformations with various CCDs

Filter	Ingredients	Band	Tek 1024 + Harris	Tek 1024 + Tek	TI + Harris	Thomson + Harris
U	UG2/1, 5mm 25% $CuSO_4$	: V	-0.03	0.02	-0.04	-0.01
B (Harris)	BG12/1, BG39/2, GG385/1	: B-V	1.21	1.05	1.09	1.08
V (Harris)	GG495/2, BG39/2	: U-B			0.98	0.95
R (Harris)	OG570/2, KG3/2	: V-R	0.98	0.98	0.95	0.96
I	Interference	: V-I	0.97	1.01	0.95	1.00
B (Tek)	BG1/2, BG39/2,GG385/1[1]	:------------------------------- -----------------				
V (Tek)	GG495/2, BG38/2	:Eqns. of the form V = v + coeff. x (B-V)				
R (Tek)[2]	OG570/3, KG3/2	: and B-V = coeff. x (b-v), etc.				

Notes: [1] GG375/1 would improve the nominal match but there is a danger that unwelcome effects would occur due to the confluence of the Balmer lines. This filter has 20% more throughput than B (Harris) and 30% more than B (Bessell).

[2] Bessell (1990) suggests OG570/2, KG3/3 but this filter has only 78% of the transmission of the two R filters here.

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uniformity of response on scales ranging from pixel-to-pixel to 100's of pixels is very important. It is obviously much easier to flat-field a CCD that is intrinsically flat to start with than one which has enormous variations on every scale (such as the TI 800^2 CCDs). Although front illuminated CCDs have traditionally a flat response, thinning technology has advanced so that large back illuminated CCDs are fully competitive in this respect. Tektronix 1024 CCDs have typically 1 percent pixel-pixel variations and 2 percent variations at lower spatial frequencies. The number of low pixels (QE less than 90 percent of their neighbors) is under 0.01 percent. Ten years ago, the first generation RCA CCDs could approach these figures, and it is to be hoped that further improvements can be made.

Full well capacities are now typically more than 250000 e^- for 15 micron pixels and more than 500000 e^- for 24 micron pixels, less by a factor ~ 2 for MPP (multi-pinned phase) CCDs. The latter have dark generation several orders of magnitude less than conventional devices at room temperature (typically they have the same dark rate as a non-MPP CCD operated 30C cooler) but in order to reduce dark to just a few e^-/hour they have to be cooled to much the same temperature (typically -100C). For most ground-based astronomical applications the non-MPP versions, with larger full-well, are preferable. Noise floors can be as low as 2-3 e^- rms, thus the full dynamic range is typically 100-400 Ke^-. To digitize this range completely 17-19 bits of resolution are needed. We will return to this point below when we discuss CCD controllers. Most CCDs appear to be linear to at least 0.1-0.5 percent from very low signals to at least 80 percent of the full well capacity. The low noise figure in itself is less important for broad-band photometry, particularly on large telescopes, than it is for narrow band imaging where sky background signal is often small.

High quantum efficiency is vital to the user. Some examples are shown in Figure 1. As will be discussed elsewhere at this conference, there are particular difficulties in reproducing UBVRI passbands with CCDs. This is for two reasons; CCDs have an extended red response even compared to Ga:As photocathodes, and the blue-UV response often falls very steeply. The latter makes U band photometry difficult or impossible, the former imposes stringent red leak requirements on all filters (see Stetson 1988). The B passband is very difficult to reproduce using available glasses without sacrificing throughput, and the I band is best reproduced with an interference filter. It is also possible to imitate the B, V and R bandpasses with interference filters (eg the "Mould sets") but caution must be taken with the red leak specification, which as Stetson (1988) has pointed out, even a very small red leak integrated over several thousand Å of bandpass can cause severe problems. Different types of CCDs have very different response shapes in the blue and UV and filters which work well for one type may not work well for another. Some examples are given in Table 2. UV flooding (eg Oke et al. 1988, Janesick & Elliot 1992) still appears to produce the best UV response in thinned CCDs on which a flash oxide has been grown, but experiments (particularly by Reticon) with flashgates and biased flashgates are encouraging. The use of boron implants (eg Tektronix and EEV) has the advantage of providing a stable UV QE. Advances in anti-reflection coatings on thinned CCDs have resulted

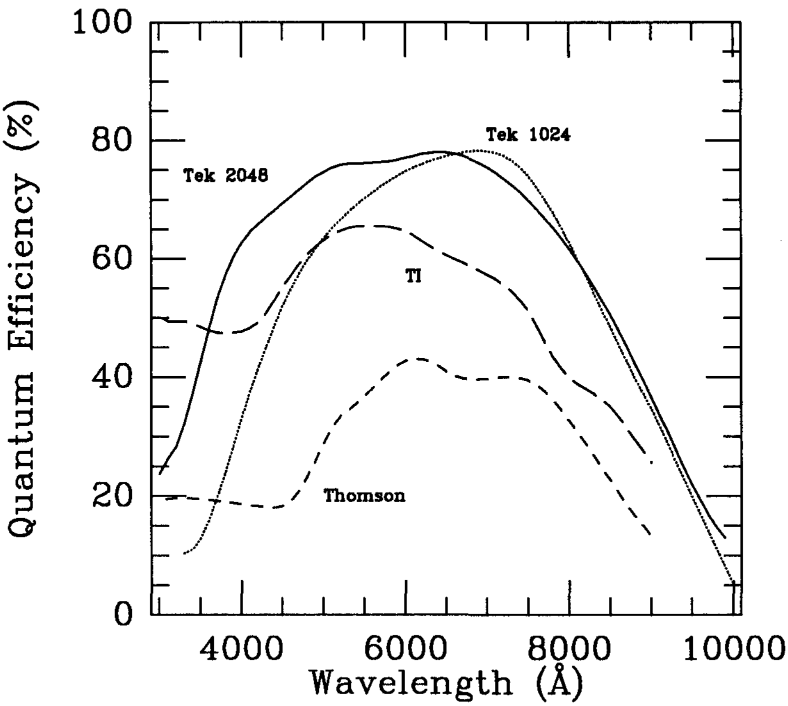

Figure 1: Quantum efficiencies for several CCDs as a function of wavelength. That for the Thompson CCD is typical for front-illuminated CCDs that have been coated to improve the response below 4500Å. The TI curve is typical for a thinned, UV flooded CCD, while an AR coating is responisble for the high peak QE of the thinned Tektronix CCDs.

in excellent QE's peaking near 80 percent, and even better can be expected in the future since M. Lesser (JPL CCD newsletter no. 3) has coated thinned Loral CCDs with Hafnium oxide and by tuning the coating thickness can obtain over 90 percent QE over a wide wavelength range including the UV.

6. CCD Controllers and the Data-taking environment

Second generation CCD controllers are beginning to appear, replacing the controllers used for the past decade. There are many motivations, including improving reliability by using modern techniques and components, improving performance, providing facilities for more efficient optimization, lowering power consumption, integrating cleanly with instrumentation and telescope control systems, etc. Controllers can be given enough computing power to allow such features as a real-time display capable of scaling and displaying the image as it is read out, with zero overhead. Pre-processing can

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be incorporated so that a single controller architecture can be used for both optical and IR arrays. User interfaces can run in modern environments (such as X-Windows) to better help the observer obtain and reduce his or her data. Three aspects will be considered in more detail.

Firstly, it is now feasible to read out CCDs with multi-amplifiers in parallel, and to build mosaics of CCDs. This directly decreases the fraction of time that data is not being taken. Several recent designs use architectures based on Inmos transputers which are designed for parallel processing applications and thus are particularly suitable. Enough computing power can be incorporated in the controller so that the time needed for unscrambling the data from multi-amplifier CCDs can be just a small fraction of the readout time. There is then little excuse for skimping on (short exposure) standard star observations, particularly since CCD-sized fields are now available containing standards with a wide range in color (Landolt 1992). Secondly, the utility of the data from the CCD depends critically on the faithfulness with which the analog signal from the CCD is amplified and converted into digital form. There are now much improved analog-to-digital (ADC) converters available, driven by the audio market. Further improvements are likely in the whole area of analog and digital signal processing, driven by medical imaging requirements. The latest generation of ADCs use less power, are faster, have no missing codes and offer impressive linearity. Very importantly, they are self-calibrating so that this level of performance can be maintained indefinitely. They can also be very small. Examples are the Crystal CS5101, Datel ADS-930 (both 16-bit) and the Analogic ADC5030 (18 bits). Even with the 16 bit units and gain set at several electrons/adu, these ADCs, particularly the Crystal unit, have such high accuracy that it is feasible to work with the least significant bit set equal to half the readout noise without ADC errors and digitization noise dominating. This is of most important in situations where there is little background.

Finally, if efforts are made to optimize the data flow right through into the data reduction environment then it is practical to process data while observing. Often it is best to have two observers (one taking the data, the other reducing it – networking and high bandwidth satellite links can mean that one or both observers can be remote from the telescope). Although it is not viable to completely reduce all types of data this quickly, it is certainly possible to carefully evaluate data, and to reduce standard star observations in this way. With readily available computing power, it is possible to read a large quad-amplifier CCD, unscramble the data and remove the instrumental signature in under 30 seconds. Representative figures for a Thomson 1024^2 CCD and the CTIO ARCON controller are: readout 11 seconds; reformat 8.5 seconds; trim, de-bias and flat field 15 seconds (reformatting and subsequent processing using a Sparcstation 2 with a 12 ms SCSI disk – this is 1991 technology; faster processors and disks are now available for much the same price). The raw data can be inspected as readout occurs on a display with 1152x900 pixels. Features such as rapid field

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preview can be built into the hardware and the software.

7. Calibration and Test Procedures

Test procedures are those which evaluate whether the instrument is functioning correctly, whereas calibration procedures include removal of the instrumental signature from the data followed (for photometry) by determination of response sensitivity usually from observations of standard stars. Massey & Jacoby (1991) show how to recognize "good data".

More stringent tests to verify operation with "second generation" controllers are desirable given that the data path from the detector to the data reduction computer is generally more complex than before. Probably the best way to accomplish this is by incorporating an Artificial Data Generator in the controller itself, at the start of the digital part of the signal chain. The read-out sequence for this data is exactly the same as for the CCD itself, and at the end of the readout the data can be compared with that expected. Telemetry of clock and bias voltages can be checked against a table of expected values. ADCs can be self-calibrating. Beyond these system checks, correct operation of the shutter (and the measurement of the usual offset from the integral number of seconds selected for the exposure time), plus various CCD parameters such as read out noise, gain calibration, linearity, etc. can be checked with a suitable series of exposures.

Another valuable technique is to plot the histogram of counts on a frame. The most suitable frame is one containing a ramp of counts ranging from the zero level up to the maximum allowed by the ADC (or full well, whichever is the lowest). A short exposure of a globular cluster is a good approximation. The histogram, after trimming of the CCD edges and any major defects, should show a smooth distribution with no "bumps" or missing codes.

Removal of the instrumental signature is some variant of subtracting a zero-level (bias) frame and then divison by a flat field frame, with removal of defects by interpolation, or simple flagging, as necessary. Dark frames are generally not needed except for very narrow band work, since most CCDs at temperatures of -100C have a dark rate of only a few e^-/hour. In practice several frames of each type are combined together, in order to improve the Poisson statistics and to allow removal of cosmic ray events. The generation of a truly "flat" flat field is something to be aimed for, but unfortunately never achieved. Djorgovski (1984) and Djorgovski & Dickinson (1988) have discussed flat fielding procedures in some detail, and only a few points will be made here.

Dome flats (exposures of an illuminated white spot inside the dome) are very popular since they do not occupy any observing time. Therefore many can be accumulated and statistical counting errors can be very small. Thus pixel to pixel QE variations can be accurately removed. Lower spatial frequencies are less well removed and there are several unfortunate effects which can conspire to make dome flats work poorly. The following are some guidelines: 1) Have a well baffled telescope, else illumination onto the CCD can be very different from the night sky. Sharp edges (dust on filters, window) may not divide out correctly, due presumably to illumination differences; part of this may be due to specular reflections off the white spot which should be made from suitable materials (see Jacoby et al. 1991). 2) You should use lamps with as a high a color temperature as possible, quartz halogen lamps with color temperatures in excess of 3000K are suitable (3300K is the upper limit, and these lamps have typically only 100h lifetime). Since this color temperature is still some 3000K too low, the lamps should be used together with a color balance filter of value -200 mred for BVRI dome flats (not U). Schott BG34 in 2mm or 3mm thickness is suitable. The Melles Griot filters are not suitable as they have high transmission in the far red, as shown in Table 3. Metal halide lamps have color temperatures of 6000K and may be an alternative; their spectra consist of many densely packed lines (rare earth elements) but they do not seem to have strong lines. 3) Your filters must not have red leaks (see Stetson 1988).

Table 3: Color Balance Filters

Band	Effective Wavelength (Ångstroms)	Transmission BG34/3	Transmission MellesGriot -180mred
U	3659	0.10	?
B	4382	0.60	0.62
V	5448	0.18	0.20
R	6407	0.05	0.07
I	7982	0.035	0.15?
	9000	0.045	high
	10000	0.07	high

Twilight sky flats can be used alone, or smoothed and used as illumination corrections to rectify the incorrect lower spatial frequencies of dome flats. Twilight and dawn are fleetingly short when one is waiting for a 2048^2 CCD to read out, and the color match is not exact; but if one is using these frames as illumination corrections only then the CCD can be suitably binned to speed read out. Other types of flat fields impact on observing time. Multiple exposures of "star-less" fields can be used as illumination corrections, after removal of the few remaining stars, or, as a variant, some or all of the object frames for a night (or the whole run) can be combined. The latter will not work well if all the frames contain images of globular clusters (see Kuhn et al. 1991 for an opposing view) but can be very successful if many relatively star-free frames can be used. Tyson (1988) has used this technique to reduce his systematic flat field errors from 20 to 0.03 percent. Drift scanning techniques (continuously reading out the CCD while moving it in synchronization) makes flat fielding a 1-D problem but sky brightness, transparency and seeing are then not constant over the whole frame. Careful reduction techniques can minimize these variations, and the method is most valuable when surveys of a large area of sky are required. A variant on this method is short-scanning, in which the CCD is read out only a few (20-100) rows during the exposure. The CCD is moved in synchronization via a precision stage (eg KPNO) or else the TV guider (and thus the telescope) moves on a precision stage (eg CTIO). As pointed out by Djorgovski & Dickinson (1988) this method should have wide application, but has seen little use.

References:

Aldering, G.S., and Bothun, G.D., 1991, PASP, 103, 1296

Bessell, M.S., 1990, PASP, 102, 1181

Devaney, M.N., 1992, A&A, 257, 835

Djorgovski, S., 1984, in: *Proceedings of the Workshop on Improvements to Photometry*, eds. W. Borucki & A. Young, p152

Djorgovski, S., and Dickinson, M., 1988, Highlights of Astronomy, 8, 45

D'Odorico, S., 1990, ESO Messenger, 61, 51

Jacoby, G.H., Schoening, W., and de Veny, J., 1991, NOAO Newsletter, 28, 25

Janesick, J., and Elliot, T., 1991, in: *Astronomical CCD Observing and Reduction Techniques (A.S.P. Conferences Series*, ed. S. Howell, in press

Kuhn, J.R., Lin, H., and Loranz, D., 1991, PASP, 103, 1097

Landolt, A.U., 1992, AJ, in press

Massey, P., and Jacoby, G.H., 1991, in: *Astronomical CCD Observing and Reduction Techniques (A.S.P. Conference Series*, ed. S. Howell, in press

McClure, R.D., et al., 1991, PASP, 103, 570

Oke, J.B., Harris, F.H., Oke, D.C., and Wang D., 1988, PASP, 100, 116

Racine, R., and McClure, R.D., 1989, PASP, 101, 731

Stetson, P.B., 1988, Highlights in Astronomy, 8, 635

Tanvir, N.R., et al., 1991, MNRAS, 253, 21P

Tyson, J.A., 1988, AJ, 96, 1

Young, A.T., 1967, Appl. Optics, 6, 1063

Discussion

M. Zeilik: *What is done at Cerro Tololo to archive CCD frames, especially the large format ones?*

Walker: At present, nothing.

A.T. Young: *Be careful with twilight flats. The twilight spectrum is heavily mutilated by ozone absorption, so it contains almost no UV and has a big dip around 6000 Å due to the Chappius bands.*

R.P. Edwin: *Would you please comment of the spectral variation of flat field calibrations. Pixel to pixel variations are maybe 1% but what is the spectral dependence, typically, in this variation?*

Walker: Photons with shorter wavelengths get converted into electrons nearer the surface of the CCD than do photons with longer wavelenths. U-band photons get converted very near the surface and the resulting U-band quantum efficiency depends critically on surface conditions. On the other hand, I-band flat fields depend little on surface properties. Thus there is little correlation between (say) U-band and I-band flat fields, even though both may have similar pixel-pixel and lower spatial frequency errors. Indeed, thickness variations in thinned CCDs may cause an *anti-correlation* between short and long wavelength flat fields.

D.H.P. Jones: *On La Palma we have been experimenting with running our CCDs 40 ° hotter than normal in order to extend their red response. In this way we have made successful observations of the HeI 10830 A line. Also, on the 1-meter telescope on La Palma, we have a drift-scanning arrangement where the CCD is driven by a lead screw. Every time the lead screw advances the appropriate amount one row of the CCD is read out. This is used to extend the size of the CCD.*

Walker: Referring to your first point, some CCDs now are of MPP design and have a lower dark rate than non-MPP CCDs. These would seem to be particularly suitable for being operated at elevated temperatures.

I. van Breda: *What are the limitations on the type of chip to which you can apply UV flooding?*

Walker: The CCDs must be thinned and have a 'steam oxide' layer grown.

T.J. Kreidl: *I think it is impressive to see the new developments in hardware at large institutes. Many smaller establishments are forced to buy commerical systems which often have older technology. One hopes many of the new developments will eventually trickle down to smaller observatories, and it's important that experiences gleaned from observatories with major development programs are made widely known within the astronomical community.*

Walker: Instrumentation at National Observatories tends to be very well documented, and there is no reason why detailed information cannot be supplied to anyone who requests it.

R. L. Hawkins: *Where is your colour correction filter for dome flats located? Also, how do you then deal with dust spots and irregularities in the colour correction filter which affect your flats?*

Walker: In answer to your first question: in the optical path above the other filters. With regard to the second point: we try to minimize those as much as possible, but I agree that it is a problem.