Direct Imaging Manual for Kitt Peak

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1 Introduction

1.1 About This Manual

This manual is intended to serve as a reference guide and as a source of advice for direct imaging with the Kitt Peak telescopes.

Other resources you may find useful are listed below; they are all available via the Kitt Peak documentation page on the web at:http://www.noao.edu/kpno/docs.html.

- *NOAO CCD Mosaic Imager User Manual.* This describes the 8K × 8K Mosaic Imager used at the 4-m and 0.9-m.
- *The Mini-Mosaic Manual.* This describes the 4K × 4K Mini-Mosaic Imager in use at WIYN.
- *An Observer's Guide to Taking CCD Data with ICE.* This is the manual describing the data-acquisition software for non MOSAIC ccds.

The Mosaic Imager (8K × 8K) has become the premiere imaging camera at the 4-m, and is used at the 0.9-m on a shared basis with the 0.9m WIYN consortium. WIYN has the Mini-Mosaic 4K × 4K as its imager. plus the CCD dedicated to the WIYN tip/tilt module (WTTM). The 2.1-m uses the T2KA CCD.

- *4-m:* The Mosaic Imager consists of 8 2K× 4K SITe CCDs with 15μm pixels. It is used at the 4-m for very deep imaging with a large field of view (36 × 36 arcmin) and good sampling (0.26 arcsec/pixel). There is a corrector which includes an atmospheric dispersion compensator (ADC) to provide excellent image quality. Sub-arcsecond images are not uncommon. Mosaic has two TV cameras mounted on it, either of which will serve as a guider.
- *WIYN:* The 3.5-m WIYN telescope provides superb image quality (0.7 arcsec median seeing) with the capability of going deep. The WIYN science imager is the Mini-Mosaic, consisting of two 2K × 4K SITe CCDs, identical to the excellent Mosaic devices. The scale is 0.14 arcsec/pixel, and the FOV is 9.6 arcmin on a side, with a small gap between the two CCDs. Guiding is accomplished using a single movable guide probe. NOAO has 40% of the observing time at WIYN.

The WTTM provides fast guiding correction, resulting in a typical improvement of 0.13 arcseconds FWHM. The module feeds a 2K × 2K section of an engineering-grade, thinned, AR coated EEV CCD. The 15 micron pixels sample the image at a scale of 0.12 arcseconds.

- *2.1-m:* This CCD system is used primarily for applications where good image sampling (0.3 arcsec/pixel) and deep imaging are crucial but large field size is not. The CCD camera is mounted at the Cassegrain focus of the 2.1-m. The field of view with the Tektronix 2048^2 CCD is 10.2×10.2 arcmin; there is some vignetting on the south side of the field ($<$ 200 columns, higher column numbers); the unvigenetted field is thus 10.2×9.4 arcmin. Guiding is accomplished using a TV on a movable x-y stage. The field size is similar to that of Mini-Mo on WIYN, but the median seeing at the 2.1-m is substantially worse; sub-arcsec images are not uncommon, but certainly cannot be counted upon. On the other hand, there is considerably more observing time available at the 2.1-m than at WIYN.

- *0.9m:* The Mosaic camera on the 0.9m offers a 59×59 arcmin FOV with 0.43 arcsec/pixel sampling. Mosaic is used on a shared basis with the 0.9m WIYN consortium.

2 The Facts

In the following sections we will present the basic parameters characterizing the CCDs and telescopes.

2.1 CCD Characteristics

The following table gives the physical characteristics of the CCDs used for direct imaging.

CCD Characteristics

Chip	Use	Size (pixels)	Pixel Size (μm)	0.1% Linearity Limit (e^-)	Read Noise (e^-/pixel)	Dark Current (e^-/hr/pixel)	Radiation Events (events/hr)	Default Gain (e^-/ADU)
T2KA	2.1-m	2048^2	24	180,000	4.0	5.0	3000	3.6
SITe	Mosaic	2048 × 4096	15	70,000	6.0	5.0	?	3

2.2 FOV, Scale, Orientation

The following table gives the field-of-view (FOV), scale, and orientation for telescope and CCD combinations commonly used for direct imaging. The Mosaic and Mini-Mosaic CCDs have small gaps between them; common practice is to dither exposures with the Mosaic and fill in the gaps, and to simply ignore the gaps with the Mini-Mosaic. Some dithering is also done with Mini-Mosaic.

Telescope + CCD Characteristics

	f/ratio	FOV	Scale	Display Orientation	
		(arcmin)	("/pixel)	N	E
4m+Mosaic	3.1	36 × 36	0.26	left	down
WIYN+Mini-Mo	6.5	10 × 10	0.141	left	down
2.1m+T2KA	7.5	10.2 × 10.2*	0.305	left	down
0.9m+Mosaic	7.5	59 × 59	0.43	left	top

*Unvigenetted FOV at the 2.1-m is 2048 × 1850 pixels, or 10.2 × 9.4 arcminutes, with the vignetted region being to higher column numbers (south).

2.3 Limiting Magnitude

An approximate guide to the limiting magnitude you will achieve for a given SNR for an isolated stellar image under average seeing conditions in shown in Fig. 2.3. You can compute exposure times a function of signal-to-noise for various lunar phases as described in Appendix A; there is also an IRAF task "ccdtime", and a Web version on the Kitt Peak home page that you may find useful.

Limiting Magnitude for 1 Hr Exposure

	4m+T2KB/Mosaic					WIYN+Mini-Mo					2.1-m+T2KA					0.9m+Mosaic				
SNR	U	B	V	R	I	U	B	V	R	I	U	B	V	R	I	U	B	V	R	I
	New Moon																			
100	22.0	23.5	23.2	22.8	21.9	21.9	23.3	23.1	22.7	21.9	20.7	22.5	22.5	22.2	21.3	19.4	21.2	21.2	20.9	20.1
50	22.9	24.3	24.0	23.6	22.7	22.8	24.3	24.0	23.5	22.7	21.7	23.2	23.1	22.8	22.0	20.7	22.3	22.1	21.8	21.0
10	24.9	26.1	25.8	25.4	24.5	24.7	26.1	25.7	25.3	24.4	23.7	25.1	24.9	24.6	23.7	22.9	24.4	24.1	23.7	22.9
3	26.2	27.4	27.0	26.7	25.8	26.0	27.3	27.0	26.6	25.7	25.1	26.5	26.3	26.0	25.1	24.3	25.7	25.4	25.0	24.2
	Quarter Moon																			
100	21.1	23.0	23.0	22.7	21.9	21.0	22.8	22.9	22.6	21.8	20.1	22.0	22.2	22.0	21.2	19.0	20.9	21.0	20.8	20.1
50	22.1	23.6	23.7	23.5	22.8	21.8	23.6	23.6	23.4	22.6	20.8	22.7	22.9	22.6	21.9	19.9	21.8	21.8	21.6	20.8
10	23.6	25.4	25.4	25.3	24.6	23.6	25.4	25.4	25.1	24.3	22.6	24.5	24.7	24.4	23.6	21.8	23.7	23.7	23.4	22.6
3	25.0	26.9	26.9	26.5	25.7	24.9	26.7	26.7	26.4	25.6	24.1	26.0	26.2	25.9	25.1	23.3	25.2	25.2	24.8	24.1
	10^d Moon																			
100	20.6	22.7	22.8	22.6	21.7	20.4	22.5	22.6	22.5	21.7	19.5	21.6	22.0	21.8	21.1	18.5	20.5	20.7	20.5	19.8
50	21.4	23.4	23.5	23.3	22.6	21.2	23.3	23.4	23.2	22.5	20.3	22.4	22.8	22.6	21.9	19.3	21.3	21.5	21.4	20.6
10	23.1	25.1	25.3	25.1	24.3	23.0	25.0	25.2	25.0	24.2	22.1	24.2	24.5	24.4	23.6	21.1	23.1	23.3	23.2	22.4
3	24.5	26.4	26.6	26.4	25.6	24.3	26.4	26.5	26.3	25.5	23.4	25.5	25.8	25.7	24.9	22.4	24.5	24.6	24.5	23.7
	Full Moon																			
100	19.7	22.0	22.3	22.4	21.6	19.6	21.9	22.2	22.3	21.5	18.7	21.0	21.6	21.6	20.9	17.7	19.9	20.3	20.3	19.6
50	20.5	22.7	23.1	23.1	22.4	20.3	22.6	23.0	23.0	22.3	18.7	21.0	21.6	21.6	20.9	18.5	20.7	21.1	21.2	20.5
10	22.2	24.5	24.9	24.9	24.1	22.1	24.4	24.8	24.8	24.1	21.2	23.6	24.1	24.2	23.5	20.2	22.5	22.9	22.9	22.2
3	23.6	25.8	26.2	26.2	25.5	23.4	25.7	26.1	26.1	25.4	22.6	24.9	25.4	25.5	24.8	21.5	23.8	24.2	24.3	23.6

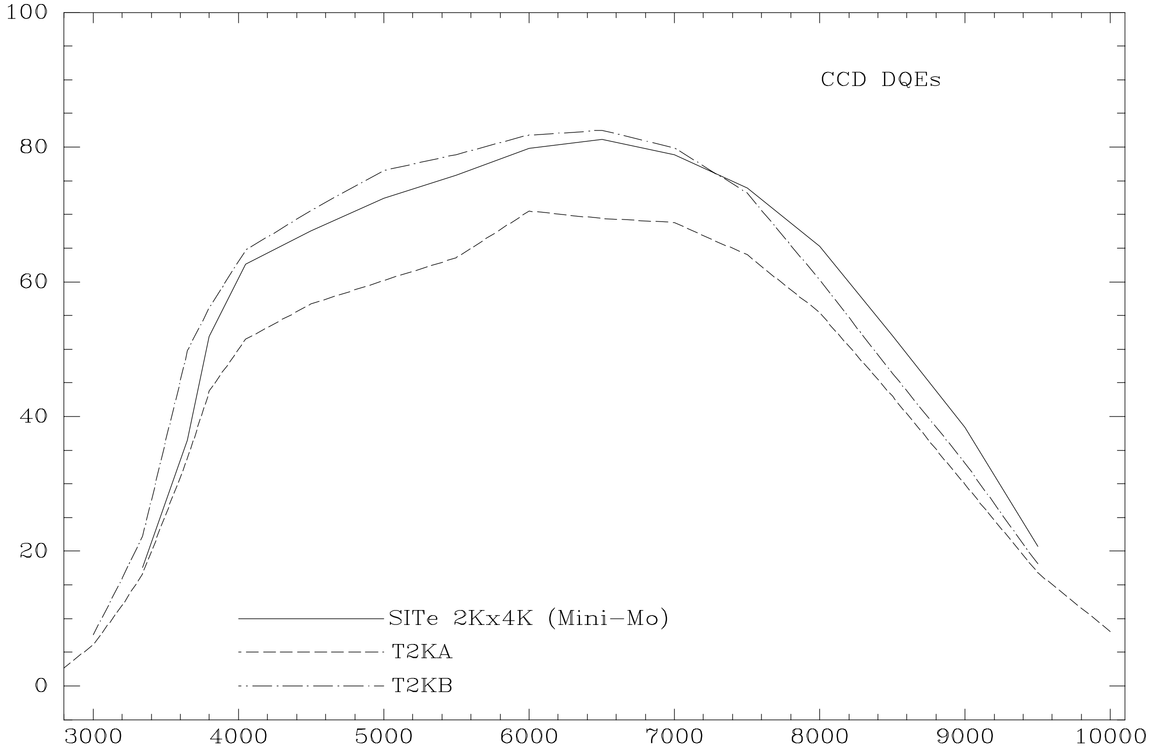

Figure 1: The relative DQEs of the CCDs used for direct imaging are shown above. The SITe DQE curve is typical of the Mosaic and Mini-Mosaic chips.

2.4 Filters

Mosaic requires 5.75 inch square filters; a complete list is available in the Mosaic manual. The other two cameras (WIYN Mini-Mosaic, and the 2.1-m 2048 CCD) take 4inch filters; adapters are also available for 2inch filters, but the vignetting will be quite large.

The standard *UBVRI* broad-band set is kept with each camera. In addition we have numerous other filters available in either 4in × 4in or 2in × 2in size, including a Gunn set, a Stromgren set, and a Washington system set, as well as numerous interference filters for narrow-band work. A complete listing of filters, and copies of their transmission plots is available via the Kitt Peak home page.

In selecting narrow-band filters for your observing run, keep in mind that there is a significant shift of the central bandpass to the blue (by as much as 20Å) when using interference filters in fast f-ratio beams. The transmission of a narrow-band filter in these fast beams can be simulated; if you need information about a particular filter please contact us via ”kpno@noao.edu”.

2.5 Focusing

Users of Mosaic should refer to the Mosaic manual; similarly, users of Mini-Mo should refer to the Mini-Mosaic manual for focusing procedures. Typical focus values and offsets for our commonly used filters are given in the table below, along with recommended step sizes to use when focusing. The focus offsets for other 4x4-inch filters, is given later in this section. By interpolating you will likely be able to determine the best focus to half of one of these steps or better; this has been made particularly easy for the user with the IRAF task *kpnofocus* (see the ICE manual).

Typical Focus Values and Offsets

	V	Offsets				Step
	@10 °C	U	B	R	I	
2.1m	20500	+150	0	0	0	+25

There is a fairly strong focus dependence on temperature at all telescopes; in addition, the 2.1-m shows a pronounced effect with zenith distance. Once you have a good focus, the coefficients below will guide you in refocusing as the temperature and airmass changes.

Focus Change (ΔF) with ΔT(°C) and ΔX

	$\Delta F/\Delta T$	$\Delta F/\Delta X$
4m	-90	0
2.1m	-75	-130
0.9m	$+1.8$	0

Thus the focus for the *BVRI* filters at the 2.1-m can be predicted as:

$$F \approx 20500 - 75 \times (T - 10) - 130(X - 1.0)$$

where the temperature T is measured in °C and X is the airmass.

2.6 Guiding and Acquisition

All of the telescopes used for direct imaging have automatic guiders that should be used for exposures longer than a few seconds. The following is a brief description of the guider characteristics. At the 4m and WIYN the telescope operators handle setting up for guiding; complete details of how to use the guiders at the 2.1-m and 0.9-m can be found in the telescope operating manuals.

- MOSAIC: The Mosaic camera has its own pair of TVs; either TV can be used for guiding.

- *WIYN:* Guiding at WIYN is handled by an off-axis TV. Unfortunately, there is no capability to make minor corrections to the rotator angle (i.e., two-star guiding). If the rotator needs to “unwrap”, make sure you terminate the exposure rather than pause!

- *2.1-m:* The 2.1-m guider has an ILS TV mounted on a movable x-y stage on the side of the telescope. The x-y stage is 30 arcmin by 18 arcmin with a modest gap in the middle. The brightness range of guide stars is approximately $9 < V < 14$. A TV camera mounted on the side of the telescope (FOV = 5’ × 5’) can be used for acquisition, if needed, by putting a remote-control mirror into the beam to direct the on-axis light to it, but this is seldom needed.

2.7 Shutter Corrections

None of the shutters is instantaneous, and if you use short exposures (<20 sec) we recommend you measure the shutter corrections yourself. This is easily done by using both long and short exposures on a star near zenith, on a good, photometric night, or by using dome flats. (In the case of the latter care must be taken to allow for the possibility of slow, monotonic drifts in the intensity of the lamps; i.e. by doing exposure sequences that are short, long, long, short. There is an IRAF routine, *findshutcorr*, which will help analyze flat-field data; see the ICE manual for a description.) The shutter corrections do appear to vary in the long-term, so it is probably useful to measure these during each observing run. The following table reflects our experience.

Note that in the case of all of the shutters that the entire field is illuminated for the identical time: these shutters are of "guillotine" type, with the blades moving the same way on opening and closing for one exposure, and then the opposite way on the following exposure.

Exposure Time Corrections

Shutter	Correction(sec)
2.1-m	-0.100 ± 0.050
WIYN	?.???
MOSAIC	-0.03 ± 0.01

3 Observing Hints

3.1 How To Choose A Gain Setting

"How do I choose a gain setting?" is one of the most asked questions. All of our chips have gains which are adjustable by the software. Why would you want to adjust the gain? The Tektronix chips have a a full-well capacity of ≈200,000 e^-, before there is any detectable deviation from linearity. However, the A/D converters are limited to 16-bits, and cannot output data that is greater than 65,535. Thus to make full use of the dynamic range you would like the gain factor to be about 3. Why not simply set it to 3? The reason is that our chips also have very low read-noise, and thus if the gain is greater than the read-noise, you will be undersampling the read-noise—in effect, increasing the read-noise to the level of the gain simply because of digitization noise. (You don't quite recover a read-noise of $4.0e^-$ if each data unit is equivalent to $3e^-$.) So like most things in life, there are trade-offs.

If you are attempting to do 1% stellar photometry of stars in a cluster, you are probably interested in covering as large a magnitude range as possible, and furthermore, your noise is going to be primarily photon-noise, not read-noise. Go for the largest value of e^- per ADU as you can without exceeding the linearity of the particular chip. Generally, this will be the default gain, which is also the gain that will give you the least amount of horizontal bleeding from very saturated stars and the most uniform noise characteristics.

If you are doing surface brightness studies of objects through narrow-band filters, and the read-noise is significant but the dynamic range of your objects is limited, you may wish to stay with the largest gain number (smallest number of e^- per ADU). Similarly in some very low-signal spectroscopic applications you are limited by the read-noise.

Note: T2KA shows some very low-level "streaking" to the right of the most heavily exposed stars. The electronics has been adjusted to minimize this problem for the default gain setting. If you are concerned about the effects of very saturated stars, you would do well to stay with the default gain setting.

3.2 Dealing with Cosmic Rays

If you were to take a 15-minute "dark" exposure you would be struck by the large number of 1-2 pixel radiation events present. Fortunately, most of these are of modest amplitude and would be lost in the sky-noise for broad-band work. However, some would not. These "radiation events" are often dubbed "cosmic rays", although in fact many of them are secondaries that originate in the CCD substrate itself.

In order to filter out these radiation events most observers will divide their long exposures (> 10 min) into 2 or 3 pieces. With the low read-noise present in our CCDs, combining three 10 minute exposures usually has the same signal-to-noise as a single 30 minute exposure. The only loss is the extra read time.

3.3 Calibration Data

By "calibration data" we refer both to what is needed to remove the "instrumental signature" of the CCD (biases and flat-fields, say) as well as what is needed to provide photometric and/or flux calibration.

3.3.1 What Calibration Data You Need and Why

Instrumental Signature

The goal in removing the instrumental signature is to transform the data so that the output signal is linearly proportional to the amount of light entering the telescope, at least as linear as the CCD allows. To do this one needs to first remove the additive terms (such as bias structure and dark current) and then remove both the pixel-to-pixel gain variations and the lower frequency response of the telescope/detector to a uniform (flat) level.

Over-scan and bias: With every exposure there is a pedestal level which is added to the output signal: "the bias", typically several hundred ADUs. As the temperature of the electronics changes during the night this bias level will also change by a few ADUs. All of our chips are read with an extra 32 columns of "overscan" which provides a measurement of this bias level. In data reductions one can use this strip to determine either a scalar correction, or fit a smooth function to the level as a function of line number.

Some chips exhibit a spatial bias *structure* as well, and it is necessary, in those cases to use zero-second *bias frames* to correct for this (constant) two-dimensional structure. By using 10 or so frames to construct an average one obtains a calibration frame which will not increase the noise much on one's data frame.

One thing that you may notice on your bias-frames is "banding"—these are usually low-amplitude (1-3 ADU) bands that extend across all columns (including the over-scan) and are perhaps 20-100 lines in width. These bands are due to slight electronic noise, and unfortunately will vary with every exposure. One has two recourses: (a) either one can ignore these (for most direct imaging applications these bands will be completely lost in the sky-noise), or (b) one can remove these by using a high-order fit in the overscan (cubic-spline of order 100-200, say). Although these may appear to be quite severe in the bias frames, one should measure their amplitude before panicking. If the amplitudes are appreciable ($>$ 10 ADU, say) then these are probably curable and a call for help is warranted.

Dark-current: All CCDs suffer from thermal "noise" as electrons jitter around and are occasionally liberated; these non-photon events are then trapped in the potential well. To reduce the size of this dark-current our CCDs are cooled to approximately $-100°$C with the result that dark-current on our chips is barely detectable (3-4 e^-/hr/pixel). The dark-current is usually quite uniform and hence has no effect on photometry if the sky value is being determined from the program frames themselves. One might still wish to take several *dark-frames* to substantiate that the effect is small. In practice, light-leaks can exceed the level of the dark current level, so care should be done to do this with the dome darkened. The exposure time on your dark-frames should equal or exceed your longest exposure time, and if there is any possibility that you may actually need to use these dark-frames to correct your data, you should take a minimum of 3 of these to allow cosmic-rays and radiation-events to be filtered out in determining the average.

Flat-fields: Each pixel in the CCD responds to light a little differently. Modern CCDs are surprisingly "flat" in their response (i.e., the gain of each pixel is nearly the same), but as Mackay (1986 ARAA 24, 255) put it: "The only uniform CCD is a dead CCD." In practice there are slight color-dependent gain differences between each pixel that must be removed for good photometry.

To remove this pixel-to-pixel gain variation one needs a series of well-exposed "flats", obtained through each filter. The total exposure in one's flats should be such that one never degrades the signal-to-noise in your program frames; in practice, accumulating 4 or 5 flats with 20,000 e^-/pixel will amply suffice to remove the pixel-to-pixel variation. Better matching of response to very low illumination levels could require a more extensive series of exposures at an even lower fraction of full well.

However, even if the telescope were being illuminated completely uniformly (by, say, the night sky) the CCD is unlikely to be illuminated uniformly. Instead, vignetting due to guider mirrors, non-uniformities in the filters (and dust on the filters) require that large-scale flat-fielding is necessary.

How to best achieve this appears to be telescope-dependent on Kitt Peak, and we give our recommendations in Sec. 3.3.2. Possibilities include:

- **dome-flats:** Exposures of illuminated white spots mounted in the domes will provide excellent pixel-to-pixel responses and may match the night-sky to $< 1 - 2\%$.

- **twilight-flats:** Exposures of the bright, twilight-lit sky alternatively can be used to provide both good pixel-to-pixel response and a better match to the night-sky.

- **dark-sky flats:** Shifted exposures of the dark sky in regions where there are few stars may be combined and smoothed to provide the utmost in removing large-scale gradients; these are usually used in conjunction with well-exposed dome or twilight flats in order to remove the pixel-to-pixel variations. Often a carefully combined set of your program frames themselves may suffice to serve as a dark-sky frame.

Fringes: Even after flat-fielding, fringing will often still be apparent in your broad-band R and I exposures. These fringes are simply interference fringes produced in the surface layers of thinned chips by strong night-sky emission lines. A "fringe-frame" may be constructed from dark-sky flats, scaled, and subtracted in the final reduction process. (The "fringe pattern" that results from use of narrow-band filters, or that which is evident in I even with dome-flats, will come out naturally in the flat-field division.)

Photometric Calibration

Observations of standard stars permit removing the effects of atmospheric extinction and transforming your instrumental magnitudes to "standard magnitudes" and/or flux. Since the scientific goals of some programs require only good relative photometry, while others ask for (and should be able to achieve) 1% all-sky photometry, we can offer you only general guidelines in obtaining adequate photometric calibration of your data. The definitive and best-calibrated set of *UBVRI* photometric standards are those of Landolt (1973, AJ 78, 959; 1983, AJ 88, 439; 1992 AJ 104, 340); copies of these papers, including finding charts, are kept at each telescope in a single binder. Most observers' choice for flux calibration of narrow-band images are the "Kitt Peak Spectrophotometric Standard" stars found in Massey et al (1988, ApJ 328, 315) and Massey et al (1989 ApJ 358, 344) or the KPNO-produced IRS and IIDS Standard Star Manuals. There are caches of the coordinates of the Landolt and Spectrophotometric Standards on the computers at the 4-m, 2.1-m.

3.3.2 Recommendations

Bias frames: Obtain 20 of these each afternoon and compare the combined, overscan-corrected frame to that from the previous day. Daily bias frames provide a good check that the instrument is performing normally.

Dark frames: Obtain a 15-minute dark-frame with the dome as dark as possible. Process it and examine for excess counts. If your program requires dark frames, obtain a minimum of 4 over the course of your run, each with an exposure time equal to your longest exposure time.

Flat-fields: The *procedures* for obtaining good flat-field exposures are given below, followed by our telescope-specific recommendations of what you may need.

Dome-flats: Obtain 5 or more of these (each 20,000 e^- per pixel) through each filter at the white spot. For *BVRI* use the lamps with the blue, "color-balance" filters; for *U* or for narrow-band interference filters, use the lamps without the color-balance filters. The table below will give an approximate guide to exposure times, but by all means check these by first doing a "test" exposure with each filter to substantiate that the exposures are neither saturated nor underexposed. (Note: "doobs" is available for running through such a sequence automatically if the lamps do not have to be adjusted; see the Mosaic Manual, Mini-Mosaic Manual, or the ICE manual.)

Note that dome flats run during the daytime (particularly at the 0.9m) may be seriously compromised due to daylight leaking into the dome and straying into the telescope. We recommend that before you run your dome flats you try an exposure with the appropriate exposure time *with the flat-field lamps off.* This will tell you whether or not scattered light will contribute significantly. You will have to try this at various wavelengths, as the scattered light problem can be especially bad at R and I.

Settings and Exposure times for Dome Flats

	4-m Mosaic			WIYN+Mini-Mo			2 Meter+t2ka			0.9-m+Mosaic		
	Lamps	Set	Exp	Lamps	Set	Exp	Lamps	Set	Exp	Lamps	Set	Exp
U	High	max	10^s	High	3200	10^s	High	max	30^s	High	100%	10^s
B	Low	max	10^s	High	3200	1^s	Low	max	40^s	Low	100%	5^s
V	Low	max	7^s	High	1500	5^s	Low	max	30^s	Low	100%	3^s
R	Low	max	7^s	High	1500	1^s	Low	max	30^s	Low	100%	2^s
I	Low	max	12^s	High	1000	1^s	Low	max	40^s	Low	100%	2^s

Twilight-flats: At the 4 meter Mosaic, as soon after sunset as possible obtain twilight flats with the telescope tracking and the dome clear. For broad-band work, begin with your bluest filter and wait until a one-second exposure no longer saturates the chip. Obtain 3-4 exposures through each filter, stepping the telescope by 30 arcsec between each exposure, and changing the exposure time as needed to avoid underexposing or saturation. It is possible but difficult to obtain a complete set ($UBVRI$) during a single twilight, so this may take several evenings and mornings to obtain a complete set. Twilight flats obtained during partially cloudy conditions do not appear to work. *Twilight flats do not appear to work at either WIYN or the 2.1-m, both open-tube telescopes, probably due to the large amount of scattered light present in the dome during bright twilight.*

Dark-sky flats: If your program frames are relatively sparse and contain sky levels at least $100e^-$ above bias, you can probably use these frames themselves as the ultimate correction for large-scale illumination errors. You will have to combine them with scaling by the mode and experiment with the various rejection algorithms to remove all your interesting stuff (stars/galaxies) and leave you only sky.

Alternatively, you can obtain 4-5 exposures (the more the better) of relatively "blank sky" fields, offsetting the telescope by 30 arcsec or more between each exposure. When done you will be able to "clip" out the stars and smooth the result. Still, you will want at least 100 e^- per pixel above sky if you want to use these to correct to a small fraction of the night sky.

Although stars appear to be just about everywhere, the following fields are not as full of them as others:

Blank Sky (sort of)

α_{1950}	δ_{1950}
04:25:46	54:09:00
13:04:33	29:50:50
19:19:09	12:22:05

Fringe Frames: However obtained, your dark-sky flats will also suffice for removing the average fringing in R and I. However, as the relative intensities of the night sky lines that cause fringing in the I band are quite variable during the night, don't expect to do a perfect job. Remember that fringing from night-sky lines can be treated as *additive*, and that an appropriate scale-factor must be determined. See the "User's Guide to Reducing CCD Data With IRAF" guide.

What Works/What Doesn't

- *4-meter:* For Mosaic, twilight flats are essential for good flat-fielding.

- *WIYN:* Dome flats and bright twilight flats also differ here by $\approx 2\%$ in large-scale gradients, but here the dome flats agree with dark-sky. We attribute this to scattered light with the open tube. We have only ever used the "high" bank of dome lamps ourselves, but found excellent agreement with the night sky.

- *2.1-meter:* Dome flats and bright twilight flats (not recommended), also differ here by $\approx 2\%$ in large-scale gradients, but here the dome flats agree with dark-sky. We attribute this to scattered light with the open tube.

- *0.9-meter:* Dome flats and bright twilight flats differ by $\approx 2\%$ in large-scale gradients, particularly at U and even at B (despite the use of different lamp banks). Twilight flats do agree with dark-sky, however, and we recommend you get a good set of twilight flats if you are interested in $< 2\%$ photometry. Dome flats run during the late afternoon, particularly at R and I, are nearly useless due to scattered daylight within the dome. With Mosaic you definitely do not have a choice: twilight flats and dome flats can differ by $> 10\%$, and it is the twilight which matches the night-sky.

3.4 Things to Check Your First Afternoon

The following is not meant as a complete list but will cover many of the "gotcha's" that we commonly experience.

- Check with your instrument assistant that you understand what filters are loaded into which filter positions.
- Examine a bias frame.
    - Does it look normal? In particular:
        - Is there banding present? Most of our CCDs show low-level bands of rows with slightly elevated levels (a few ADUs); usually these are completely drowned out in the photon noise from the sky. If the levels are appreciable ($>$ 10 ADU, say) you may need to call for help. Note that since these bands extend into the overscan region you can remove them by using a high-order fit to the overscan.
        - Are ripples or moiré (herring-bone) patterns visible? If so what is their amplitude in ADUs? If they are no greater than the read-noise, you may simply have to live with them.
    - Plot a column.
        - Is the pedestal level reasonable (100-1000 ADU)? If the level is within a few ADUs of being zero, call for help!
        - Is it nice and flat? Or does the pedestal ramp from bottom to top? We expect a ramp of $\approx$ 5 ADU on our large chips (easily removed when you fit the overscan), but a significantly larger ramp may indicate that the chip is not uniformly cold.
    - Plot a row.
        - Is it nice and flat?
        - Measure the read-noise. Is it about what you expect? The RMS cannot be much less than 1.0 ADU, so don't expect the read-noise to be any less than 1 ADU times the gain. (See Sec. 3.1.)
        - The overscan region will be the last 32 columns. We expect it to be a few ADUs above or below the bias level on the rest of the chip. Is it?

- Examine a flat-field exposure.
  - Check the frame for (a) gradients, (b) dead columns, and (c) charge traps.
  - You may also wish to check for "stuck bits" by plotting a histogram. A stuck bit will result in periodic drop-outs of data values, but care must be taken not to over interpret such histograms. If a problem is suspected, Electronics Maintenance can diagnose this by putting a ramped signal through the electronics.
  - Are any dust doughnuts present? (You bet there are!) The ones that remain constant from filter to filter are actually on the dewar window; larger doughnuts that change from filter to filter are on the filters themselves. It is not unusual for these doughnuts to "come and go" during your run; this is the primary reasons that flats are needed each night. A constant change in the positions of all your "filter" doughnuts from one day to the next may indicate that the filter wheel is not positioning correctly.
  - If you are planning to run dome flats during the day, it would be good idea to get an idea of how much stray light is entering the telescope. Once you've determined the correct exposure time for each filter/lamps combination, try taking an exposure with the lamps turned off.
- Examine the header of one of your exposures. Is all the telescope/filter information getting in there correctly?

A Computing Exposure Times

The *easiest* way to compute an exposure time for a given SNR, magnitude, and lunar phase for one of the Kitt Peak telescopes and CCD systems is to use the IRAF routine *ccdtime*. The version distributed with IRAF V2.10.3 has been updated with following information.

However, in the interest in building character (and since it is important to document this *somewhere*) the following explains how to do this the painful way!

We begin with the measured count rates corrected to a Johnson-Kron-Cousins broadband $U = B = V = R = I = 20$ mag star. Note that the rates are in e^-/sec integrated over the entire spatial profile of the star.

Count Rates (e^-/sec/image) at 20th mag

	U	B	V	R	I
WIYN+Mini-Mo	20	230	270	310	180
2.1m+T2KA	7.2	65	95	110	60
0.9m+Mosaic	2.0	14	15	16	9

These numbers are not from stone tablets, but you should see similar count rates to within 25% or so.

How long do you have to integrate to obtain a given signal-to-noise ratio (SNR) at some magnitude? The SNR will simply be

$$SNR = \frac{Nt}{\sqrt{Nt + pSt + pR^2}}$$

where
N=count rate in electrons per second per image.
t=integration time.
R=Read-noise in electrons; this can be taken to be 4 e^- for all practical purposes (see Sec. 2.1
p=Number of pixels in stellar image. If the seeing profile FWHM of r (in pixels), then it is not unreasonable to use an area of $\pi \times (0.67 \times r)^2 = 1.4 \times r^2$.
S=electrons per second *per pixel* from sky.

Thus the integration time needed to reach a given signal-to-noise will be

$$t = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

where
$A = N^2$
$B = -(SNR)^2(N + pS)$
$C = -(SNR)^2 pR^2$

What do we use for the sky brightness? The table below is taken from Alistair Walker's article on the sky brightness at Tololo in *NOAO Newsletter No. 10*; photometry of the Kitt Peak night sky is consistent with these numbers.

Sky Brightness (mag/$arcsec^2$)

lunar age (days)	U	B	V	R	I
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

We can easily turn this into a count in electrons per second per pixel (e.g., "S" in the above equation by simply using the telescope/chip sensitivities given above and the scale (arcsec per pixel) given in Sec. 2.1. The table below gives this for new moon; other lunar phases can thus be readily computed using the sky brightness relative to new moon.

Sky Brightness (S) at New Moon (e^-/sec/pixel)

	U	B	V	R	I
4m+Mosaic	0.5	1.5	4.2	9.9	13.0
WIYN+Mini-Mo	0.06	0.4	1.0	2.6	3.2
2.1m+T2KA	0.1	0.4	1.7	4.4	6.0
0.9m+Mosaic	0.05	0.16	0.51	1.3	1.7

Thus the (very rough!) expected count rate from the sky in V at WIYN with Mini-Mo at full moon will be $10^{(21.8-20.0)/2.5} \times 2.0 = 10.5$ e^-/sec/pixel.

We can attempt to duplicate the result given in our "Limiting Magnitude" table in Sec. 2.3: What is the integration time required at WIYN and S2KB obtain a SNR of 50 at V for a star of 23.6 magnitude during with a Quarter Moon (lunar age=7 days) in the sky? We expect the answer to be about an hour!

The count rate N for a $V = 23.5$ mag star will be $10^{(20.0-23.6)/2.5} \times 270 = 9.8$ e^-/sec/image.

The sky counts S will be $10^{(21.8-21.4)/2.5} \times 1.0 = 1.5 e^-$/sec/pixel.

The number of pixels will of course depend upon the seeing; if it is something like 1.0 arcsec then the number of pixels will be $1.4 \times (1.0/0.14)^2 = 71$ pixels.

We then have:

$A = N^2 = 9.8^2 = 96$

$B = -(SNR)^2 \times (N + pS) = -50^2 \times (9.6 + 71 \times 1.5) = -290250$

$C = -(SNR)^2 \times pR^2 = -50^2 \times 71 \times 6^2 = -6390000$

and the time will be:

$$t = \frac{-B + \sqrt{B^2 - 4AC}}{2A} = 3050.$$

close enough for government work.

B Color Transformation and Extinctions

The following are "typical" values from a run on the 2.1-m with T1KA. The color terms may be considered typical of our thinned, AR-coated, backside-treated CCDs (e.g., T2KA). If you have recently done a color transformation, let us know!

$$\begin{aligned}
u &= U + C_U - 0.10 \times (U - B) + .50 \times X \\
b &= B + C_B - 0.10 \times (B - V) + .25 \times X \\
v &= V + C_V + 0.02 \times (B - V) + .15 \times X \\
r &= R + C_R - 0.03 \times (V - R) + .10 \times X \\
i &= I + C_I + 0.00 \times (R - I) + .07 \times X
\end{aligned}$$

In the above, lower-case are the instrumental magnitudes, C_i are zero-point constants, and X is the airmass. Don't be surprised if your extinction terms vary by 0.1 mag from the values listed, although such variations are typically grey (i.e., all coefficients vary by a single additive value from those above).

C Standard *UBVRI* Filters

Our "standard" *UBVRI* filters are collectively known as the "Harris" set. Historically the *B* and *V* filters are glass sandwiches designed by Hugh Harris (USNO) in order to yield small color-terms. The *R* filter is a glass sandwich designed by Alistair Walker (1986, IAU Symp. 188, p. 33) to match the Kron-Cousins system. The *I* filter is an interference filter designed by Jeremy Mould. Our *U* filter is a liquid $CuSO_4$ plus UG1 glass sandwich, the origin of which has been lost in the mists of time. (Schott quit making UG2, so UG1 is used in its place in the newer filters; the difference is very slight.) Specifically our filters are constructed as follows:

- *U*: 7mm $CuSO_4$ + 1mm UG1 (or UG2)
- *B*: 1mm BG12 + 2mm BG39 + 1mm GG385
- *V*: 2mm GG495 + 2mm BG39
- *R*: 2mm OG570 + 2mm KG3
- *I*: Interference filter, with $\lambda_c = 8290 \pm 40$Å, and $\Delta\lambda = 1950 \pm 40$Å.

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Note that our *UBVRI* filters are *not* all quite identical; tracings of individual filters reveal differences as great as 70 Å in the central wavelengths.

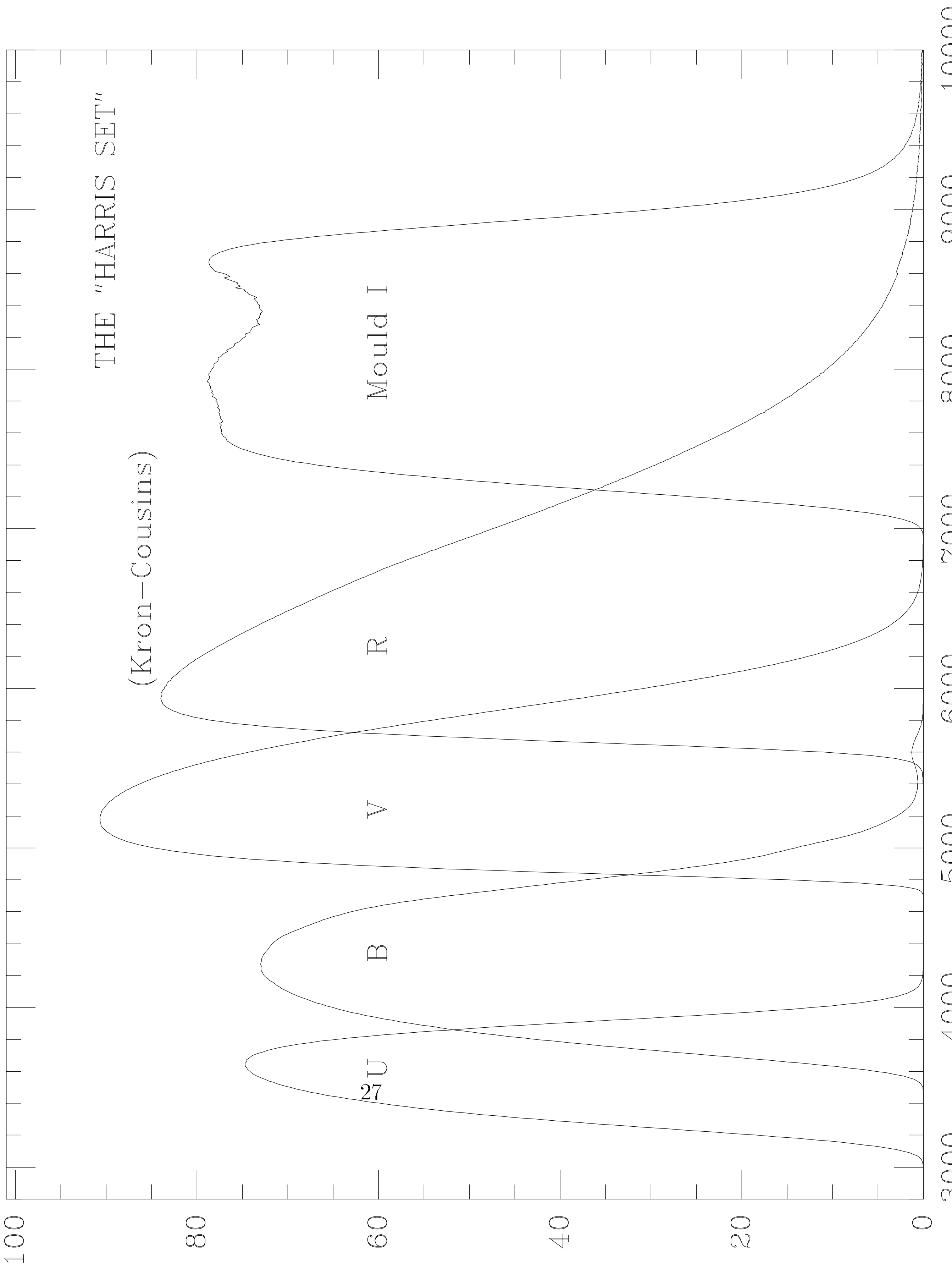
D Sending Coordinates to Kitt Peak in Advance of Your Run

The telescope control computers at the 4-m, 2.1-m, 0.9-m, and WIYN can all be loaded with coordinates of your objects in advance of your run, simplifying your first afternoon and possibly avoiding last minute chaos. Coordinate lists should be at least two weeks before your observing run. Instructions and the form to submit your coordinates is available on the NOAO and Kitt Peak home page

E What To Specify On the Observing Run Preparation Form

You must fill out the Observing Run Preparation Form (ORPF). This is on the Web page. You should specify the following:

- Filters. Specify “UBVRI” or “4x4inch Washington system”; if you want a particular narrow-band interference filter, give us the Kitt Peak “filter number” found as described in Sec. 2.4 above. This way we can be sure that we have available the filter you really want, and that we can identify any conflict between telescopes.


THE "HARRIS SET"
(Kron-Cousins)
U
B
V
R
Mould I
100
80
60
40
20
0
3000
4000
5000
6000
7000
8000
9000
10000