CTIO CFCCD USER MANUAL

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1. INTRODUCTION

At CTIO all CCDs are now operated using ARCON controllers. These controllers consist of a small box bolted to the dewar, which contains all the electronics needed to operate that particular CCD, followed by a fiber−optic link to a TRAM BOX "Silicon City" which sits beside a SUN 10/41 computer to which it is connected. The astronomer operates the Arcon from within an IRAF−based integrated data acquisition−data reduction environment. A real−time monitor, which displays the CCD image as it is read out, is attached to the TRAM box, while status and image statistics are displayed in a status window on the Sun screen. Apart from gains in reliability expected to follow from the affixing of the CCD dewar to its electronics, the use of fiber−optics, and the great attention that has been paid to mechanical and electronic construction, there are a number of performance gains:

- quad channel readout for CCD's with multi−amplifiers
- unsigned 16 bit data (0−65535) allows greater dynamic range
- dc coupled preamp means no memory of image in overscan

- real time display with saturated pixels in red
- direct data interface to SUN/IRAF
- faster readout in single channel mode for most CCD's

The conversion to Arcon's is an unfortunately rather slow process, due to the need to schedule the CCD's we have, implement new CCD's, and also to convert instruments to operate in the new (SUN, Arcon, IRAF) environment. We are taking the opportunity to simultaneously update the motor controllers on some instruments, using STD Bus controllers, and where possible, DC and DC servo motors. At present we have the following Arcon's:

- Arcon 3.1, Thomson #2 CCD, used as Lab. development system.
- Arcon 3.2, Tektronix 1024 #2 CCD
- Arcon 3.3, Tektronix 2048 #3 CCD (dedicated to the 0.9m telescope)
- Arcon 3.5, Loral 3K #1 (4m spectroscopy)
- Arcon 3.6, Tektronix 2048 #4 CCD
- Arcon 3.7, STIS 2048 (dedicated to the Schmidt telescope)
- Arcon 3.9, Loral 1K (1.5m spectroscopy)

Detector characteristics are summarized in section IV below. We will schedule the CCD that we think is the optimum one for your program, taking into consideration the device specifically requested on the Visitor Support Questionnaire and the proviso that in cases of conflict the larger telescope has priority. As indicated above, some CCDs (eg both Lorals) are in specialized dewars), while others are dedicated to a particular telescope (0.9m, Schmidt).

2. INSTRUMENT AND COMPUTER CONFIGURATION

2.1 SUN computers

Nelson Saavedra and Mauricio Navarrete are our Tololo computer specialists and can assist with the computer systems. They will assign you a visitor account number on the SUN computer network. You will be the sole user of this account while you are at CTIO. Each telescope has two SUN computers in the control room. The present configuration is that a SUN 10/41 operates the Arcon, and the data ends up on its disk. The below examples are described for the 0.9−m, but at the 1.5−m and 4−m the configurations are equivalent. At the 0.9−m this computer is ctioa4. The other SUN computer (at the 0.9−m it is called ctio36) has some of the peripherals (dat, exabyte, laser printer, mag tape drive) attached. You can do all your observing and reduction using a single terminal (ie the one directly connected to ctioa4) but many observers prefer to do reductions using the ctio36 terminal, preferably just remote login to ctioa4 and use its cpu for everything. Both are on the mountain Ethernet. You will find in the control room a full set of IRAF manuals, and COOKBOOKS containing advice and directions for reducing your data. **Refer also to the manual: "The Arcon−IRAF Interface A Preliminary User's Guide for Direct Imaging"**

2.2 Telescope

Each telescope has a telescope control computer (TCS). On the 4–m and 1.5–m this is a VME bus computer with a program written in C. The 0.9–m has a DFM Engineering TCS. The TCS computer will be operated by your Observing Assistant. All telescopes are operated remotely from the control room. For the 0.9–m there is a cook–book style manual that is particularly useful if you have to operate the telescope yourself:

"Observing Procedures – 0.9m Telescope"

2.3 CFCCD

All hardware functions in the CCD camera head (with the exception of the CCD shutter are controlled by a STD bus computer (actually a PC) mounted on the telescope. The operation of this computer should be transparent to the user. At the 4–m, 1.5–m f/13.5 and 0.9–m, the light is reflected from only the primary and secondary mirrors before passing through two filter bolts, and finally a fused silica window before reaching the CCD. On the 1.5–m f/7.5 there is a fused silica corrector element above the filter bolts. Each filter bolt can hold up to seven 3 inch square filters, which must be less than 1 cm thick, plus a clear position. There are 3 inch square UBVRI sets for use with the Tektronix CCDs. A single 5–position module which holds up to five 4x4 filters can be used if need be. In all cases the CCD is focused by moving the telescope secondary mirror. The filter bolts are contained in a shutter–filter unit, which also holds dark slides (manual), preflash arm and light–emitting–diodes (leds), plus a shutter. Your telescope will be operated by an Observing Assistant who is familiar with the operation of both the telescope and the CCD system. The Observer Support section will have helped in the setup and check out the instrument, and they will respond to any problems that might arise. The telescope should point to better than 10 arc sec rms (0.9– m, 15 arc sec rms) assuming accurate input co–ordinates. If the pointing is much worse than this then you should complain; on the 0.9–m and 1.5–m the collimation co–efficients may not have been re–entered following reset of the Telescope Control System. It is a short (10 min.) procedure to re–determine the collimation coefficients).

Peltier cooled CCDTV cameras are used for acquisition and guiding. The configuration is different for the three telescopes. At the 0.9–m the TV can be scanned in 1–D over an area approx 12x3 arcmin. The useable field is a little less than 4x3 arc min. At the 1.5–m the TV is mounted on an X–Y stage ("the GAM") which can be moved until a guide star is found. At the 4–m, the TV views a fixed position of sky via an f/2.5 focal reducer. The guiding is done in a PC via a program written by Steve Shectman (LCO).

2.4 HELP!

Observers needing further information should consult the following persons, in the first instance contacting people who are actually on Tololo (Tol) at the time:

- General help on the mountain: Ricardo Venegas, Daniel Maturana, Arturo Gomez, Eduardo Cosgrove (all Tol).
- Questions regarding observing procedures: Your staff contact or Alistair Walker (LS).

- Specifics concerning CCDs: Alistair Walker (LS)
- Arcon hardware/software : Tololo electronicers, Roger Smith (LS), Dan Smith (LS)
- Arcon user interface: Nelson Saavedra (Tol), Mauricio Navarrete (Tol), Steve Heathcote (LS)
- Reduction and IRAF Procedures: Mauricio Navarrete (Tol), Nelson Saavedra (Tol), Pedro Gigoux (LS), Steve Heathcote (LS).

3. DATA−TAKING PROCEDURES.

3.1. Introduction

The IRAF−based user interface allows observing commands to be sent to Arcon from within the IRAF cl. This results in a single uniform user interface for data taking and data reduction and allows the Arcon user to employ features of the cl such as the parameter mechanism and the history editor. It also allows advanced users to write cl scripts which freely mix data acquisition and data reduction operations. We have tried very hard to make the user interface look very similar to "ICE" as used at KPNO, and it should become more similar in the future. The underlying hardware is, of course, very different. So users should be aware that it is NOT identical and parameter lists, etc. will differ.

Below we describe recommended observing procedures. You are recommended to use IRAF for reducing your data, and for writing your frames to magnetic tape or exabyte. Information on the use of CCDRED, and IRAF in general, is given in the manuals and cookbooks kept near the SUN terminal. Observer Support personnel and the Data Reductions Specialists can assist you with IRAF. But you should not go to the telescope and expect to learn IRAF at the same time as you observe!

THE MANUAL <u>"THE ARCON−IRAF INTERFACE − A PRELIMINARY USER'S GUIDE FOR DIRECT IMAGING"</u> Describes observing software and procedures. You should refer to this manual for details on how to take data. Only a brief outline is given below.

3.2 Starting Up, and Some Miscellaneous Advice

3.2.1 Loading & Running the Software. You should login on the data acquisition computer using your VISITOR username and password. When you login for the first time, you will be offered a choice of OPENWINDOWS or SUNTOOLS environments. On subsequent occasions your initial choice will be loaded automatically. Several windows will open automatically, including a (blue−colored) IRAF Arcon user−interface window via which you interact with the CCD. There is also a (brick red−colored) IRAF reduction window, an Arcon console window, an Arcon status window with countdown timer, and an SAO−image (or XIMTOOL) display window (in OPENWINDOWS). You will almost certainly want to re−size and move some the windows around to get a display that you are comfortable with.

The Arcon controller boot−up is automatic (watch the Arcon console window). See the Observing Software Manual for procedures. IRAF should automatically start in the two IRAF windows, load the **arcon** package and **connect** itself to the controller.

1. **observe** this command controls data−taking via two parameter files **obspars** and **detpars**. You can also use **bias**, **comp**, **dark**, **pflat**, **dflat**, **sflat**, **zero**.
2. **focus** a special form of the **observe** task, for focussing the telescope.
3. **abort**, **stop**, **pause**, **resume**, **tchange** interupt an exposure (temporarily or permanently)
4. **preview**, **movie** read out the CCD without storing the data, once (**preview**) or continuously (**movie**).
5. **doobs** chain together a series of observations.
6. **more** n do n more exposures the same as the previous one.

As with ICE, most of the details are hidden in four parameter files, **obspars**, **instrpars**, **detpars**, and **telpars**. You will need to set these up at the start of your run, afterwards they should need little or no modification. In particular (and if you need to re−load the software, you should run **setdetector force=yes** in order to synch the controller to the parameters you have set in detpars.

3.2.2 Data Storage. You should check you know where your home directory is (**show home**) and where your pixel files are going (**show imdir**). Check that you have lots of disk space (**disks**). Make sure that when you do an **observe** that an IRAF image ends up where you expect it do be. Display the image in IRAF, using **display**. See below for instructions on how to check whether your CCD system is functioning correctly.

3.2.3 CCDs with Multiple Outputs. Some of the CCDs now converted to Arcon operation have more than one (usually four) output amplifiers available. The CCD is read out through each amplifier in parallel, the data is then digitized through (1,2,4) 16−bit analog−to−digital converters and then transmitted on a single serial fiber−optic line to the SUN computer to a spool file, and then converted to an IRAF image file. A raw quad−amplifier picture looks a little unusual. Each quadrant has a slightly different electrical offset (ie overscan level), and the four overscan segments are in the center of the picture. A CCD read out through two amplifiers can either have two overscan strips at the right hand side of the picture (parallel split) or two parallel strips in the center of the picture (serial split, eg Tek 2048 #3)). The real time display automatically removes the overscan and applies an offset to each quadrant to normalize the DC level. In addition, the real time display colors any saturated (ie 65535) pixel in red.

3.2.4 Processing Quad Images. "Quad" CCD pictures are trimmed and overscan−subtracted in a separate pre− processing task called **quadproc** (in the **quad** package). You will need to load this package into your **IRAF DATA REDUCTION** window. Run **setinstrument** to set up **quadproc**. Note that even after the pictures are trimmed and overscan subtracted the sky levels in each quadrant will not be identical (unless sky level is zero). This is because each of the four CCD amplifiers has a slightly different gain. The procedure of quadproc'ing the pictures, plus the usual zero (bias) subtract, flat−fielding etc is now all been integrated into **quadproc**.

3.2.5 Writing Tapes. 5. There should be an exabyte drive (at the 0.9−m, ctio36!mtx), a 9−track

drive (at the 0.9– m, ctio36!mta) and probably DAT drive available in your dome. The Arcon produces 16 bit data of type 'unsigned short integer' with valid data ranging from 0 to 65535. Thus the unprocessed frame from a 1K CCD requires about 2.2 Mbytes. If you wish to write this data to a FITS file using the standard IRAF **wfits** defaults, a 4.4 Mbyte file of 32 bit data of type 'long integer' will be written. This is because there is no standard FITS data type of 'unsigned short integer' and so the IRAF default is not to scale the data, and instead it writes 'long integers' in order to avoid losing precision. To circumvent doubling your image size with 2.2 Mbyte of zeros, use

wfits bscale=1 bzero=32768 bitpix=16 autoscale– scale+

and to read this back use

rfits datatype=ushort

Normally you will have selected **setinstrument** processing to generate data of type "real", so that the above formalism is likely to be useful only when writing raw data, ie before running **quadproc**.

3.3 Instrument Setup and Checkout

3.3.1 Introduction. At the start of your observing run, Observer Support personnel will check that the CCD is operating correctly, and that all the hardware functions. They will fit your selected filters into the filter bolts. They will also ask you which gain setting you require. The various options are listed by typing

ccdinfo and you change the gain by doing **setdetector force=yes**. For direct imaging gain = 1 (2 for Tek 2048 #3) is in almost all cases the best to choose. The gain and read noise are calculated using the **gfind** task which is in the **contributed** package. You will first need to do two low level (bias) exposures, and two high level exposures such as dome flats (both at the same light level).

You can also choose to bin the CCD if you wish. Given that the read–out times are short, even for the Tek 2048, this is not a very popular option in general. If you wish to read out a region–of–interest rather than the whole CCD, this is also an option, and you can change from reading a quad amplifier CCD to using only 1 or 2 amplifiers if need be. All these options are controlled by parameters in **detpars**. You should consult with Observer Support or your Support Astronomer if you wish to make changes, not all options are possible for all CCDs, and at time of writing, some options are possible but not advisable...

It is your responsibility to check that the instrument is operating to your satisfaction.

A few tests are suggested below which should aid you in this evaluation. You should also be on the lookout for any changes in the CCD characteristics during the run, which may signal the onset of CCD or dewar problems. Count rates from dome flat field (white spot) exposures should be the same from day to day, to better than 10 percent. You should also divide the night's flats by the previous night's and check to see that the division is quite flat, with perhaps only the addition of one

or two "rings" due to specks of dust falling on the filters or CCD window (ask for these to be cleaned if the number of spots seems excessive, but don't try to use your old flats later on). Examine bias exposures, they should not show horizontal or diagonally slanting noise "stripes", which move position from frame to frame. Sometimes very low level noise features are seen on bias frames, before complaining check whether these are at a significant level to affect your data. Most of our CCDs have very low level fixed pattern noise (1 adu or less). Use of the IRAF **Imhist** command is also recommended. Histograms should exclude bad columns, edges etc., they should be smooth with no missing codes.

It is worthwhile making a few test exposures before proceeding further. These tests can be repeated as desired throughout your run. All can be done during the daytime.

3.3.2 Zero (Bias) exposures. These zero illumination exposures should show no noise patterns down to about the 1 adu level. They should be approx. flat although bright columns will show up (Tek 2048 #3, STIS 2048). Now do an exposure (dome flat) that adds a small signal. Any exposure with some illumination (preflash, flats) should show the overscan strip on the right hand side of the picture (single channel readout, or down the center (quad readout). Don't forget that the Real Time Display automatically clips out the overscan so you will need to display the image within IRAF.

3.3.3 White Spot exposures. Ask for the telescope to be pointed at the white spot on the dome, and turn on the quartz halogen lamps. Make sure the telescope focus is approximately correct for the filters you will be using during the night. Put the color balance filter in the beam. This filter makes the 3000 C quartz lamps look more like the 5500 C night sky. Take a trial exposure, typically a few seconds through a broadband (B,V,R,I) filter. Display the frame, and do a row plot across it. The response should be reasonably flat (say 10 percent in general). After (quadproc if you are using a quad or dual readout CCD) subtracting off the bias exposure you can try dividing frames at two different count levels whereupon all the structure seen in the dome exposures should disappear to better than a few 0.1%.

3.3.4 Dark Exposure. A five minute dark exposure (lights off in dome) with no preflash should only show the hot columns and hot pixels and a few cosmic rays. The general background should be at the same level as the overscan. Cosmic rays will be slightly trailed column−wise with a TI CCD otherwise most events should not show trails. For all these CCDs, the dark rate is so low in comparison to sky background rates as not to warrant doing long dark exposures.

3.3.5 Shutter Timing. The shutter unit has a 100mm clear aperture. The effective "open" time is always longer than the nominal number of seconds requested for your exposure time. This is a delay prior to opening and closing. The speed of the shutter blades is high and the corner−center exposure difference is only a few ms for the smaller CCDs. For the Tek 2048 the center−to−corner difference is some 50 ms (ie exposures are 50 ms longer than nominal at the center, and 0 ms longer at the corners). So beware when doing short exposures for flat fields and standards. Sometime during your run, it is a good idea to determine this correction. The easiest way of doing this is to compare (for example) a 20 second dome flat with the sum of 20 1s dome flats. The latter can be done extremely quickly using the focus procedure but not bothering to

move the telescope, whereupon you can avoid reading the CCD out 20 times but the shutter will have opened and closed 20 times. Bracket this exposure with normal 20s exposures (just choose a filter and exposure time to give several thousand adu total counts), the bracketed exposures can be averaged to take out any drifts in the lamp output, but in any case it is wise not to begin this test until several minutes have elapsed after turning on the lamps. Subtract bias off the two frames, then if the counts are C1 for the sum of the 20 1s exposures, and C2 for the single 20s exposure, then to first order we have

shutter delay time (s) = (C1/C2) − 1.

You can easily do a contour plot which is probably the best way of displaying the result. You could also in principle correct all your data. Remember −− you are likely to compromise your photometry with the Tek 2048 if you take flat or object exposures shorter than 5 seconds and do NOT take account of the radial variation of the shutter timing.

Shutter times less than one second are possible, but below about 0.1s shutter operation is unreliable. Non integral shutter times are possible, and are correctly recorded in the image header. They will most likely be seen when using **pause** and **resume**.

3.4 Calibration Frames.

3.4.1 Introduction. Most of the calibration frames can be taken during the afternoon. Almost all observers prefer to take calibration frames each day, and we also recommend this, but it is not absolutely essential. Observer Support personnel will help you to get set up if required. If you have special requirements (dome flats in the morning etc) please consult with Observer Support in advance so that arrangements can be made. Note that in order to ventilate the domes so as to minimize "dome seeing" it is normal for the shutters to be opened approximately one hour before sunset. Please try to finish your calibration frames prior to this time. This is particularly important for the 0.9−m where the focus is a strong function of temperature and very poor images can be expected unless the telescope is at a similar temperature to the outside air

3.4.2 Zero (bias) Exposures. These zero exposure can be started using the commands **zero** or **observe**. You should obtain between 5 and 25 exposures, if you are doing really low S/N photometry through narrow band filters then you should aim for the higher number. These can be combined into a single frame with an "average sigma clipping" or "ccdclip" algorithm (IRAF), the idea being to produce a "zero level" frame from which any cosmic ray events have been removed. You will get plenty of cosmic rays on the Tek 2048 biases due to the relatively long readout time and large area, so make sure you have at least 5 biases for this CCD

3.4.3 Dome (white spot) Flat Fields. These exposures map the sensitivity variations of the CCD, and since the response alters as a function of wavelength it is necessary to prepare a flat field for each filter. Ultimately, the quality of your data will depend on how well you prepare your flat fields. You can use the **dflat** or **observe** commands to take dome flats. Broad band (eg BVRI) dome flats require use of a color balance filter. Do not use the color balance filter for U, or for medium band (eg Stromgren, DDO) or narrow band filters. You should aim for flat levels of several

thousand (say 5000 – 40000) counts. Take a sequence of exposures per filter

The resulting frames can then be averaged to produce a single dome flat field frame for each filter. Data frames should successfully be flattened with dome flats to 1–2 %, perhaps a little better for redder passbands such as V,R,I. To do better than this there are two alternatives –either to use twilight flats alone, or to correct the low spatial frequencies in the dome flats by using a dark sky exposure(s) or with the twilight flats. However you are advised to take dome flats anyway, just in case the twilight or dark sky flats are unsuccessful. You may find the dome flats are good enough for your purposes. NOTE – You can get excellent pixel to pixel statistics with dome flats, and in some cases this may be more important than low spatial frequency errors

3.4.4 Twilight Sky Flat Fields. Broadband B and U (especially) twilight sky flat fields appear to flatten data frames better than do dome flats. Unfortunately, twilight is short and the number of flats you can take is limited, which can limit S/N. CCDs up to 1024x1024 can be read in just a few seconds, but with 2048's, particularly if you are using several filters, other techniques include using smoothed twilight sky flats to take the low spatial frequencies out of your dome flats, thus preserving the good high spatial frequency S/N of the dome flats, or consider taking 2x2 or 4x4 binned frames and later use them as smoothed corrections to your dome flats in order to correct the low spatial frequency errors in the latter

You will need to point the telescope towards the east (HA −3 hrs) in order to lessen polarization effects (in theory −− or just leave it at the zenith, polarization effects seem to be minimal). Do not use color balance filters. As the sky darkens after sunset, take one second exposures (with U if you are using it) until the sky is dark enough so that an exposure of a few seconds gives about 20000 counts. Use the **preview** command, and look at the counts in the Arcon STATUS window. You should have time to take several flats in each filter, and if so these can be combined later (IRAF **combine** in the **ccdred** package). To make it easier to remove star images from your flats, take the flats with the TELESCOPE DRIVE ON, and jog the telescope a little after each exposure. If you wait until it's too dark, then your exposures will be longer and the chances of getting significant contamination by stars is greater, particularly in R and I. Twilight flats should be done in the order UBVRI. Exposures should be at least 5 seconds long in order to reduce the center−corner variation due to the shutter to negligible (<0.1%) proportions. Start the test U exposures at sunset or just a few minutes after. **DON'T ZAP THE THOMSON CCD BY DOING (FOR INSTANCE) I FLATS JUST AFTER SUNSET! THIS CCD SUFFERS FROM AFTER−IMAGES (REMNANTS).**

3.4.5 Dark Sky Flats. Exposures of "star−less" high galactic latitude fields can be used to provide an "illumination correction" to flat fields. The technique is to take several stepped (e.g. 20 arc sec) exposures of the field then combine the exposures in such a way (e.g. median filtering) that faint stars are removed. Since the final frame will be heavily smoothed a sky level of 200−300 ADU over bias is sufficient. Be sure to remove any bad pixels before smoothing. The resulting smoothed frame can then be combined with the corresponding dome flat to form a master flat. That is, the sky flat removes low spatial frequency errors in the dome flat. The advantage of this procedure over using twilight sky flats is that you retain the good pixel to pixel statistics of the dome flats, and the color match is improved. In practice the latter advantage does not seem to be

very important. The disadvantage of using a combination of dome flat + smoothed sky flat is that any high spatial frequency errors in the dome flats will not be removed, however in general these are few

Note that dark sky flats are necessary to remove any fringes due to night sky emission lines causing interference in the thinned CCD (Teks). None of these CCDs fringe excessively (<1% in the I band is typical) and so you may not need to de−fringe

It is also possible to prepare flat fields from combinations of your object frames. This is generally only possible if they contain few bright stars, and even then it may be necessary to "patch" out the brighter objects prior to combining the frames. If you are unfamiliar with these rather specialized techniques you are encouraged to consult with CTIO staff prior to your observing run.

3.5 Night Time Procedures.

3.5.1 Start of the night procedures. About an hour before sunset the dome shutters will be opened unless calibration frames are still being taken. All doors should be closed and lights turned off. During twilight, your Observing Assistant will fill the dewar with liquid nitrogen and check the telescope pointing on a bright star near the zenith. If it is the first night that the CCD has been installed then the offset between the CCD and the acquisition TV camera will also be determined, and the focus of the TV camera checked. Your Observing Assistant is familiar with focussing methods, offset determinations, operation of the TV and Guider, and will help if required.

3.5.2 Focusing the Telescope. On the first night set the telescope focus to the "nominal" value. Ask your Observing assistant or look amongst old Observing Record Sheets to ascertain the relevant value. If the focus is far from correct, read the CCD out using **movie** while you adjust the focus. Choose a focus star with V 10−11 (0.9− m, scale to other apertures) whereupon your exposure time will be a few seconds.

Accurate focus is found by taking several snapshots of the star, each at a different focus position. Use the **focus** command, with the relevant **obspars** parameters set. It is normal to choose **shtype = detector** (charge will be reverse−clocked rather than the telescope moved between exposures), and at the 0.9−m and 1.5−m **focmode=manual**, ie you need to change the focus manually between exposures. NOTE in all cases the double−spacing is made between the first and second exposures. And for **shtype = detector**, on quad readout CCDs the stars in upper and lower halves of the CCD will move in opposite directions.

Please save your focus frames and write a note on the night report sheet saying where they are, they will be written to tape and kept as a database for seeing and optics improvements. Offsets for the standard UBVRI sets are known (ask Observer Support) so you need only focus one filter.

When focusing, always focus against gravity: move out (to larger readings of the pedestal). The procedure is as follows:

Once rough focus is known, move focus in (lower numbers) about 500 units (0.9−m) to take up

backlash. Exact focus is determined by doing 8 − 10 exposures at different focus settings, offsetting the telescope slightly between each one. The CCD will be read out after the last exposure. Vary the focus by 40 units (0.9−m, Futaba) between each exposure.

The quickest way to examine your images is to use **imexam** to plot profiles. Best focus will be that with highest peak intensity and minimum distortion in the wings. This last criterion is perhaps the most stringent one. The focus will change during the night, as it appears to be a function of temperature and possibly telescope position. In good seeing (FWHM <1.5") frequent focus checks are recommended especially if you move the telescope more than 10 or 20 degrees.

3.5.3 TV Camera. A Peltier−cooled CCDTV camera serves both for field acquisition and for guiding. Field of view is approximately 4 by 3 arc minutes. On the CCDTV control panel integration time can be switch selected and gain/offset controls are available. Try integration time of 1−2 seconds, gain = 2 and offset so that you see star images.

Focus the TV after focusing the CCD. Watch for smallest images, preferably with the Leaky Guider switched to "digital". This focus is not that critical, as the guider will work fine on slightly out of focus images.

Normally the determination of the TV−CCD offset will be carried out entirely by Observer Support personnel on the first night only. In any case, in these days of large CCDs it is more efficient to find objects and center up using the CCD in **preview** mode. But if you want to determine the offset, see the Software Manual.

3.5.4 Guider Operation. We are changing over to using a program written by Steve Shectman, which runs in a PC and displays the star−field on the VGA monitor. At the 1.5−m, the TV is feed by a moveable guide probe. Be careful not to get the probe vignetting the beam. For the Tek 2048, allowable guide probe co−ordinates are X = anything, Y > 50.

3.6 Observing.

3.6.1 Finding Your Object: The quickest procedure is to point the telescope at the correct position and take a **preview** or **movie**. Alternatively the telescope can be positioned such that the object is on the TV, and then offset back to the CCD. Then find a guide star.

3.6.2 Exposure times: All the CCDs bleed charge down columns, and to a lesser extent across rows, when an integration is long enough for a star image to become saturated. All recover well from over−exposure, however excessively bright stars should be avoided. All the CCDs have very low readout noise so there is an advantage in dynamic range by splitting a long exposure up into a number of shorter ones. You should also beware of bright stars just outside the CCD field. These can easily scatter light onto the CCD frame and make photometry difficult.

Cosmic rays tend to be either single or double hot pixel events. The standard way to remove them is to do at least 3 exposures (4 or more give better statistical results) of the same field and median (or use avsigclip option in the IRAF combine command) filter to remove transient events. The

IRAF cosmicray and imedit commands can be effectively used to remove cosmic rays from single frames.

You should be careful not to over–exposure your object(s) of interest. Saturated pixels are colored RED on the real–time display. Beware that for 2048 CCDs the display averages four CCD pixels for each display pixel. It is not (yet) clever enough to color the display pixel red if one or more of the component CCD pixels is saturated.

3.6.3 Bad pixels: there are two types: 1) hot (above local background) and 2) cold (less than local background). Sometimes hot pixels tend to be found at the beginning of a column of cold pixels – it appears that most of the charge finds its way into just one pixel. Neither type are transient events: they are both permanent defects in the CCD. However, the number of bad pixels is a function of intensity: there are many more at low light levels. The STIS 2048 and Tek 2048 #3 have both hot columns and blocked pixels. These are obvious, and should be avoided. The Thomson CCD has about 20 short traps visible only at low background levels; at higher backgrounds almost all of these shorten to a single low pixel.

3.6.4 Standard Stars: In broadband UBVRI work excellent results have been achieved by using standards from Landolt (AJ 104, 340, 1992). There are fields (eg T Phe, SA 98, SA 110) which contain several stars in a 3–4 arcmin diameter field with a wide range in color, and so are invaluable for use with large CCDs. John Graham's uncrowded E region standards (PASP, 94, 244, 1982) in the magnitude range of 10 to 16, the older Landolt standards (AJ, 78, 959, 1973; AJ, 88, 439, 1983) and some of the fainter (10–11 mag) Cousin's stars (J.W. Menzies et al., SAAO Circ., 13, 1) are useful. Copies of these lists are kept in each of the console rooms. Look carefully at the quoted errors on the standards before observing them. Residuals in the photometric solutions are a few percent at worst, and standard stars (properly done) repeat to 0.005 mag or better from night to night. It is preferable not to mix Landolt standards with those of Cousins/Graham if you are covering a wide range in color and are interested in getting systematics down to the 0.01 mag level.

For narrow band imaging one can try using spectrophotometric standards (R. Stone, J. Baldwin, 1983. MNRAS, 204, 347 and 1984. MNRAS, 206, 241, D. Hayes, 1970. ApJ, 159, 165, M. Hamuy et al., PASP 104, 533, 1992).

The biggest mistake made in observing standards is to underexpose: try for a peak in the star of at least a few thousand ADU above background (exposure times of 5–20 seconds for V = 12–14 at the 4–m, with the Tek CCDs and gain at 10 e–/adu you can go a magnitude brighter than these figures). For such short exposures the dominant source of error is the readout noise in the large measurement aperture necessary to contain 99% of the stellar light. Shutter clocking is accurate enough to permit 1 second exposures, but be aware of the shutter delay discussed above. If necessary you can remove the shutter timing effect from the data (Stetson, 1988 IAU reports).

Use of faint photoelectric sequences (particularly those in crowded fields) requires caution; these often have proven to have systematic errors, and require long exposure times in each filter to reach the desired accuracy in a large measurement aperture.

The care with which one observes standards will be reflected in the accuracy of one's photometric calibration. It is common to observe several standards at the start of a photometric night, several more in the middle, and still more at the end. If you have fields with only one or two standards, try taking two exposures of a standard field per filter, stepping the telescope by 20 arcseconds between exposures. The extra frame takes very little time, and insures against your star landing on a bad pixel or cosmic ray. You could even use the **observe** command with focus mode enabled to give you several images of the standard but only one readout. For the highest accuracy one should definitely observe enough standards at a range in airmass to solve for the extinction coefficients. Tololo extinction can be as low as $kV = 0.12$, or > 0.2 if conditions are dusty, so one should not rely on the nominal values (in 1991 volcanic dust caused elevated extinctions). The CCD camera has shown itself capable of doing better than 1% photometry: it seems a shame to skimp on the external calibration necessary to achieve this. Furthermore, to make proper use of such an accurate calibration will require the existence in the object frames of uncrowded stars exposed to the same level as the standard.

4. DETECTOR CHARACTERISTICS

4.1. General Principles

CTIO operates several types of CCDs. There is, as yet, no general purpose CCD and a CCD suited to your program will be the one scheduled. Loral CCDs require periodic UV– flooding in order to provide enhanced sensitivity below 5000Å, and must be kept cold in order to retain the improved response. The output signals from CCDs are extremely small (remember 1 electron = 1.6×10^{-19} Coulomb!) and the electronics must not allow significant extra noise to degrade the performance. In case of problems, electronic components can be replaced (at the board level) and if necessary, the CCD can be changed. If you are dissatisfied with the performance of the CCD system, please consult with Observer Support personnel.

At PFCCD the CCD is mounted in a downward looking liquid nitrogen filled dewar, and is kept at a constant temperature by a small heater. This temperature is displayed in the console room and should remain constant. If the temperature appears to be rising immediately alert either your Observing Assistant or Observer Support personnel. After initial power on and the dewar has been filled with liquid nitrogen for the first time, it requires at least 4 hours for all temperatures and operating voltages to stabilize. The dewar hold time is over 12 hours –filling at the start of the night will generally do for the whole night, except in winter time when, near midnight, the night assistant will ask for permission to return the telescope to the access platform in order to fill the dewar.

At CFCCD the dewar is upward–looking, otherwise procedures are as in the above paragraph. All the dewars have the fill–tube extending only half–way into the Liquid Nitrogen can. Although this has the disadvantage that the can cannot be filled to more than half–capacity, the advantage is that the dewar can be used in any orientation.

The analog signal (which can be considered to be some number of electrons) from each pixel of

the CCD is first amplified, then passes through an integrator which discriminates against various noise sources, and is then converted into a digital signal by an analog–digital– converter (ADC). Hence the signal at this stage is measured in "counts" or " adu's" (analog– to–digital–units). The ratio adu/electrons is called the gain, although by convention we usually talk about the inverse gain, electrons/adu. The gain is an adjustable parameter on the CTIO CCD systems. The range of data numbers possible extends from 0 to 65535 (0 to 216–1, 16 bits).

4.2 Detector Options

A summary of the characteristics of the detectors normally used for direct imaging is as follows:

```
                            Tek 1024    Tek 2048    STIS 2048   Thomson

Pixels                      1024x1024   2048x2048   2048x2048   1024x1024
Pixel size (microns)        24          24          21          19
Pixel size (arcsec)         0.3         0.43        0.38        0.34
Field size (arcmin          7.3x7.3     14.7x14.7   12.9x12.9   5.8x5.8
Readout noise (electrons)   4-6         3-5         3-5         3-5
Electrons/ADU (typical)     1-4         1-4         1-2         1-3
Cosmic ray rate (per min)   20          100         ?           15
U: Sensitivity at the 4m    20          70          40          40
B:    ( U=B=V=R=I   )       280         320         100         100
V:    ( = 20 mag    )       350         350         150         150
R:    ( star, in    )       400         400         220         220
I:    (electrons/sec)       300         300         140         140
Read time (quad, secs)      10          25          25          14
```

Notes:

1. The full well capacity is the limit above which charge "spills" out of a CCD pixel into adjacent pixels. At some level below full well the response of the CCD becomes non–linear to incident light. Some CCDs retain excellent linearity right up to full well, but for others the departure from linearity becomes severe well below full well. This will define the practical maximum charge capacity per pixel. It may depend on details (slope, amplitude, levels) of the clocking voltages and for some of our devices there is some hope of improving the values given. Typically a factor 20 more charge must be accumulated before noticeable bleeding occurs. This bleeding is stronger in the column direction for our CCDs. With normal gain settings the data system limit of 65535 counts is reached prior to entering the CCD non–linear region. Care should be taken always to operate the CCDs in the linear part of their response.

2. The readout noise is somewhat dependent on gain, larger values of readout noise correspond to larger values of e–/ADU. Similarly, the read time is given for gains of 3–4 e–/adu.

3. The Thomson CCDs suffer from after–images. If at all possible do not subject the Thomson CCDs to more than 10 times full well signal (bright stars, flat fields). The strength of the after–image depends on the degree of over–illumination, and they make take many hours to

disappear. The only way to get rid of after–images is to cycle the CCD temperature to –70C and back again. This procedure will take about 30 minutes.

4.3 Detector Notes

4.3.1 The Tek 1024 CCDs We have two Tek 1024 CCDs, #1 and #2. At the present time only #2 (a quad amp devices) is being scheduled. Read noise is very low. Cosmetics are superb. QE is poor in the UV and U band photometry is not recommended. Note that these CCDs do not have the serial registers and amplifier areas shielded from light, consequently on high light level flat field exposures the overscans show an exponential decay and during reduction should be fitted with high–order splines. See the software manual for more details.

4.3.2 The Tek 2048 CCDs We have two Tek 2048 CCDs (#3 and #4).These are thinned, AR coated devices like our Tek 1024s. Read noise is very low, and QE is like the other Teks, except the U band response is much improved. Tek 2048 #4 is cosmetically perfect but #3 has several column defects. There are bright columns on each side and three major column traps near the center. These should all be avoided. Tek 2048 #4 is the CCD normally scheduled at the 4–m PF, while #3 is dedicated to the 0.9m. Both these CCDs are four low–noise amplifiers and thus have short read time, typically 30 seconds. #3 has effective full–well near 220000 e–. #4 was for some time operated with clock volatges which gave full well near 300000 e–, however significant departures from linearity occur above 210000 e–. A very annoying feature of this CCD was that when very bright (highly saturated) stars were imaged in the upper half of the CCD, low level bleeds occurred in the serial direction. It was discovered that lowering a parallel clock voltage fixed this problem, at the expense of lowering full well to 150000 e–. The CCD appears to be linear right up to this (rather low) limit. We plan to investigate this effect further.

4.3.3 The Thomson 1024 CCDs CTIO has two Thomson 1024 CCDs. They are thick devices, and thus have QE generally about half that of the thinned Tek CCDs. They have been coated with Metachrome to give some UV QE; this is almost flat at 20% from 3000Å to 4700Å. Both these CCDs have quad amplifiers, and perfect cosmetics except for some imaging area traps visible only at very low background levels. They suffer from after–images and exposure to very bright stars and flat fields should be avoided if at all possible (ie avoid signals more than about 10 x full well). Thomson #1 is now not scheduled, while Thomson #2 is part of the lab CCD test set–up.

4.3.4 The STIS 2048 CCD The STIS CCD was made by Tektronix as part of the development of the CCDs for the Space Telescope Imaging Spectrograph. It has slightly smaller pixels than regular Tek 2048's, and our example is front–illuminated with a metachrome coating, thus its QE is just like the Thomsons (see above). The CCD is very low noise, and reads through all four amplifiers (initially we are using just one). It has a few column defects. It is dedicated to the Schmidt telescope.

4.4 Detector Control Options

The observer can control and change several CCD parameters. These are: the CCD readout

format, the binning, the preflash time, and the gain. Observers should think carefully whether they need all the field (if not read a ROI) or the resolution (if not, bin 2x2). Even though the CCDs with quad readout have short read times by big–CCD standards, substantial gains in efficiency are possible by reducing the format.

4.4.1 CCD Readout Format A single region–of–interest can be read out, positioned at an arbitrary place on the CCD. These operate very efficiently, for instance a 1024x1024 ROI centered on a Tek 2048 takes under 10 seconds to read out, while a 256x256 takes just 2 seconds.

4.4.2 Binning The ARCON controllers are able to bin pixels in various ways. The readout noise per pixel remains the same as in the unbinned case. The gain calibration is unchanged from the unbinned mode. For most direct imaging applications at CTIO the CCDs tend to undersample the images, so there is little advantage in binning. The main advantages of binning are that the readout time is shorter, and less data is created.

4.4.3 Preflash Time Default is zero. All our CCDs operate without preflash. At the 4–m PFCCD the preflash illumination is rather uneven and thus of little use.

4.4.4 Gain Generally you will find for direct imaging a gain of about 3–5 e–/adu is a good compromise between sampling the read noise and achieving good dynamic range. Excessively high gain (ie small e–/adu) does little good since digitization noise is soon masked by CCD readout noise and photon statistical fluctuations. Different CCDs are somewhat different in their photon/adu conversion, noise and points at which non–linearities begin to occur. The method used to calculate the gain is described in Appendix II.

4.5 CCD scales at various foci

(1) Pixel sizes (arc sec)

	Tek 1024	Tek 2048	Thomson 1024	STIS 2048
4–m f/2.85	0.43	0.43	0.34	0.37
4–m f/7.5	0.16	0.16	0.13	0.14
1.5–m f/7.5	0.44	0.44	0.34	0.37
1.5–m f/13.5	0.24	0.24	0.19	0.21
0.9–m f/13.5	0.40	0.40	0.32	0.35
Schmidt f/3.5				2.0

(2) Field Sizes (arc min per side)

	Tek 1024	Tek 2048	Thomson 1024	STIS 2048
4–m f/2.85	7.34	14.7	5.81	12.9
4–m f/7.5	2.70	5.40	2.13	4.73
1.5–m f/7.5	7.41	14.8	5.87	13.0
1.5–m f/13.5	4.09	8.18	3.25	7.15

```
0.9-m f/13.5          6.76          13.5          5.35          11.8
Schmidt f/3.5                                                    68
```

APPENDIX I:FILTERS FOR CCD IMAGING

A filter list is available in Mosaic and will also be found in NOAO Newsletter No. 34. A complete CTIO filter list is also available via ftp. Login to ctios1 (139.229.2.1) using "anonymous" as your user name and your email address as password.

The data are in directory /pub/manuals/filters; consult the file README in that directory for further instructions.

4−m PFCCD

The PFCCD has two filter wheels each holding 5 filters. F1 is the wheel furthest from the CCD and normally contains only a color balance filter for use when doing dome flats. F2 usually contains U,B,V,R,I filters. Other filters can be installed when required. The nominal filter size is 4x4 inches. However 3x3 inch filters in wheel F2 do not vignette CCDs up to a Tek 2048 (49 mm square) in size. We have adaptors to accommodate 3x3 inch filters.

The (4x4 inch) filters we have available for the 4−m PFCCD are as follows:

1. UBVRI set. These are identical to the 3x3 inch filter sets we use at the 0.9−m and 1.5− m telescopes, and similar to the "Harris" implementation of BVR as used elsewhere, except that the prescriptions for B and V have been tweaked slightly. I is an interference filter and U uses a Copper Sulphate solution blocker.
2. Washington set (CMT1). Made according to prescriptions supplied by Doug Geisler. The T2 filter is identical to I (from UBVRI).
3. DDO 51, Gunn griz, Strömgren uvby, Tyson J (A very broad−band filter which approximately matches the photographic J passband), H 6563/75 and 6600/75. [OIII] 5007/50, [SII] 6723/50, HST F−555W and F−814W.

CFCCD

The 0.9m, 1.5m and 4m CFCCD systems have two filter wheels each holding seven filters up to 3x3 inches square. These wheels are modular, and we have a single wheel which holds five 4x4 filters. This is useful when an observer brings 4x4 filters for use at these telescopes, or it is desired to use a filter which we have in 4x4 size and not in 3x3.

SCHMIDT

The Schmidt has a single filter bolt which holds five filters up to 4x4 square.

APPENDIX II: GAIN AND READOUT NOISE CALCULATION

The gain in electrons/adu is usually accomplished using the **gfind** command (in the **contributed** package). Here is a cookbook recipe for determining the gain in electrons/adu, for anyone who wants to do all the steps one by one.

1. Take a sequence of 2 bias frames. Make sure that the preflash is set to **zero**.

2. Take a sequence of 2 dome flats or, better yet, 2 bias frames with a big preflash value (giving a total signal of approximately 1/2 saturation).

3. Subtract these frames as follows:

BIAS1−2 = BIAS1 − BIAS2 (use **imarith**)
FLASH1−2 = FLASH1 − FLASH2

4. Use the IRAF **imstat** task to determine MEAN(FLASH1), MEAN(FLASH2), MEAN(BIAS1), MEAN(BIAS2), RMS(FLASH1−2), and RMS(BIAS1−2). Note that it is very important that the stats box be positioned on a region of the CCD free from traps, bad columns, or any bad pixels.

5. Calculate the gain,

e/adu = (MEAN(FLASH1)+MEAN(FLASH2)) − (MEAN(BIAS1)−MEAN(BIAS2))
RMS(FLASH1−2)2 − RMS(BIAS1−2)2

6. The readout noise in electrons is

RON(e) = RMS(BIAS1−2) * (e/adu) / 1.41

Footnote 1
At time of writing, use **smcinit** instead **of motorinit and instrument instead of motormove.**