A User's Guide to CCD Reductions with IRAF

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Contents

1 Introduction

This document is intended to guide you through the basic stages of reducing your CCD data with IRAF, be it spectroscopic or direct imaging. It will take you through the removal of the "instrumental signature", after which you should be ready to extract your spectra or to do your photometry.

Additional resources you may wish to review are:

- *A Beginner's Guide to Using IRAF* by Jeannette Barnes by Jeannette Barnes

Once you are done with this manual you may wish to go on to do stellar photometry on direct frames or to reduce slit spectrograph data. You can find details and sage advise in the following sources:

- *A User's Guide to Stellar Photometry with IRAF* by Phil Massey and Lindsey Davis

- *A User's Guide to Reducing Slit Spectra with IRAF* by Phil Massey, Frank Valdes, and Jeannette Barnes

Copies of all these documents are available over the net; contact the IRAF group for details.

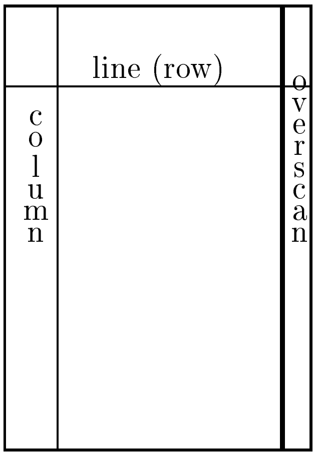
In Sec. 2 we will discuss whys and wherefores of CCD reductions in general terms. In Sec. 3 we will go through the actual IRAF steps involved in implementing these reductions, using spectroscopic data as the primary example. In the Appendices we provide a guideline to what calibration data you may want to collect while you're observing (Sec. A), and discuss the nitty-gritty of the algorithms available to you in IRAF for combining images (Sec. B). Finally we close with a summary of the reduction steps for spectroscopic data (Sec. C.1) and the reduction steps for direct imaging (Sec. C.2).

2 Why Your Data Needs Work And What to Do About It

This section will briefly outline how and why your CCD images need work. For a less heuristic treatment, see Sec. A, which discusses how many of what kind of calibration frames you need.

Most of the calibration data is intended to remove "additive" effects: the electronic pedestal level (measured from the overscan region on each of your frames), the pre-flash level and/or underlying bias structure, and, if necessary, the dark current. The flat-field data (dome or projector flats and twilight sky exposures) will remove the multiplicative gain and illumination variations across the chip. Fringes are an additive effect that must be removed last.

When you obtained your frames at the telescope, the output signal was "biased" by adding a pedestal level of several hundred ADU's. We need to determine this bias level for each frame individually, as it is not stabilized, and will vary slightly (a few ADU's) with telescope position, temperature, and who knows what else. Furthermore, the bias level is usually a slight function of position on the chip, varying primarily along columns. We can remove this bias level to first-order by using the data in the *overscan region*, the (typically) 32 columns at the right edge of your frames.



We will average the data over all the columns in the overscan region, and fit these values as a function of line-number (i.e., average in the "x" direction within the overscan region, and fit these as a function of "y"). This fit will be subtracted from each column in your frame; this "fit" may be a simple constant. At this point we will chop off the overscan region, and keep only the part of the image containing useful data. This latter step usually trims off not only the overscan region but the first and last few rows and columns of your data.

If you pre-flashed the chip with light before each exposure, there will still be a non-zero number of counts that have been superimposed on each image. This extra signal is also an additive amount, and needs to be subtracted from your data. In addition, there may be column-to-column variation in the structure of the bias level, and this would not have been removed by the above procedure. To remove both the pre-flash (if any) and the residual variation in the bias level (if any) we will make use of frames that you have obtained with a zero integration time. These are referred to in IRAF as "zero frames" but are called "bias frames" in KPNO and CTIO lingo. We need to average many of these (taken with pre-flash if you were using pre-flash on your object frames), process the average as described above, and subtract this frame from all the other frames.

"Dark current" is also additive. On some CCD's there is a non-negligible amount of background added during long exposures. If necessary, you can remove the dark current to first-order by taking " dark" exposures (long integrations with the shutter closed), processing these frames as above, and then scaling to the exposure time of your program frames. However, it's been my experience that the dark current seldom scales linearly, so you need to be careful. Furthermore, you will need at least 3 dark frames in order to remove radiation events ("cosmic rays"), and unless you have a vast number of dark exposures to average you may decrease your signal-to-noise; see the discussion in Sec. A. The bottom line of all this is that unless you really need to remove the dark current, don't bother.

The next step in removing the instrumental signature is to flat-field your data. The variations in sensitivity are multiplicative, and we need to divide the data by the flat-field to remove the pixel-to-pixel gain variations, and (in the case of long-slit spectroscopy and direct imaging) the larger-scale spatial variations. If you are doing direct imaging, or plan to flux calibrate your spectroscopic data, then you are probably happy to just normalize the flat-field exposures to some average value, but if you are interested in preserving counts for the purposes of statistics in spectroscopic data we may want to first fit a function to remove the color of the lamp. The final step in the flat-fielding process is to see if your twilight sky exposures have been well flattened by this procedure—if not, we may have to correct for any remaining illumination gradients.

Some CCDs have a few pixels and/or partial columns where the response to light is *not* linear. For direct imaging one is usually happy to leave these bad regions alone: they're perfectly apparent on the reduced frames. But for spectroscopic reductions you may want to interpolate over these bad pixels. This step is known as "fixing bad pixels", and there are some new, powerful tools for constructing bad pixel maps and then applying the interpolation.

Finally, if you have broadband direct images and absolutely must remove fringes, then this will be your last step. but it will be a long and lonely one—IRAF currently doesn't provide much help. The fringe pattern is an additive effect, and must be subtracted from each program frame that is affected. This means that you will first have to construct master "fringe frames" for each filter you are planning to defringe. If the fringe pattern on your frames simply scaled with exposure time, you would now be able to process your data, but in fact fringes are caused by night-sky lines that may change quite drastically in intensity through out the night. Thus for each and every affected program frames, you will have to "manually" determine what additional scaling factor is needed to adequately remove the fringes.

3 Doing It

Throughout this section we will assume that you know how to examine the "hidden parameters" in an IRAF task, how to change these parameters, and how to execute the task. If you don't know this already, read the *A Beginner's Guide to IRAF* mentioned above, *and* sit down with someone who knows all this stuff and have him or her give you a crash course. Everyone seems to have his or her own style of doing these things: I always like to start out by invoking the task parameter editor **epar** *taskname*, setting all the parameters, and exiting with a **:go** in order to make darn sure that I have everything set the way I thought I did.

We will often call on the IRAF **ccdred** routines for combining frames in various ways. There are a number of very sophisticated algorithms for doing this. Details can be found by doing a **help combine** from within IRAF; for convenience, there is a short summary of the nitty-gritty of these various options given in Sec. B.

3.1 Outline of Reduction Steps

The steps we will go through in order to process CCD frames are the following:

- Examine a flatfield exposure using **implot** and determine the area of the chip that contains good data and the area of the chip that contains good "overscan" information.

- Set up the translation table for the image headers by running **setinstrument**; this will also set various defaults within the **ccdred** package. Enter the proper **biassec** and **trimsec** into **ccdproc** at this time. Substantiate that the header translations are valid by running **ccdlist**.

- Combine the individual bias frames using **zerocombine** to produce an averaged, combined bias image (**Zeron3**, for example).

- Process all the frames to remove the overscan and average bias, and to trim the images (first pass through **ccdproc**). Be sure that you have the appropriate switch settings (**overscan+, trim+, zerocor+, darkcor-, flatcor-, illum-, fring-**, and that the name of the combined bias frame has been entered for the zero calibration image (**zero=Zeron3**, say).

- For spectroscopic applications, you may want to construct a bad pixel map at this point. We recommend taking five long-exposure ($\approx$ 3000 e/pixel) flats and 20-30 short-exposure ($\approx$ 50-100 e/pixel) flats (either dome flats or projector flats); combining each group using **flatcombine**; dividing one by the other; and running **ccdmask** (currently in the "nmisc" package) with its default setting. We will use this bad pixel map (**badmap**, say) at the end. Be sure to stick these images io where the subsequent reduction steps won't affect them, such as a subdirectory. Note that this does not use the "fixpix" option in **ccdproc** itself, but relies on the newer (and not yet integrated) routines in the "nmisc" package. These are available as add-ons, if they are not already in your installation.

- If you are concerned about dark current:

  - Combine your dark frames using **darkcombine** with **scale=exposure**; call the combined image **Darkn3**, for example.
  - Examine the combined dark exposure and decide if you want to use it or not.

  - If you do want to use it, run everything through **ccdproc** again, this time specifying **darkcor+** and **dark=Darkn3**, for example.

- Combine your flat-field exposures using **flatcombine scale=mode reject=crreject gain=gain rdnoise=rdnoise**. This will reject cosmic rays and scale by the mode.

- (optional) For spectroscopic data, normalize the combined flat-field exposure along the dispersion axis by dividing it by a low-order fit using **response** in the **twodspec.longslit** package.

- Process all the program frames and sky flats using the combined flat-field exposures: **ccdproc *.imh ccdtype="" flatcor+ flat=Flat*.imh** (If you used **response** for your spectroscopic data, be sure to specify the normalized image as the flat-field.) This will flatten your data to the first approximation (second pass through **ccdproc**).

- Do the final flattening correction on your data as follows:

  - Examine your longest exposures (or at least the ones with the most sky) in each filter using **display** and **imexamine** to determine if your flat-field exposures did an adequate job flattening your data. Are there significant gradients ($> 1\%$) present in your sky values in direct imaging data? Is the spatial cut in spectroscopic data flat?

  - If you need to correct your data for any illumination problems revealed by the previous step create an illumination correction:

    * Combine any blank-sky or twilight frames with **combine**, scaling and weighting by the mode.

    * For spectroscopic data, use **illum** in the **longslit.twodspec** package to create a slit function illumination correction from the combined sky flat.

    * For direct imaging, use **mkskycor** on your combined twilight or blank-sky flats to create a smooth illumination correction.

  - Finish flattening your data by turning on the illumination correction switch and specifying these illumination function in **ccdproc** (third and final pass).

- For spectroscopic applications, you may wish to fix bad pixels as a final step: run **fixpix** in the **nmisc** package, using **badmap** as the mask, and leaving things at their default setting (linterp=1, cinterp=2).

3.2 Examining Your Frames to Determine the Trim and Bias Sections

The first step in reducing your data is to decide what part of the chip contains useful data, and exactly where the overscan region is and what part of it you want to use for determining the fit to the bias-level. The **ccdred** package knows these two regions as "trimsec", the section of the raw image that will be saved, and "biassec", the section of the raw image that will be used to fit the bias-level. As a reminder, IRAF uses the notation *imagename[x1:x2,y1:y2]* to describe that part of the image that goes from column "x1" to column "x2", and from row "y1" to row "y2".

If you are using one of the Kitt Peak or Tololo chips, and have relatively recent data, you will find image sections listed for TRIMSEC and BIASSEC in your headers. Pick an image and do an **imhead** *imagename* **l+** | **lprint** to get a printed listing of everything in the header. An example is shown in Figure 1. If you are doing direct imaging and you have these things in your header, you probably can ignore the rest of this section. Still, it wouldn't hurt you to make a few plots of your flat-field data to make sure that no one was being wildly conservative when they assigned a TRIMSEC to your chip.

If we do an **implot n30010** we will get a plot across the middle line. An ":a 10" command will tell it to average 10 rows or columns (whichever it is about to plot); a ":c 250" would then plot 10 columns centered on column 250. Similarly a ":l 300" would plot 10 lines centered on line number 300. You can expand by placing the cursor on the lower-left corner of the region you want to expand and hitting "e" (that's a lower-case "e"), and then placing the cursor in the upper-right corner of the region you wish to expand and hitting any key. A "C" will tell you the cursor position—but you may have to type it twice. A space bar [amazing!] will also do this, kind of. You can also expand with an "E" (upper-case "E") but you will then have to follow this with an "A" to get a scale.

The plots (Fig. 2) reveal that the first few rows of our chip were not

```
n30010[3104,101][short]: flat grat 23.75 grat 35 Red. Very.
    No bad pixels, no histogram, min=unknown, max=unknown
    Line storage mode, physdim [3328,101], length of user area 1339 s.u.
    Created Sat 19:26:33 18-Apr-92, Last modified Sat 19:26:34 18-Apr-92
    Pixel file 'tofu!/data1/massey/pixels/n30010.pix' [ok]
    New copy of dum$n30010.imh
    OBJECT  = 'flat grat 23.75 grat 35 Red. Very.'  /
    OBSERVAT= 'KPNO               '  /  observatory
    OBSERVER= 'Jacoby/Massey/Silva'  /
    COMMENTS= 'T&E WCAM           '  /  comments
    EXPTIME =                  10.  /  actual integration time
    DARKTIME=                  10.  /  total elapsed time
    IMAGETYP= 'flat               '  /  object, dark, bias, etc.
    DATE-OBS= '18/04/92           '  /  date (dd/mm/yy) of obs.
    UT      = '22:55:42.00        '  /  universal time
    ST      = '05:18:31.00        '  /  sidereal time
    RA      = '01:50:19.00        '  /  right ascension
    DEC     = '12:59:58.00        '  /  declination
    EPOCH   =               1992.3  /  epoch of ra and dec
    ZD      = '51.230             '  /  zenith distance
    AIRMASS =                  1.6  /  airmass
    TELESCOP= 'kp09m              '  /  telescope name
    DETECTOR= 'gcam               '  /  detector
    PREFLASH=                    4  /  preflash time, seconds
    GAIN    =                  4.5  /  gain, electrons per adu
    DWELL   =                    5  /  sample integration time
    CAMTEMP =                  -89  /  camera temperature
    DEWTEMP =                 -169  /  dewar temperature
    BIASSEC = '[3074:3104,1:101] '  /  overscan portion of frame
    TRIMSEC = '[1:3064,1:101]    '  /  region to be extracted
    DATASEC = '[1:3072,1:101]    '  /  image portion of frame
    CCDSEC  = '[1:3072,450:550]  '  /  orientation to full frame
    ORIGSEC = '[1:3072,1:1024]   '  /  original size full frame
    CCDSUM  = '1 1                '  /  on chip summation
    INSTRUME= 'test               '  /  instrument
    DISPERSE= '26                 '  /  disperser
    TILTPOS = '16.5               '  /  tilt position
    POSANGLE= '0                  '  /  position angle
    DISPAXIS= '1                  '  /  dispersion axis
    FILTERS = '0                  '  /  filter position
```

Figure 1: A sample of a long header. Note the values for TRIMSEC and BIASSEC.

illuminated, and that the last few columns (3065-3072) are not good. We decide to keep the section [1:3064,10:101] for our TRIMSEC. Note that if had the slit extended over the entire chip format, we would in fact have been happy with the defaults in the header, [1:3064, 1:101]. In addition, the BIASSEC (=[3074:3104,1:101] appears to be fine. For direct imaging, the header values for BIASSEC and TRIMSEC are usually correct.

3.3 Setting things up: *setinstrument*, parameters of *ccdproc*, and *ccdlist*

The reduction of our CCD data mostly takes place within the **ccdred** package. The tasks in this package rely heavily on the image headers to get everything right, so our first operation has to be to set up the translation table between the header information and things that **ccdred** will want to know, such as what a "zero frame" is called, what distinguishes a U filter flat-field from a R filter flat-field, and so on. The command for setting up this translation file is **setinstrument** in the **ccdred** package. So load **noao**, **imred**, and **ccdred**, and then type **setinstrument**. If you type a **?** you will get the list shown in Figure 3. In this case we are trying to reduce spectroscopic data taken with the FORD 3K$\times$1K chip (formatted to 3072×101) in the Kitt Peak 0.9m spectrometer WhiteCam (=GoldCam, but on the White Spectrograph). We select **specphot** as good generic spectroscopic defaults.

As soon as you do this you will find yourself in the parameter editor staring at the page for the entire package **ccdred**. The only thing to check at this point is that the pixel type of the output images, and the pixel type that will be used in our calculations, are both **real**. If you want to keep your output images in 16-bit "short" integer format, you should nevertheless retain the calculation type to be "real" or serious problems may occur when you do flat-field division. Getting out of this with a **CNTL-Z** will put us in the parameter editor for the **ccdproc** task (Fig. 6). This task is what we will use for doing the "image crunching"—removing bias, trimming, and flatfield division.

At this point we should enter the values for the **biassec** and **trimsec** parameters. Note that the default (for "specphot") is that **biassec=image**, which is correct—we are perfectly happy with the answer we found in the image header above for the bias-section ([[3074:3104,1:101]). We need to

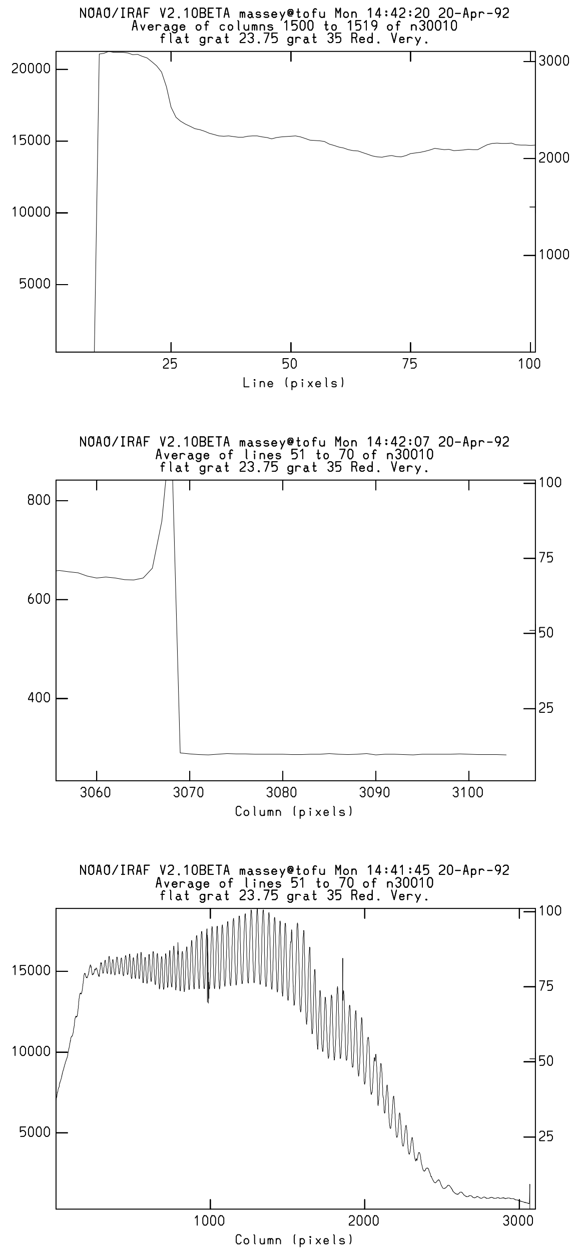


Figure 2: Plots through a flat-field exposure. Note the rather severe fringing evident in the flat-field exposure along the dispersion axis. These will hopefully come out in the flatfielding.

```
cc> setinstrument
Instrument ID (type ? for a list) (?): ?

direct          Current headers for Sun plus CCDPROC setup for direct CCD
specphot        Current headers for Sun plus CCDPROC setup for spectropho-
                  tometry, ie GoldCam, barefoot CCD
foe             Current headers for Sun plus CCDPROC setup for FOE
fibers          Current headers for Sun plus CCDPROC setup for fiber array
coude           Current headers for Sun plus CCDPROC setup for Coude
cyrocam         Current headers for Sun plus CCDPROC setup for Cryo Cam
echelle         Current headers for Sun plus CCDPROC setup for Echelle
kpnoheaders     Current headers with no changes to CCDPROC parameters
fits            Mountain FITS header prior to Aug. 87 (?)
camera          Mountain CAMERA header for IRAF Version 2.6 and earlier

Instrument ID (type q to quit): specphot
```

Figure 3: Possible answers to **setinstrument**. The user has chosen the "specphot" default.

explicitly enter the value for the trim-section, however, as [1:3064,10:101]. Had we selected, say, "direct" rather than "specphot", the values both for **biassec** and **trimsec** would have defaulted to "image", would probably have been correct.

Rather than worry about the other parameters now, let us simply exit with a **CNTL-Z**.

Did **setinstrument** do its job in setting up the translation table? To check this, we can run **ccdlist** on our images to see if IRAF is going to successfully recognize the type of image (object, comp, flat, zero) and the filter number (for direct imaging). So we will want to say **ccdlist *.imh** at this point to get a list like that shown in Figure 4.

Note that in the case of the spectroscopy example shown here the filter numbers are all "[0]", but in the case of direct imaging the filter numbers correspond to the filter bolt positions. The image type ("zero", "flat", "object", "comp") are also shown. These must be right if the tasks in **ccdred** are to succeed.

The things you should check at this point are whether the filter numbers are correct (that number in square brackets), and whether the object types make sense. If they don't, there is some inconsistency between the keywords in your headers, and the translation table set up by your having

```
n30004.imh[3104,101][short][comp][0]:comp 23.75 gr 35
n30007.imh[3104,101][short][flat][0]:flat grat 23.75 grat 35 Red. Very.
n30008.imh[3104,101][short][flat][0]:flat grat 23.75 grat 35 Red. Very.
n30009.imh[3104,101][short][flat][0]:flat grat 23.75 grat 35 Red. Very.
n30010.imh[3104,101][short][flat][0]:flat grat 23.75 grat 35 Red. Very.
n30011.imh[3104,101][short][flat][0]:flat grat 23.75 grat 35 Red. Very.
n30012.imh[3104,101][short][flat][0]:flat grat 23.75 grat 35 Red. Very.
n30013.imh[3104,101][short][zero][0]:zeron3
n30014.imh[3104,101][short][zero][0]:zeron3
n30015.imh[3104,101][short][zero][0]:zeron3
n30016.imh[3104,101][short][zero][0]:zeron3
n30017.imh[3104,101][short][zero][0]:zeron3
n30018.imh[3104,101][short][zero][0]:zeron3
n30019.imh[3104,101][short][zero][0]:zeron3
n30020.imh[3104,101][short][zero][0]:zeron3
n30021.imh[3104,101][short][zero][0]:zeron3
n30022.imh[3104,101][short][zero][0]:zeron3
n30023.imh[3104,101][short][object][0]:sky
n30024.imh[3104,101][short][object][0]:sky
n30031.imh[3104,101][short][comp][0]:comp after tour group
n30033.imh[3104,101][short][flat][0]:pflat near zenith
n30034.imh[3104,101][short][flat][0]:pflat at F66
n30035.imh[3104,101][short][flat][0]:pflat near zenith
n30036.imh[3104,101][short][object][0]:F66 way in the red
n30037.imh[3104,101][short][object][0]:pflat near zenith
n30038.imh[3104,101][short][object][0]:pflat near zenith
n30039.imh[3104,101][short][object][0]:F66
n30040.imh[3104,101][short][object][0]:F67 in da red!
n30041.imh[3104,101][short][object][0]:beta leo (std)
n30042.imh[3104,101][short][flat][0]:project flat beta leo
n30043.imh[3104,101][short][flat][0]:project flat eta UMa
n30044.imh[3104,101][short][object][0]:eta UMa
   [more]
```

Figure 4: Sample outputs from **ccdlist**.

run **setinstrument**. If you are stuck, try looking at a long version of your headers (**imhead *.imh l+ | page**) and then nose around by doing a **dir ccddb$kpno/*** until you find a file that will provide an appropriate translation.

If you are reducing non-KPNO/CTIO data and have different key-words for flats and bias's and so on, you will need to set up your own translation file; just follow the example in "ccddb$kpno/direct.dat", say. If you don't have the necessary information (really just the image type and filter numbers) you can add this information using **ccdhedit**; the best way would be to put the names of all the biases in a file *biasfile*, say, and then do a **ccdhedit @biasfile imagetype zero**; other examples can be found by doing a **help ccdhedit**. If you are going to be subtracting darks you are also going to need to translate some exposure time into the word "darktime" so that ccdproc can scale the darks. If you want to use a "superior" combining algorithm, it would also be convenient to have the read-noise (in electrons) and gain (in electrons/ADU) in your headers, although you could simply enter these values in the various combining tasks.

3.4 Combining Bias Frames with *zerocombine*

For our next act we want to combine the bias frames into an average frame. To combine the bias frames we will use **zerocombine** with the parameters shown in Figure 5.

The default parameters will result in all the images with type "zero" being averaged together, but with the highest value being ignored when forming the average for any given pixel. In other words, if you have 10 bias frames, 9 will be averaged in producing the value for each pixel in the image "Zeron3", ignoring the highest value at each pixel. (The various options available for combining images are discussed in Sec. B). This option will do a good job of keeping radiation events out of your average bias frame. Note that even though the images were "short integer" (16-bit) to start out with, the averaging will be done as "reals" (32-bit) and that your final image, *Zeron3*, will be a 32-bit real image. The output will look like that shown in Figure 5, in which we see that **zerocombine** has successfully picked up all the right images and averaged them together using the "minmax" option.

```
PACKAGE = ccdred
   TASK = zerocombine

input   =              n3*.imh  List of zero level images to combine
(output =               Zeron3) Output zero level name
(combine=              average) Type of combine operation
(reject =               minmax) Type of rejection
(ccdtype=                 zero) CCD image type to combine
(process=                   no) Process images before combining?
(delete =                   no) Delete input images after combining?
(clobber=                   no) Clobber existing output image?
(scale  =                 none) Image scaling
(statsec=                     ) Image section for computing statistics
(nlow   =                    0) minmax: Number of low pixels to reject
(nhigh  =                    1) minmax: Number of high pixels to reject
(mclip  =                  yes) Use median in sigma clipping algorithms?
(lsigma =                   3.) Lower sigma clipping factor
(hsigma =                   3.) Upper sigma clipping factor
(rdnoise=                   0.) ccdclip: CCD readout noise (electrons)
(gain   =                   1.) ccdclip: CCD gain (electrons/DN)
(pclip  =                 -0.5) pclip: Percentile clipping parameter
(mode   =                   ql)
cc> zerocombine
List of zero level images to combine (n3*.imh):

Apr 20 13:34: IMCOMBINE
  combine = average
  reject = minmax, nlow = 0, nhigh = 1
  blank = 0.
                Images
             n30013.imh
             n30014.imh
             n30015.imh
             n30016.imh
             n30017.imh
             n30018.imh
             n30019.imh
             n30020.imh
             n30021.imh
             n30022.imh

  Output image = Zeron3, ncombine = 10
```

Figure 5: Parameters and Output of **zerocombine**.

3.5 The First Pass Through *ccdproc*

We are now ready to process our data through **ccdproc** in order to do the "simple" stuff: we will subtract the pedestal determined from the overscan region, remove any remaining bias structure, and trim the image. Edit the parameters for **ccdproc** as shown in Fig. 6, making sure that the switches **overscan**, **trim**, and **zerocor** are on, but that **darkcor**, **flatcor**, and **illumcor** are off. Check that the correct values have been entered for **biassec** and **trimsec**. Finally, edit in the name of the combined bias frame as the **zero** image.

When we run **ccdproc** we will be asked if we want to fit the overscan vector interactively. The first couple of times through, answer "yes", and you will see a plot something like that shown in Fig. 7.

The fit shown in Fig. 7 is somewhat unusually flat. It is not unusual for bigger chips to exhibit a gradient of an ADU or two from one end to the other. However, even in these cases one might want to retain a single scalar (**order=1**) as the fit, as we will be subtracting off the combined bias frame. Thus any residuals not removed by fitting the overscan region will probably be removed in subtracting the combined bias frame: remember, the overscan region exists in order to monitor things that **change** from exposure to exposure—such as small differences in the pedestal level. If you were to find that you had different gradients from frame to frame, then you would want to use a higher order fit— but still maybe nothing higher than a straight line. (You can change the order while looking at the plot by doing a **:order 2**, say, followed by an **f** for a new fit. The new order will be retained for subsequent frames.)

After you have looked at a few of the overscan plots, answer **NO** (note the capitals) to the question "Fit overscan vector for bleh-bleh interactively?". Fig 8 shows the output from this first pass through **ccdproc**.

Note that **ccdproc** is smart enough to know what steps have and haven't been done—you are never in any danger of redoing a particular step. If you were to rerun **ccdproc** at the end of this step, without changing any of the switches, nothing would happen. However, if you were to turn other switches on (such as flat-field division!) those steps would then take place.

```
PACKAGE = ccdred
   TASK = ccdproc

images  =              n3*.imh  List of CCD images to correct
(ccdtype=                     ) CCD image type to correct
(max_cac=                    0) Maximum image caching memory (in Mbytes)
(noproc =                   no) List processing steps only?

(fixpix =                   no) Fix bad CCD lines and columns?
(oversca=                  yes) Apply overscan strip correction?
(trim   =                  yes) Trim the image?
(zerocor=                  yes) Apply zero level correction?
(darkcor=                   no) Apply dark count correction?
(flatcor=                   no) Apply flat field correction?
(illumco=                   no) Apply illumination correction?
(fringec=                   no) Apply fringe correction?
(readcor=                   no) Convert zero level image to readout correction?
(scancor=                   no) Convert flat field image to scan correction?

(readaxi=                 line) Read out axis (column|line)
(fixfile=                     ) File describing the bad lines and columns
(biassec=                image) Overscan strip image section
(trimsec=      [1:3064,10:101]) Trim data section
(zero   =               Zeron3) Zero level calibration image
(dark   =                     ) Dark count calibration image
(flat   =                     ) Flat field images
(illum  =                     ) Illumination correction images
(fringe =                     ) Fringe correction images
(minrepl=                   1.) Minimum flat field value
(scantyp=            shortscan) Scan type (shortscan|longscan)
(nscan  =                    1) Number of short scan lines

(interac=                  yes) Fit overscan interactively?
(functio=            chebyshev) Fitting function
(order  =                    1) Number of polynomial terms or spline pieces
(sample =                    *) Sample points to fit
(naverag=                    1) Number of sample points to combine
(niterat=                    1) Number of rejection iterations
(low_rej=                   3.) Low sigma rejection factor
(high_re=                   3.) High sigma rejection factor
(grow   =                   1.) Rejection growing radius
(mode   =                   ql)
```

Figure 6: The parameters for **ccdproc**. We have left the parameter **biassec** equal to "image" to use the region listed in the header, but explicitly stated the image section to use for trimming (**trimsec**). We have inserted the name of the combined bias image as the **zero** image.

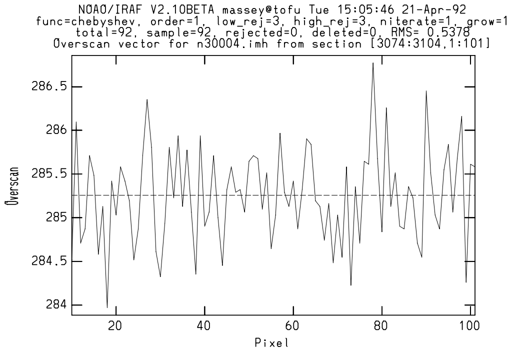


Figure 7: The overscan region for this chip is exceptionally well behaved, and a constant value is an excellent fit. However, one should not exceed a straight-line fit (**:order 2** followed by an **f**) if one can help it.

3.6 Constructing a bad pixel mask

For spectroscopic applications, we may wish to interpolate over bad pixels. By "bad pixels" we mean pixels—usually partial columns—that are nonlinear. For this, we use (a) a series of exposures of a projector lamp or dome flat that were exposed at a high enough level to have "lots of counts"—perhaps several thousand electrons per pixel, and (b) a series of exposures of the same type but at a much lower count-level: say 50-100 electrons per pixel. Combine each group using "flatcombine", being careful to keep the long exposures and the short exposures separately. Divide one by the other to reveal the non-linear pixels. The "nmisc" routine **ccdmask** will construct a bad pixel map. This map will be the same size as the data images, with values of 0 for normal pixels, 1 for regions where the "skinny" direction (the direction over which we wish to interpolate) is a line, and a 2 where the "skinny" direction is across a column. Be sure to move all of these images (and particularly the mask!) into a subdirectory where subsequent reductions won't affect them.

The steps involved in making a bad pixel map and preserving it would be something like the following, if a0001-5 were your long exposures and a0006-a0019 were your short exposures.

- **files a0001,a0002,a0003,a0004,a0005 > longflats**
- **files a0006,a0007,a0008,a0009,a001* > shortflats**

```
n30004.imh: Apr 21 15:02 Trim data section is [1:3064,10:101]
Fit overscan vector for n30004.imh interactively (yes):
n30004.imh: Apr 21 15:06 Overscan section is [3074:3104,1:101] with mean=285.2577
Zeron3: Apr 21 15:06 Trim data section is [1:3064,10:101]
Fit overscan vector for Zeron3 interactively (yes):
Zeron3: Apr 21 15:06 Overscan section is [3074:3104,1:101] with mean=285.8963
n30004.imh: Apr 21 15:06 Zero level correction image is Zeron3
n30007.imh: Apr 21 15:06 Trim data section is [1:3064,10:101]
Fit overscan vector for n30007.imh interactively (yes): NO
n30007.imh: Apr 21 15:14 Overscan section is [3074:3104,1:101] with mean=286.9531
n30007.imh: Apr 21 15:14 Zero level correction image is Zeron3
n30008.imh: Apr 21 15:14 Trim data section is [1:3064,10:101]
n30008.imh: Apr 21 15:14 Overscan section is [3074:3104,1:101] with mean=287.0747
n30008.imh: Apr 21 15:14 Zero level correction image is Zeron3
n30009.imh: Apr 21 15:14 Trim data section is [1:3064,10:101]
n30009.imh: Apr 21 15:14 Overscan section is [3074:3104,1:101] with mean=287.1335
n30009.imh: Apr 21 15:14 Zero level correction image is Zeron3
n30010.imh: Apr 21 15:14 Trim data section is [1:3064,10:101]
n30010.imh: Apr 21 15:14 Overscan section is [3074:3104,1:101] with mean=287.0952
n30010.imh: Apr 21 15:14 Zero level correction image is Zeron3
n30011.imh: Apr 21 15:14 Trim data section is [1:3064,10:101]
n30011.imh: Apr 21 15:14 Overscan section is [3074:3104,1:101] with mean=287.0601
n30011.imh: Apr 21 15:14 Zero level correction image is Zeron3
n30012.imh: Apr 21 15:14 Trim data section is [1:3064,10:101]
n30012.imh: Apr 21 15:14 Overscan section is [3074:3104,1:101] with mean=287.1636
n30012.imh: Apr 21 15:14 Zero level correction image is Zeron3
n30013.imh: Apr 21 15:14 Trim data section is [1:3064,10:101]
n30013.imh: Apr 21 15:14 Overscan section is [3074:3104,1:101] with mean=286.3238
[more]
```

Figure 8: Output from this first pass through **ccdproc**.

- **flatcombine @longflats out=FlatL reject=crreject scale=mode rdnoise="rdnoise" gain="gain"**
- **flatcombine @shortflats out=FlatS reject=crrejct scale=mode rdnoise="rdnoise" gain="gain"**
- **imarith FlatL / FlatS Flatdiv**
- **nmisc**
- **unlearn ccdmask**
- **ccdmask Flatdiv mask=badmap**
- **display FlatL 1**
- **display Flatdiv 2**
- **display badmap 3**
- **imdelete @longflats,@shortflats,FlatL,FlatS**
- **mkdir calib**
- **imrename badmap calib/badmap**

3.7 Dealing with The Darks

We argued earlier that the dark current is unlikely to be significant, but it wouldn't kill us to check that. We have already removed the the overscan and bias level from our dark exposures, so any counts we see on the dark frames are probably real dark current (or a light leak!).

We can either examine an individual dark exposure, or combine our dark exposures using **darkcombine**. The parameters for **darkcombine** are shown in Fig. 9. The *reject* algorithm chosen is again the simplest (and safest); we throw away the highest value at each pixel in constructing the average by specifying **minmax** with **nlow=0** and **nhigh=1**; see Sec. B for more details.

Note that **darkcombine** is smart enough to select only **dark** frames—and furthermore, will combine them scaling by the exposure times if they are different.

```
PACKAGE = ccdred
   TASK = darkcombine

input   =             n3*.imh  List of dark images to combine
(output =              Darkn3) Output flat field root name
(combine=             average) Type of combine operation
(reject =              minmax) Type of rejection
(ccdtype=                dark) CCD image type to combine
(process=                 yes) Process images before combining?
(delete =                  no) Delete input images after combining?
(clobber=                  no) Clobber existing output image?
(scale  =            exposure) Image scaling
(statsec=                    ) Image section for computing statistics
(nlow   =                   0) minmax: Number of low pixels to reject
(nhigh  =                   1) minmax: Number of high pixels to reject
(mclip  =                 yes) Use median in sigma clipping algorithms?
(lsigma =                  3.) Lower sigma clipping factor
(hsigma =                  3.) Upper sigma clipping factor
(rdnoise=                  0.) ccdclip: CCD readout noise (electrons)
(gain   =                  1.) ccdclip: CCD gain (electrons/DN)
(pclip  =                -0.5) pclip: Percentile clipping parameter
(mode   =                  ql)
```

Figure 9: Parameters for **darkcombine**.

Examine your dark exposure by using **display** and **imexamine**. Are there significant counts there? If the answer is yes, we could choose to do the dark scaling and subtraction now: simply run

- **ccdproc n3*.imh darkcor+ dark=Darkn3**

3.8 Combining the Flat-field Exposures

We next want to combine the flat-field exposures. For direct imaging a separate flat-field image is needed for each filter. Fortunately, the **ccdred** tasks pays attention to the "subset parameter", which, for direct imaging, is defined in terms of the filter position. (For coude data, the subsect parameter is the grating position, "gratpos", which makes sense.)

The parameters for the **flatcombine** task are shown in Fig. 10. The **reject** option is now set to **crreject** rather than the **minmax** option used for the bias frames; this will do a fine job of removing any radiation events from your flat-field exposures. (You could have equally well used **avsigclip**, in which case the "typical" sigma would have been determined from the data itself rather than an *a priori* knowledge of the noise characteristics of your CCD; see Sec. B for more details.) However, none of these options would work right if the data had not first been processed.

Note that we have decided not to use as input simply **n3*.imh** for running **flatcombine**; if you refer back to Fig. 4 you will see that there are actually projector flats taken at each new telescope position, in addition to the dome-flats exposures (n30007-12). Until we have reduced these data we do not know exactly the best way to remove the horrendous fringing pattern evident in Fig. 2, but for now we simply want to use the dome-flats. When we run **flatcombine** we will see output like that in Fig. 10.

The default parameter of **flatcombine** also called for scaling each of the individual frames by the [inverse] of the mode. This then allows for the possibility that lamps providing the flat-field illumination have varied during the series of exposures—usually a true assumption! By scaling these to some common value one obtains a less biased average given that we are rejecting some pixels.

Had we been doing direct imaging through a variety of different filters, we would have obtained one averaged flat-field exposure for each filter; **flatcombine** would have (by default) used the filter number shown by **ccdlist** to decide what to combine with what.

3.9 Normalizing Spectroscopic Flats using *response*

For direct imaging flat-fields, the only normalization we want to do is to divide the flat by the average value before flat-field division so that we roughly preserve the correct counts in our objects. This will happen automatically when we use **ccdproc** for flat-field division. For spectroscopic data, however, we might elect to also take out some of the shape of the flat-field lamp along the dispersion axis. One has to be very careful here that one does not do more harm than good, however, in fitting the flat-field. We would like to remove the large-scale, wavelength-dependent structure that is peculiar to the flat-field itself, e.g., removing bumps and wiggles which are found in the flat-field source but **not** found in the stellar or sky spectrum. These bumps, wiggles, and color effects can exist due to (a) the lamps being of a very different temperature than the celestial sources you are observing, (b) transmission features in any color-balance filters used with the projector lamps, and (c) the wavelength-dependence reflectivity of whatever you are

```
PACKAGE = ccdred
   TASK = flatcombine

input   =        n3000*,n3001*  List of flat field images to combine
(output =                Flat) Output flat field root name
(combine=             average) Type of combine operation
(reject =            crreject) Type of rejection
(ccdtype=                flat) CCD image type to combine
(process=                 yes) Process images before combining?
(subsets=                 yes) Combine images by subset parameter?
(delete =                  no) Delete input images after combining?
(clobber=                  no) Clobber existing output image?
(scale  =                mode) Image scaling
(statsec=                    ) Image section for computing statistics
(nlow   =                   1) minmax: Number of low pixels to reject
(nhigh  =                   1) minmax: Number of high pixels to reject
(mclip  =                 yes) Use median in sigma clipping algorithms?
(lsigma =                  3.) Lower sigma clipping factor
(hsigma =                  3.) Upper sigma clipping factor
(rdnoise=             rdnoise) ccdclip: CCD readout noise (electrons)
(gain   =                gain) ccdclip: CCD gain (electrons/DN)
(pclip  =                -0.5) pclip: Percentile clipping parameter
(mode   =                  ql)

cc> flatcombine
List of flat field images to combine (n3000*,n3001*):

Apr 22 10:55: IMCOMBINE
  combine = average
   reject = crreject, mclip = yes, rdnoise = rdnoise, gain = gain, hsigma = 3.
  blank = 0.
                Images    Mode Rdnoise   Gain  Scale
             n30007.imh 15172.      4.   4.2   0.985
             n30008.imh 14959.      4.   4.2   0.999
             n30009.imh 15010.      4.   4.2   0.996
             n30010.imh 14787.      4.   4.2   1.011
             n30011.imh 14962.      4.   4.2   0.999
             n30012.imh 14821.      4.   4.2   1.009

  Output image = Flat0, ncombine = 6
```

Figure 10: Parameters and Output for **flatcombine**.

```
PACKAGE = longslit
   TASK = response

calibrat=               Flat0  Longslit calibration images
normaliz=               Flat0  Normalization spectrum images
response=              nFlat0  Response function images
(interac=                 yes) Fit normalization spectrum interactively?
(thresho=               INDEF) Response threshold
(sample =                   *) Sample of points to use in fit
(naverag=                   1) Number of points in sample averaging
(functio=             spline3) Fitting function
(order  =                   1) Order of fitting function
(low_rej=                  3.) Low rejection in sigma of fit
(high_re=                  3.) High rejection in sigma of fit
(niterat=                   1) Number of rejection iterations
(grow   =                  0.) Rejection growing radius
(graphic=            stdgraph) Graphics output device
(cursor =                    ) Graphics cursor input
(mode   =                  ql)
```

Figure 11: Parameters for **response** in the **twodspec.longslit** package.

shining the project lamps on.

The task **response** in the **twodspec.longslit** package allows us to interactively fit a function in the dispersion direction. The output of this task is an image that is the ratio of the flat to the fit; e.g., one can use the fit to take out large-scale variations in the wavelength direction. The fit is performed by first summing all the rows or columns (depending on whether the dispersion goes along columns or rows) of the spatial axis, so that you are not affecting the slit illumination function.

To run **response**, load **twodspec** and then **longslit**. The parameters for **response** are shown in Fig. 11. Note that some of the parameters (namely the **low_reject** and **high_reject**) have been changed from their defaults. Note also that the **normalization** spectrum should be set equal to the **calibration** spectrum, *Flat0* in this case. The output image will be called **nFlat0**.

When we run **response**, we are confronted by a plot such as that shown in Fig. 12.

We finally choose an order=6 cubic spline as the fit to the flat-field. The case we are using to illustrate this manual with is, admittedly, a particularly grungy one. You are unlikely to encounter a flat-field this bad under normal

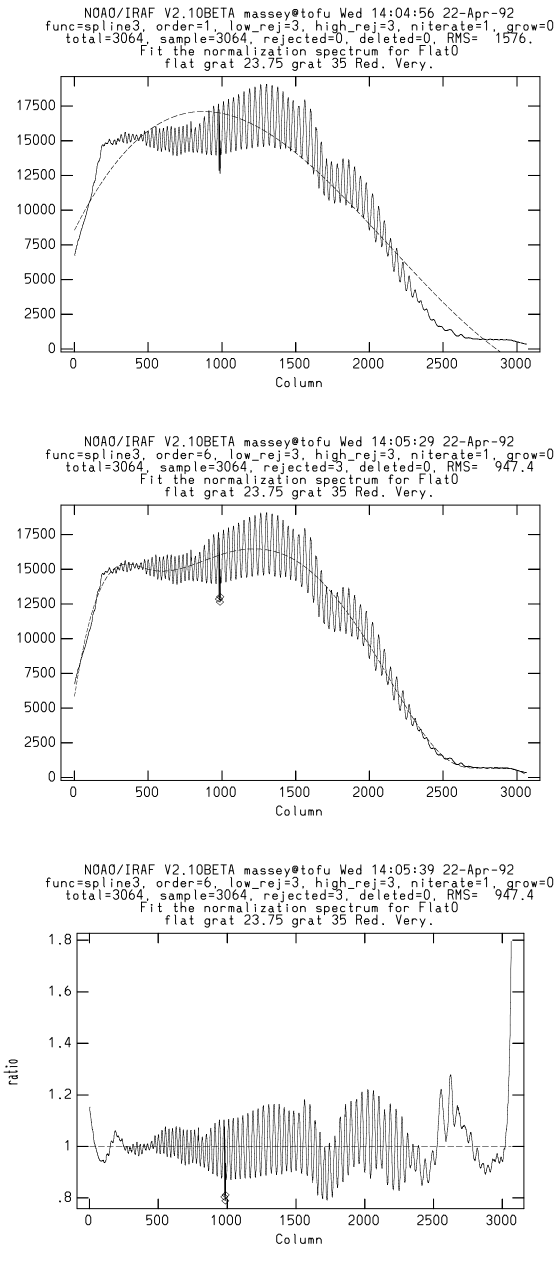


Figure 12: The top plot shows the fit of an order=1 cubic spline on the flat-field data. The middle plot shows an order=6 fit obtained by typing a **:order 6** followed by an **f**. The bottom plot shows the ratio of the data to the fit, which can be viewed by hitting the **j** key. An **h** brings back the data vs. pixel number plot. For more information do a **help icfit**.

observing conditions (unless you too decide to observe out to 1.1 μm with a thinned chip). We won't know until we do the processing in the next step, but our choice of order 6 seems reasonable—the fringes are **not** fit, but the large-scale features of the lamp are being fit.

3.10 Flat-field Division: *ccdproc* Pass 2

We now will make our second pass through *ccdproc*, this time letting it do the flat-field division. Although we *will* be overwriting the images (it's hard to avoid this in **ccdproc**), this step is still perfectly reversible, and if we find that we need additional corrections to the flat-fields, that is easily made by a third pass through *ccdproc*. So we first edit the parameters of **ccdproc** to turn on **flatcor** and to explicitly give it the correct name of the flat-fields, which in this case is the *normalize* output from **response**: *nFlat0*. The parameters are shown in Fig. 13

In the case of direct imaging we would likely have set the flat-field names to **Flat*.imh**. See Sec. C.2 for a full example.

3.11 Getting the Flat-Fielding Really Right

How well did we do on our flat-fielding? We need to now to *really look* at our data to evaluate this. Start with a long exposure (something containing lots of sky) and **display** it and use **imexamine** to make cuts at various places on the images. For spectroscopic data, we want to mainly see that the spatial cut is uniform.

For the data reduced here, our longest exposure was none too long. The left plot in Fig. 14 shows the sky averaged over many columns for the longest exposure. This plot was made by using **implot** *imagename* and then an **:a 100** and a **:c 1500** to plot the average of 100 columns centered on column 1500. We can see that we don't have many counts in the sky! However, it does look like the right side is a bit lower than the left side.

We next examine one of our twilight sky exposures. This is shown in the right panel of Fig. 14. In this spatial cut there *is* a clear gradient present, although it is only 2% from one side to the other. This is consistent with what we see in the exposure of the object, however, and we decide to remove it.

```
PACKAGE = ccdred
   TASK = ccdproc

images  =              n3*.imh  List of CCD images to correct
(ccdtype=                     ) CCD image type to correct
(max_cac=                    0) Maximum image caching memory (in Mbytes)
(noproc =                   no) List processing steps only?

(fixpix =                   no) Fix bad CCD lines and columns?
(oversca=                  yes) Apply overscan strip correction?
(trim   =                  yes) Trim the image?
(zerocor=                  yes) Apply zero level correction?
(darkcor=                   no) Apply dark count correction?
(flatcor=                  yes) Apply flat field correction?
(illumco=                   no) Apply illumination correction?
(fringec=                   no) Apply fringe correction?
(readcor=                   no) Convert zero level image to readout correction?
(scancor=                   no) Convert flat field image to scan correction?

(readaxi=                 line) Read out axis (column|line)
(fixfile=                     ) File describing the bad lines and columns
(biassec=                image) Overscan strip image section
(trimsec=      [1:3064,10:101]) Trim data section
(zero   =               Zeron3) Zero level calibration image
(dark   =                     ) Dark count calibration image
(flat   =               nFlat0) Flat field images
(illum  =                     ) Illumination correction images
(fringe =                     ) Fringe correction images
(minrepl=                   1.) Minimum flat field value
(scantyp=            shortscan) Scan type (shortscan|longscan)
(nscan  =                    1) Number of short scan lines

(interac=                  yes) Fit overscan interactively?
(functio=            chebyshev) Fitting function
(order  =                    1) Number of polynomial terms or spline pieces
(sample =                    *) Sample points to fit
(naverag=                    1) Number of sample points to combine
(niterat=                    1) Number of rejection iterations
(low_rej=                   3.) Low sigma rejection factor
(high_re=                   3.) High sigma rejection factor
(grow   =                   1.) Rejection growing radius
(mode   =                   ql)
:go
[more]
n30023.imh: Apr 22 14:47 Flat field image is nFlat0 with scale=1.
n30024.imh: Apr 22 14:47 Flat field image is nFlat0 with scale=1.
n30028.imh: Apr 22 14:47 Flat field image is nFlat0 with scale=1.
n30029.imh: Apr 22 14:47 Flat field image is nFlat0 with scale=1.
n30030.imh: Apr 22 14:47 Flat field image is nFlat0 with scale=1.
n30031.imh: Apr 22 14:48 Flat field image is nFlat0 with scale=1.
n30036.imh: Apr 22 14:48 Flat field image is nFlat0 with scale=1.
n30037.imh: Apr 22 14:48 Flat field image is nFlat0 with scale=1.
[more]
```

Figure 13: Parameters for **ccdproc** with flat-field division now turned on (**flatcor=yes**) and the name of the flat-field explicitly entered.

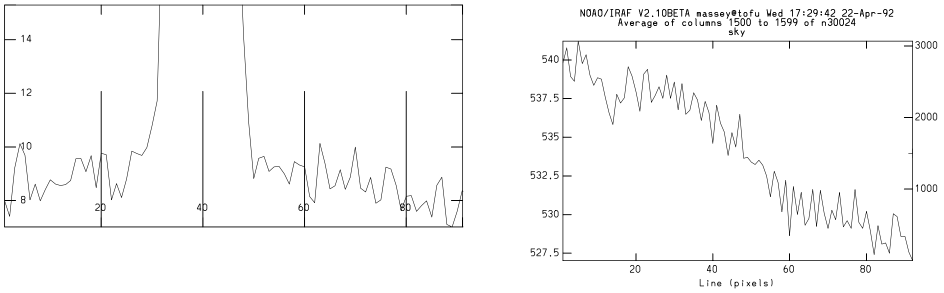


Figure 14: The cut along the spatial axis of a long program exposure appears to be consistent with a cut along the spatial axis of a bright twilight sky exposure: there is a 2% gradient from one side of the chip to the other.

3.11.1 Combing the twilight/blank-sky flats

In order to determine the slit illumination function more accurately than that likely to be achieved with the dome flat-field, two exposures of the sky were obtained. (One would like to have obtained at least three such exposures, moving the telescope slightly between each one, [see Sec. A] but you can't always get what you want.) We will combine these two frames using the generic routine **combine**:

- **combine n30023,n30024 Sky reject=avsigclip scale=mode weight=mode subsets- blank=1**

This produces output shown in Fig. 15. If we had been doing this using direct imaging, we would have specified **subsets+** to make sure this was done in a filter-by-filter manner; in that case, the output images would have been automatically named Sky1, Sky2, Sky3, and so on, with the extension determined by the filter number. This is shown explicitly in our example of direct imaging reduction in Sec. C.2.

3.11.2 Creating the Illumination Correction

Having decided to correct our data (which have already been divided by the flat-fields, remember), we need to create an illumination correction. For spectroscopic data, this will be created from the combined sky exposure (which has also been flat-fielded), and will be done by fitting a function

```
cc> combine n30023,n30024 Sky subsets- reject=avsigclip scale=mode weight=mode

Apr 22 13:56: IMCOMBINE
  combine = average
  reject = avsigclip, mclip = yes, lsigma = 3., hsigma = 3.
  blank = 1.
                Images     Mode  Scale Weight
                 n30023 177.16  0.659  0.639
                 n30024 56.393  2.071  0.361

  Output image = Sky, ncombine = 2
cc>
```

Figure 15: Combining two sky exposures, scaling and weighting by the mode.

along the spatial axis, collapsing the image in the dispersion direction. (In practice, we let the slit function be a slight function of wavelength, and so do this procedure three or four times through-out the length of the spectrum.) For direct imaging, we will use our blank-sky (or low-level twilight) exposures (which have been divided by the flat-field) by smoothing them extensively and using the smoothed image to correct any large-scale gradients.

Spectroscopic: *twodspec.longslit.illum* In Fig. 16 we show the parameters of the **illum** task within the **twodspec longslit** package. Note that we have changed some of the defaults, namely **low_reject** and **high_reject**, to 3.0.

When we run the task, we are first shown a plot of the spectrum with the five wavelength bins marked (see the top panel of Fig. 17). We can either accept these bins, or start over by typing a **i** and then marking each region with an **s** on the left, and an **s** on the right. When we exit this stage by a **q**, we then see the function fit in the spatial direction for each of the regions we've selected; these plots will resemble the middle panel. When we are done, we can plot the final fit; a spatial cut is shown in the bottom panel. (The image should be unity in the wavelength direction.)

Direct imaging: *mkskycor* If we have combined blank-sky flats in order to remove large-scale gradients, we can then use **mkskycor** to smooth the combined blank-sky frame. The parameters of **mkskycor** will resemble those of Fig. 18. (If you want to do this on more than one sky frame, you can do a

files Sky1,Sky2,Sky3 > skyfix

```
PACKAGE = longslit
   TASK = illumination

images  =                 Sky  Longslit calibration images
illumina=                nSky  Illumination function images
(interac=                yes) Interactive illumination fitting?
(bins   =                   ) Dispersion bins
(nbins  =                  5) Number of dispersion bins when bins = ""
(sample =                  *) Sample of points to use in fit
(naverag=                  1) Number of points in sample averaging
(functio=            spline3) Fitting function
(order  =                  1) Order of fitting function
(low_rej=                 3.) Low rejection in sigma of fit
(high_re=                 3.) High rejection in sigma of fit
(niterat=                  1) Number of rejection iterations
(grow   =                 0.) Rejection growing radius
(interpo=              poly3) Interpolation type
(graphic=           stdgraph) Graphics output device
(cursor =                   ) Graphics cursor input
(mode   =                 ql)
```

Figure 16: The parameters for the task illum.

and then set "input=@skyfix" and "output=n//@skyfix".) After you run the task, you should divide the new images into your old and examine the resultant images:

imarith @n3skyfix / n//@skyfix test//@n3skyfix

will produce images with names *testSky1, testSky2*, and so on.

If you have well-exposed twilight flats, rather than blank-sky flats, you may instead find that you wish you had used the twilight sky exposures as your flat-field instead of the dome flats. Do you have to reread all the data from disk and begin again? No! We can cheat, and fool IRAF into thinking that it is simply using the (flat-fielded) twilight flats as an "illumination correction" for the (flat-fielded) program frames. If we don't smooth the twilight-sky exposures, then this is algebraically equivalent (other than integer-truncation) to never having used the dome-flats at all. However, we must first fix the headers so that **ccdproc** will be willing to swallow the combined twilight sky exposures as an "illumination correction":

- **hedit Sky*.imh MKILLUM "fake" add+ ver- show+**

You are now ready to proceed to the final steps.

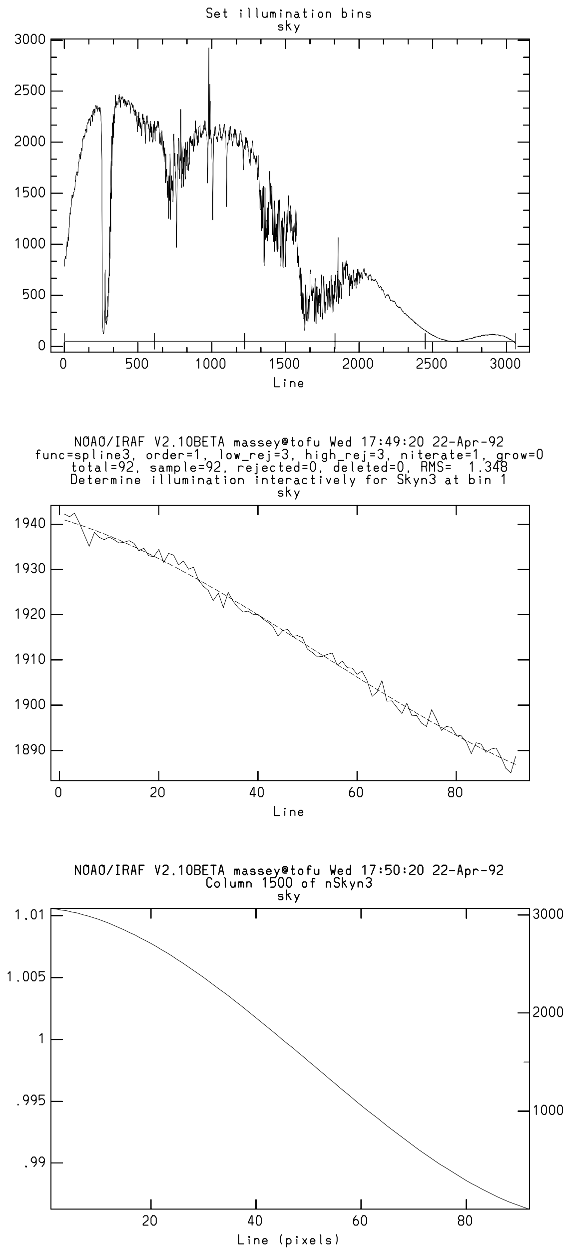


Figure 17: The wavelength bins for our **illum** run are shown in the top panel under the spectrum of the sky. The middle plot shows the fit along the spatial cut of one of the five wavelength region. the bottom plot shows the spatial plot along the output image.

```
PACKAGE = ccdred
   TASK = mkskycor

input   =                       Input CCD images
output  =                       Output images (same as input if none given)
(ccdtype=                     ) CCD image type to select
(xboxmin=                   5.) Minimum smoothing box size in x at edges
(xboxmax=                 0.25) Maximum smoothing box size in x
(yboxmin=                   5.) Minimum moothing box size in y at edges
(yboxmax=                 0.25) Maximum moothing box size in y
(clip   =                  yes) Clip input pixels?
(lowsigm=                  2.5) Low clipping sigma
(highsig=                  2.5) High clipping sigma
(ccdproc=                     ) CCD processing parameters
(mode   =                   ql)
```

Figure 18: Parameters for **mkskycor**.

3.12 Finishing the Flat-fielding

To correct for this illumination function, simply do an

- **ccdproc *.imh illumcor+ illum="nSky*.imh"** to correct whichever images need correcting. If you've created only an nSky1.imh, then only those with filter 1 will get processed. If you are using unaltered twilight flats, then of course you will have to substitute *illum="Sky*.imh"* in the above.

3.13 Fixing Bad Pixels

The final step in our reductions will be to interpolate over non-linear pixels using our bad pixel map. Do this using the task **fixpix** in the "nmisc" package.

- **fixpix *.imh mask=calib/badmap linterp=1 cinterp=2**

Congratulations! You're done, and now ready to go on to do photometry on your frames or extract some spectra!

A How Many and What Calibration Frames Do You Need?

The answer to this depends to some extent on what it is that you are doing, and what chip you are doing it with. The goal is to not let the quality of the calibration data degrade your signal-to-noise in any way. If you are in the regime where the read-noise of the chip is the dominant source of noise on your program objects, then subtracting a single "bias frame" from your data would increase the noise by $\sqrt{2}$. If instead you use the average of 25 bias frames, the noise would be increased by only 10%. However, with modern CCDs with read-noise of a few electrons, hardly anyone finds his/herself in this regime any more. Particularly if you are into high signal-to-noise spectroscopy, so you have lots and lots of signal compared to read-noise, or if you have high sky background on direct images, so that read-noise is again immaterial, then the signal-to-noise will be little affected by whether you have only a few bias frames. However, in this regime the quality of your flat fielding is all important if you want to get the most out of your data.

The following list contains the type of calibration images you may need, and provides some guide to the consideration of how many you may want to have.

bias frames. These are zero second integration exposures obtained with the same pre-flash (if any) you are using on your program objects. If read-noise will sometimes dominate your source of error on the program objects, take 25 *bias frames* per night. Take them over dinner and you'll never notice it. These days, most CCD's have read-noises on the order of a few electrons, with the gain usually set so that you are at best barely sampling the read-noise (e.g., < 3 ADU). In this case there isn't much reason for you to overdo it on the biases; 10 of them will bring the effective noise below the digitization noise of a single exposure. You may want to make a new sequence of biases each day.

dark frames. These are long exposures taken with the shutter closed. If your longest exposure time is over 15 minutes you may want to take an equal length *dark frame*, subtract a bias frame from it, and decide if you are worried about how much dark current is left. Few of the Kitt Peak or Tololo chips suffer from significant dark current, but it won't hurt you to check once or twice during your run. I usually take a few of these but never use them. Applications where dark current *will* matter are long-slit spectroscopy and surface brightness studies — cases where the background is not removed locally. If you do find that you need to take care of dark current, then you should take at least 3 and preferably 5 to 10 dark frames during your run, each with an integration time equal to your longest exposure. You had better make sure that your system is sufficiently light-tight to permit these to be done during the day—if not, hope for a few cloudy nights!

bad pixel data. If you are doing spectroscopy, and would like to correct for non-linear bad pixels/partial columns, then you should take a series of long and short exposures of some type of flat field (dome flat or projector lamp). I typically aim for five exposure of several thousand e/pixel followed by 20 or so exposures that are about 100 e/pixel.

flat field exposures. At a minimum, flat field exposures are used to remove pixel-to-pixel variations across the chip. Usually *dome flats* (exposures of an illuminated white spot) or *projector flats* (exposures of a quartz lamp illuminating the spectrograph slit) will suffice to remove the pixel-to-pixel stuff. You will want to expose the dome or projector flats so that you get sufficient counts to not degrade the signal-to-noise of the final images. If you are after 1% photometry per pixel then you will need to have several times more than 10,000 electrons accumulated in your flats, but you need to be careful not to exceed the good linearity limit in any single flat exposure. Generally if you have 5 or more flats each with 10,000 electrons per pixel you are probably fine. You will need a set like this for every filter or every grating tilt, and you probably will want to do a new sequence every day.

twilight flats. If you are interested in good photometry of objects across your field, or in long-slit spectroscopic work, you need to know if the sky looks different to your CCD than the projector lamp or dome flat. It is not unusual to find 5-10% gradients in the illumination response between a dome flat and a sky exposure, and this difference will translate directly into a 5-10% error in your photometry. For most applications, exposures of bright twilight sky (either for direct imaging or spectroscopy) will cure this problem. With direct imaging this requires you to be very quick on your feet to obtain a good level of sky exposure in each of your filters while the sky is getting darker and darker. (Only the truly desperate would take twilight flats in the morning!) For direct imaging take 3 to 5 exposures in each filter, stepping the telescope slightly in between the exposures so that any faint stars can be effectively cleaned out. For long-slit spectroscopy take a few exposures of the the twilight sky, stepping the telescope perpendicular to the slit orientation. In both cases you should make sure that tracking is on and that the telescope is clear of the dome. You will find that you need to keep increasing the exposure time to maintain an illumination level of $\approx$ 10,000 electrons.

blank sky exposures. Some observers doing sky-limited direct imaging may wish to try exposures of blank sky fields rather than twilight sky, as the color of twilight and the color of the dark sky do differ considerably. Obtain at least three, and preferably four, long exposures through each filter of some region relatively free from stars ("blank sky" coordinates can be found at Kitt Peak and Tololo), stepping the telescope 10-15 arcseconds between each exposure. The trick here, of course, is to get enough counts in the sky exposures to make this worth your while. Unless you are willing to devote a great deal of telescope time to this, you will have to smooth these *blank sky* exposures to reduce noise, but the assumption in such a smoothing process is that the color response of the chip does not vary over the area you are smoothing. You might try dividing a U dome flat by a V dome flat and seeing how reasonable an assumption this might be. Also, if the cosmetics are very bad, the smoothing process will wreak havoc with your data if you are not successful in cleaning out bad columns and pixels.

fringe frames. Some CCD's produce an interference fringe pattern when they are illuminated by monochromatic light. For spectroscopy or narrow-band imaging this won't matter, as the fringe pattern will usually come out nicely with the dome flats, but if you are doing deep exposures in V, R, or I with a chip that fringes a lot, then the night sky lines may cause a fringe pattern. The only CCD data I've had to defringe was that taken with the Tololo prime focus RCA chip, now honorably retired. Even here the fringes seldom had amplitudes greater than a few percent of the night sky. If you are after equally faint objects of small spatial scale, then you may find yourself having to defringe. For this you will need very, very long blank sky frames obtained as above, but you will not be able to smooth them without destroying the fringe information. Prevention is the best cure for fringes: avoid using chips that fringe a lot, avoid making long VRI exposures within an hour of twilight (as the night sky lines are strongest then), and avoid letting your objects fall on the part of the chip where the fringing is the most severe.

B The Ins and Outs of Combining Frames

There are a number of powerful and sophisticated algorithms available in IRAF V2.10 for combining images. In particular there are a number of clever "rejection" criterion you can use for (hopefully) eliminating cosmic-rays or stars in twilight exposures without (hopefully) eliminating the data you want to keep. A complete description can be found by **help combine**; in this section we provide a quick "astronomer's review" of the rejection choices.

The parameters for the **combine** task are shown in Fig. 19. All of the various **ccdred** combining routines (**flatcombine, darkcombine, flatcombine**) simply call **combine** with the appropriate switch settings.

In combining n images the routine must decide at each pixel which of the n data values, if any, to reject in forming the average. Deciding what point(s) might be descrepant can be broken into three categories.

The trivial. The simpliest, but for many applications the best, is the **reject=minmax** option. In this, the same number of values are excluded in determining the "best" average at each pixel. This assumes nothing about the data, or the expected spread in data value at each pixel, but is efficient at removing bad apples at the cost of always computing the average from fewer data values than what is available. Still, this works fine if you have data that you don't mind losing; e.g., in combining biases, say, or darks.

- **minmax** With this rejection algorithm, at each pixel there will be *nlow* low pixels and *nhigh* high pixels rejected. Thus to reject only the highest value in combining images we set **reject=minmax nhigh=1**

```
cc> lpar combine
        input =                 List of images to combine
       output =                 List of output images
      (plfile = "")             List of output pixel list files (optional)
       (sigma = "")             List of sigma images (optional)\n
     (ccdtype = "")             CCD image type to combine (optional)
     (subsets = no)             Combine images by subset parameter?
      (delete = no)             Delete input images after combining?
     (clobber = no)             Clobber existing output image?\n
     (combine = "average")      Type of combine operation
      (reject = "none")         Type of rejection
     (project = no)             Project highest dimension of input images?
     (outtype = "real")         Output image pixel datatype
     (offsets = "none")         Input image offsets
    (masktype = "none")         Mask type
   (maskvalue = 0.)             Mask value
       (blank = 0.)             Value if there are no pixels\n
       (scale = "none")         Image scaling
        (zero = "none")         Image zero point offset
      (weight = "none")         Image weights
     (statsec = "")             Image section for computing statistics\n
  (lthreshold = INDEF)          Lower threshold
  (hthreshold = INDEF)          Upper threshold
        (nlow = 1)              minmax: Number of low pixels to reject
       (nhigh = 1)              minmax: Number of high pixels to reject
       (mclip = yes)            Use median in sigma clipping algorithms?
      (lsigma = 3.)             Lower sigma clipping factor
      (hsigma = 3.)             Upper sigma clipping factor
     (rdnoise = "0.")           ccdclip: CCD readout noise (electrons)
        (gain = "1.")           ccdclip: CCD gain (electrons/DN)
    (sigscale = 0.1)            Tolerance for sigma clipping scaling correction
       (pclip = -0.5)           pclip: Percentile clipping parameter
        (grow = 0)              Radius (pixels) for 1D neighbor rejection
        (mode = "ql")
```

Figure 19: The parameters for the **combine** task.

nlow=0. This is the default setting for **zerocombine**, and will do an excellent and fast job.

Sigma determined from CCD noise characteristics. In the schemes **reject=ccdclip** and **reject=crreject** we assume we know what what a reasonable spread is of our data values at each pixel, given the average value and the known gain g (in e/ADU) and read-noise r (in e). If the average data value at a given pixel is I, then the number of electrons at that pixel is $g \times I$, and we expect from Poisson statistics that spread in the data should have a value of sigma (σ), in ADU's, of

$$\sigma_{ADU} = \frac{\sqrt{g \times I + r^2}}{g}$$

This is the most "legitimate" (mathematically justified) rejection criteria, and is suitable when you haven't mucked around (subtracted sky, or averaged or summed frames) with the data.

- **ccdclip** With this rejection algorithm, we first guess I at a given pixel by taking the median (**mclip=yes**), computing the expected spread in ADU's based upon this value and the specified values of the gain (*gain*) and read-noise (*rdnoise*), and then rejecting any points that are more than *lsigma* below that median or *hsigma* above that median. The process is iterated until no more values are rejected at a given pixel.

- **crreject** This is identical to **ccdclip**, except that low pixels are ignored and only high pixels are rejected.

Sigma determined empirically. Rather than determine the expected spread in our data values from the known characteristics of the CCD, we may want to make some attempt to determine the "expected" sigma based upon the data itself. Times that this might be useful would be if you have altered the data in some way, particularly by subtracting sky, say. The two primary schemes here are **sigclip** and **avsigclip**, whose effectiveness is determined by how many images you are attempting to combine.

- **sigclip** With this rejection algorithm, the median is first computed at each pixel value by first ignoring the low and high value. The sigma about this median is then determined using all the data values at this pixel. Next, the median is recomputed rejecting any data points that are *lsigma* or *hsigma* low or high. The sigma about this new median is computed as well as the new sigma, ignoring data values that were excluded in determining the median. The last two steps are repeated until no more data values are rejected. As you may guess, this works well if there are many (> 10) images.

- **avsigclip** This is a variant on the **sigclip** algorithm, and works well in the case that there are only a few images. It is also probably the hardest algorithm to understand or describe. Rather than compute the sigma from the spread in the data values at a given point, however, the algorithm assumes that the "expected" sigma is equal to the square-root of the median multiplied by some constant. (This would lead to determining the gain for a CCD in the ideal case, if there was no read-noise and the data had been unaltered.) As an extra twist, it determines this constant independently for each row of the data.

C Summary of Reduction Steps

Because examples are sometimes the easiest thing to refer to I am going to close this manual with an example of reducing a night of spectroscopic data (C.1) and an example of reducing a night of direct imaging data (C.2).

For either example we assume that the calibration exposures you have are:

- **biases (zero-second exposures)** Used to remove pre-flash illumination or any residual structure in the DC offset not removed by the over-scan region.

- **flat-field exposures** These are used to remove the pixel-to-pixel gain variations and possibly some of the lower-order wavelength-dependent sensitivity variations. Depending upon the instrument, these flat-field exposures may or may not do an adequate job of matching the illumination function along the slit (i.e., in the spatial direction).

- **twilight exposures** These are used to correct any mismatch between the flat-field exposure and the slit illumination function.

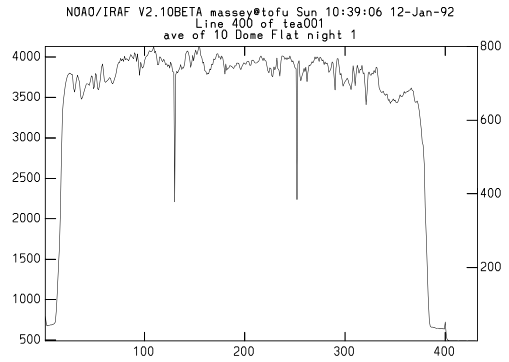


Figure 20: A line cut through this flat-field shows that the region containing good data extends from column 25 through 368. Expanding the region on the right shows that the overscan region is flat from columns 404 through 431. A plot of a column near the middle shows that the first few rows and last few rows are not of good quality, but that good data extends from lines 4 through 795.

C.1 Spectroscopic Example

The reduction steps for spectroscopic data will be dealt with in outline form, since we have used these data as the primary example through out this manual. The steps are as follows:

1. Examine a flatfield exposure using **implot** and determine the area of the chip that contains good data. Fig. 20 shows a sample cut through a chip that had been formated to $400 + 32$(overscan) $\times 800$. At the same time determine the columns where the overscan is flat. By expanding the plot and making a plot along a column near the middle, we conclude that the region containing good data is [25:368,4:795], and that the good region of the overscan is [404:431,4:795].

2. load **ccdred** and run **setinstrument specphot**. This will allow you to inspect the parameters for the **ccdred** package and the **ccdproc** task. Make sure that only *overscan*, *trim*, and *zerocor* are turned on. Insert the image section containing good data as "trimsec" and the image section containing the good overscan region as "biassec". Insert

the name “Zero” for the “zero” entry; this is the average bias frame that will be created in the next step.

3. Combine the bias frames:
   - **zerocombine *.imh output=Zero**

4. Process all the frames through **ccdproc** in order to remove the overscan, trim the image, and subtract off the average bias frame.
   - **ccdproc *.imh ccdtyp=“” overscan+ trim+ zerocor+ zero=Zero flatcor-**

5. Create a bad pixel mask and tuck it away for latter use. Let us assume that the long-exposure flats are in a0001-5, and the short-exposure flats are in a0006-19.
   (a) Combine the long-exposure flat-fields and the short-exposure flat-fields into two images:
      - **files a0001,a0002,a0003,a0004,a0005 ¿ flatlongs**
      - **files a0006,a0007,a0008,a0009,a001* ¿ flatshorts**
      - **flatcombine @flatlongs out=FlatL reject=crreject gain=“gain” rdnoise=“rdnoise” proc+**
      - **flatcombine @flatshorts out=FlatS reject=crreject gain=“gain” rdnoise=“rdnoise” proc+**
      - **imarith FlatL / FlatS Flatdiv**

   (b) Create the bad pixel map itself:
      - **nmisc**
      - **unlearn ccdmask**
      - **ccdmask Flatdiv mask=badmap**

   (c) Examine the images to see if all is as it should be:
      - **display FlatL 1**
      - **display Flatdiv 2**
      - **display badmap 3**

   (d) Get rid of the intermediate products and tuck the mask away where subsequent processing won't mess it up:

- **imdelete @flatlongs,@flatshorts,FlatL,FlatS,Flatdiv**
- **mkdir calib**
- **imrename badmap calib/badmap**

6. Create a perfect normalized, illumination corrected flat-field exposure.

   (a) Combine the flat-field exposures:

   - **flatcombine *.imh output=Flat combine=average reject=crreject gain=gain rdnoise="rdnoise" ccdtype=flat scale=mode proc+ subsets+**

   (b) Combine the twilight flats:

   - **combine** *sky1,sky2,sky3,sky4* **output=Sky ccdtype="" reject=avsigclip scale=mode proc+ subsets+ blank=1**

   (c) Fit a function in the dispersion direction to the combined flat-field using the routine **response** in the **twod.longslit** package:

   - **response Flat Flat nFlat intera+ thresho=INDEF sample=* naver=1 function=spline3 order=1 low_rej=3. high_reject=3. niterat=1. grow=0.**

   Up the order of the fit until you get something that looks good at the ends and more or less fits the shape of the flat. (See Fig. 21.) Alternatively, you may want to keep the order basically to a constant, (function=cheb order=1) if you believe that the wavelength dependence of the flat is mainly due to the instrument and not the lamps and projector screen.

   (d) Process the averaged twilight flat *Sky* through **ccdproc**, this time using the normalized flat-field exposure *nFlat* as the flat:

   - **ccdproc Sky ccdtype="" flatcor+ flat="nFlat"**

   (e) Decide how well the twilight flats and dome flats agreed: is a plot of the now "flattened" image *Sky* flat in the spatial direction? Fig. 22 shows an example where there is a significant gradient from one side of the slit to the other. At this point it is worth plotting cuts along the spatial axis of the chip, to see if these gradients change with wavelength. In the data presented here we found there was a gradual change from the blue to the red.

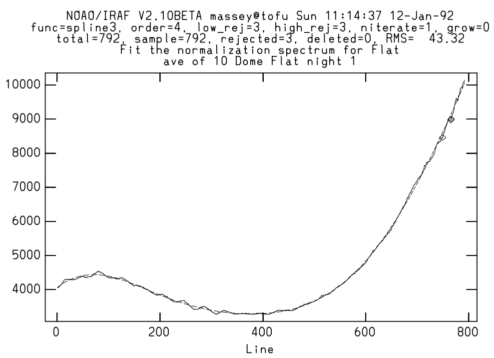


Figure 21: The fit from **response**.

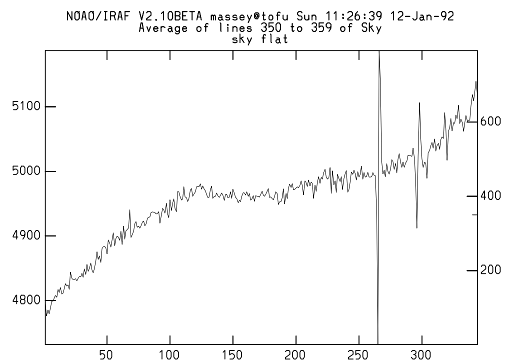


Figure 22: The number of counts in this "flattened" sky changes from 4780 on the left to 5110 on the right; this 7% gradient will lead to problems in sky subtraction if it is not removed.

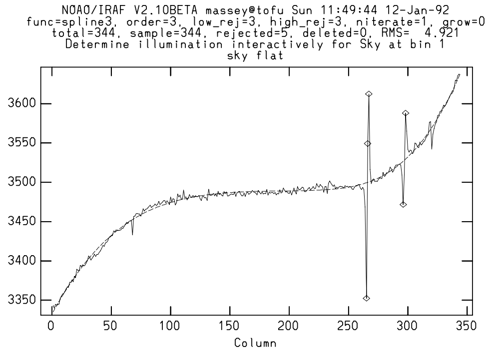


Figure 23: The fit along the spatial axis to the twilight sky exposure that has been "flattened" by the normalized dome-flat.

(f) If the previous step revealed some gradient, determine the correction for the slit function:

- **illum Sky nSky nbins=5 low_reject=3 high_reject=3**

Up the order of the fit until you get something reasonable; see Fig. 23.

(g) Having done this, we can now make the "perfect" flat:

- **imarith nFlat * nSky perfectFlat**

7. Process all of the rest of your data through **ccdproc** using *perfectFlat* for your flat:

   - **ccdproc *.imh flatcor+ flat="perfectFlat"**

8. Finally, interpolate over bad pixels:

   - nmisc (Note that there are several different "fixpix" routines; you must be in **nmisc** to be accessing the correct one!)
   - fixpix *.imh mask=badmap linterp=1 cinterp=2

The astute reader may have noticed that the outline for flat-fielding the spectroscopic data is a little bit different here than that given earlier in Sec. 3. In Sec. 3 (see outline in Sec. 3.1) a second-pass through **ccdproc** was used to flat-field all the data (including the twilight sky exposures) by the normalized (but not sky-corrected) flat. The flat-fielded twilight frames were then used to create an illumination correction image using **illum**. All the data was then run a third time through **ccdproc**, this time specifying an illumination correction. In the example given in the current section, however, we have done the illumination correction ourselves on the flat-field exposure; this decreases the number of passes through **ccdproc** from three to two. Both procedures are correct and will get you where you are going.

C.2 Direct Imaging Example

We will go through the direct imaging example in some detail, as throughout the rest of this manual we have used spectroscopic data to illustrate the steps. We show in Fig. 24 the list of images we wish to process. These are all data taken with the T2KA chip (a Tektronix 2048×2048 CCD) on the KPNO 0.9m, and kindly made available by A. Zabludoff.

Note that the images were taken in both the B and R filters, and that there are both dome-flats and twilight sky exposures taken through each filter, in addition to a hefty set of bias frames.

The reduction steps are as follows:

1. Examine a dome-flat exposure and substantiate that the BIASSEC and TRIMSEC values listed in the header are suitable. Fig. 25 shows that the header suggests the overscan to be taken from the image section [2051:2080,1:2048] and the region of the chip containing useful data is [1:2046,1:2048] (i.e., only the last two columns are a little dicey.) The plots from **implot** confirm that these are reasonable. (The first row is a little bit "hot", but we decide to live with it.)

2. Load **ccdred** and run **setinstrument direct** (Fig. 26). We decide to set **pixeltype= short real** to retain 16-bit output images, but to do the arithmetic in floating-point. A CNTL-Z then shows us the parameters of **ccdproc**. We make sure that ony *overscan*, *trim*, and *zerocor* are turned on, and we insert the name "Zeron3" for the "zero" entry. This is the name we will use when we create the average bias frame below. We also specify that "all" image types will be processed (rather than just "object", the default, by setting **ccdtype=""**.

```
c0001.imh[2080,2048][short]: bias 3rd afternoon
c0002.imh[2080,2048][short]: bias 3rd afternoon
c0003.imh[2080,2048][short]: bias 3rd afternoon
c0004.imh[2080,2048][short]: bias 3rd afternoon
c0005.imh[2080,2048][short]: bias 3rd afternoon
c0006.imh[2080,2048][short]: bias 3rd afternoon
c0007.imh[2080,2048][short]: bias 3rd afternoon
c0008.imh[2080,2048][short]: bias 3rd afternoon
c0009.imh[2080,2048][short]: bias 3rd afternoon
c0010.imh[2080,2048][short]: bias 3rd afternoon
c0011.imh[2080,2048][short]: bias 3rd afternoon
c0012.imh[2080,2048][short]: bias 3rd afternoon
c0013.imh[2080,2048][short]: bias 3rd afternoon
c0014.imh[2080,2048][short]: domeR 3rd afternoon
c0015.imh[2080,2048][short]: domeR 3rd afternoon
c0016.imh[2080,2048][short]: domeR 3rd afternoon
c0017.imh[2080,2048][short]: domeR 3rd afternoon
c0018.imh[2080,2048][short]: domeB 3rd afternoon
c0019.imh[2080,2048][short]: domeB 3rd afternoon
c0020.imh[2080,2048][short]: domeB 3rd afternoon
c0021.imh[2080,2048][short]: domeB 3rd afternoon
c0022.imh[2080,2048][short]: skyB 3rd night
c0023.imh[2080,2048][short]: skyB 3rd night
c0024.imh[2080,2048][short]: skyB 3rd night
c0025.imh[2080,2048][short]: skyB 3rd night
c0026.imh[2080,2048][short]: 100_280R
c0027.imh[2080,2048][short]: 100_280R
c0028.imh[2080,2048][short]: 100_280B
c0029.imh[2080,2048][short]: G163_50
c0030.imh[2080,2048][short]: G163_50B
c0031.imh[2080,2048][short]: 106_1024R
c0032.imh[2080,2048][short]: 106_1024B
c0033.imh[2080,2048][short]: A957B
c0034.imh[2080,2048][short]: A1213R
c0035.imh[2080,2048][short]: A1213B
c0036.imh[2080,2048][short]: N4472R
c0037.imh[2080,2048][short]: A1228B
c0038.imh[2080,2048][short]: A1541B
c0040.imh[2080,2048][short]: A1837R
c0041.imh[2080,2048][short]: A1837B
c0042.imh[2080,2048][short]: 106_1024R
c0043.imh[2080,2048][short]: 106_1024B
c0044.imh[2080,2048][short]: 104_598B
c0045.imh[2080,2048][short]: 104_598R
c0046.imh[2080,2048][short]: 108_475R
c0047.imh[2080,2048][short]: 108_475B
c0048.imh[2080,2048][short]: A1656R
c0049.imh[2080,2048][short]: A1656B
c0050.imh[2080,2048][short]: A1656B
c0064.imh[2080,2048][short]: MASS31
c0065.imh[2080,2048][short]: A2199IVR
c0066.imh[2080,2048][short]: 108_475R
c0067.imh[2080,2048][short]: 108_475B
c0068.imh[2080,2048][short]: 110_450B
c0069.imh[2080,2048][short]: 110_450R
c0070.imh[2080,2048][short]: skyR 3rd morning
c0071.imh[2080,2048][short]: skyR 3rd morning
c0072.imh[2080,2048][short]: skyR 3rd morning
c0073.imh[2080,2048][short]: skyR 3rd morning
c0074.imh[2080,2048][short]: skyR 3rd morning
c0075.imh[2080,2048][short]: skyR 3rd morning
c0076.imh[2080,2048][short]: skyR 3rd morning
c0077.imh[2080,2048][short]: skyR 3rd morning
c0078.imh[2080,2048][short]: skyR 3rd morning
```

Figure 24: The direct images we will reduce.

```
c0020[2080,2048][short]: domeB 3rd afternoon
    No bad pixels, no histogram, min=723., max=9356.
    Line storage mode, physdim [2304,2048], length of user area 1337 s.u.
    Created Thu 08:54:05 28-May-92, Last modified Thu 08:54:07 28-May-92
    Pixel file 'tofu!/data1/massey/pixels/c0020aa.pix' [ok]
    'KPNO-IRAF'           /
    '07-05-92'            /
    IRAF-MAX=           9.356000E3  /  DATA MAX
    IRAF-MIN=           7.230000E2  /  DATA MIN
    IRAF-BPX=                   16  /  DATA BITS/PIXEL
    IRAFTYPE= 'SHORT   '            /  PIXEL TYPE
    OBSERVAT= 'KPNO              '  /  observatory
    OBSERVER= 'Zabludoff         '  /  observers
    EXPTIME =                  10.  /  actual integration time
    DARKTIME=                  10.  /  total elapsed time
    IMAGETYP= 'flat              '  /  object, dark, bias, etc.
    DATE-OBS= '07/05/92          '  /  date (dd/mm/yy) of obs.
    UT      = ' 0:13:45.00'         /  universal time
    ST      = ' 7:47:45.00'         /  sidereal time
    RA      = ' 4:19:45.00'         /  right ascension
    DEC     = '13:00:00.00'         /  declination
    EPOCH   =               1992.3  /  epoch of ra and dec
    ZD      = '51.180            '  /  zenith distance
    AIRMASS =                  1.6  /  airmass
    TELESCOP= 'kp09m             '  /  telescope name
    DETECTOR= 't2ka              '  /  detector
    PREFLASH=                    0  /  preflash time, seconds
    GAIN    =                  4.2  /  gain, electrons per adu
    DWELL   =                    5  /  sample integration time
    RDNOISE =                   4.  /  read noise, electrons per adu
    CAMTEMP =                  -96  /  camera temperature
    DEWTEMP =                 -156  /  dewar temperature
    BIASSEC = '[2051:2080,1:2048]'  /  overscan portion of frame
    TRIMSEC = '[1:2046,1:2048]   '  /  region to be extracted
    DATASEC = '[1:2048,1:2048]   '  /  image portion of frame
    CCDSEC  = '[1:2048,1:2048]   '  /  orientation to full frame
    ORIGSEC = '[1:2048,1:2048]   '  /  original size full frame
    CCDSUM  = '1 1               '  /  on chip summation
    INSTRUME= 'test              '  /  instrument
    FILTERS = '1                 '  /  filter position
```

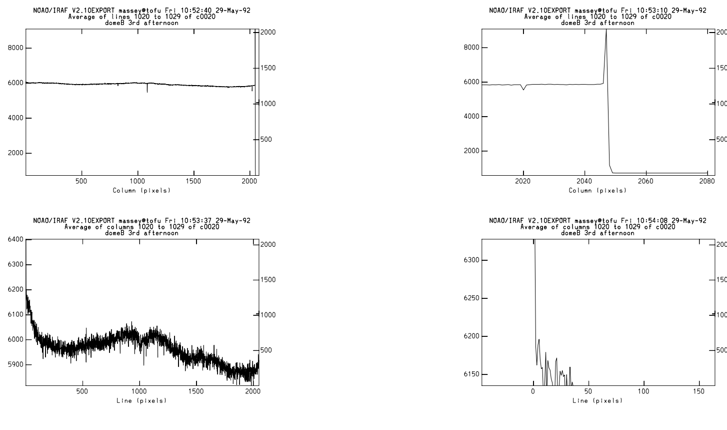


Figure 25: The bias and trim parameters in the header are confirmed to be reasonable by **implot**ing a dome-flat exposure.

```
setinstrument direct

PACKAGE = imred
   TASK = ccdred

(pixelty=          short real) Output and calculation pixel datatypes
(verbose=                 yes) Print log information to the standard output?
(logfile=             logfile) Text log file
(plotfil=                    ) Log metacode plot file
(backup =                    ) Backup directory or prefix
(instrum= ccddb$kpno/direct.dat) CCD instrument file
(ssfile =             subsets) Subset translation file
(graphic=            stdgraph) Interactive graphics output device
(cursor =                    ) Graphics cursor input
(version=     2: October 1987)
(mode   =                  ql)
($nargs =                   0)

(CNTL-Z)

PACKAGE = ccdred
   TASK = ccdproc

images  =                      List of CCD images to correct
(ccdtype=                    ) CCD image type to correct
(max_cac=                   0) Maximum image caching memory (in Mbytes)
(noproc =                  no) List processing steps only?

(fixpix =                  no) Fix bad CCD lines and columns?
(oversca=                 yes) Apply overscan strip correction?
(trim   =                 yes) Trim the image?
(zerocor=                 yes) Apply zero level correction?
(darkcor=                  no) Apply dark count correction?
(flatcor=                  no) Apply flat field correction?
(illumco=                  no) Apply illumination correction?
(fringec=                  no) Apply fringe correction?
(readcor=                  no) Convert zero level image to readout correction?
(scancor=                  no) Convert flat field image to scan correction?

(readaxi=                line) Read out axis (column|line)
(fixfile=                    ) File describing the bad lines and columns
(biassec=               image) Overscan strip image section
(trimsec=               image) Trim data section
(zero   =              Zeron3) Zero level calibration image
(dark   =                    ) Dark count calibration image
(flat   =                    ) Flat field images
(illum  =                    ) Illumination correction images
(fringe =                    ) Fringe correction images
(minrepl=                  1.) Minimum flat field value
(scantyp=           shortscan) Scan type (shortscan|longscan)
(nscan  =                   1) Number of short scan lines

(interac=                 yes) Fit overscan interactively?
(functio=           chebyshev) Fitting function
(order  =                   1) Number of polynomial terms or spline pieces
(sample =                   *) Sample points to fit
(naverag=                   1) Number of sample points to combine
(niterat=                   1) Number of rejection iterations
(low_rej=                  3.) Low sigma rejection factor
(high_re=                  3.) High sigma rejection factor
(grow   =                  0.) Rejection growing radius
(mode   =                  ql)

(CNTL-Z)
```

Figure 26: Running **setinstrument direct** allows us to specify that we would like the output images to be 16-bit integers ("short") but to retain "real" for the calculation type; we also turn **flatcor=no** and specify the image name "Zeron3" for the name of the average bias frame (**zero=Zeron3**).

3. Run **ccdlist *.imh** to substantiate that the type of object is correct ("zero", "object" or "flat") and that filter number is being picked up correctly. As can be seen in Fig. 27, the observer had taken her twilight exposures identifying them as "flat's". Since this will complicate how we plan to do the reductions, we change the twilight exposure types to "object" by doing a

   - **files c0022,c0023,c0024,c0025,c007* > skies**
   - **hedit @skies IMAGETYP "object" verify- show+ update+**

4. Combine the bias frames:

   - **zerocombine *.imh output=Zeron3**

   We see in Fig. 28 that the routine picked out the correct images to combine.

5. Next run all the frames through **ccdproc** in order to remove the overscan, trim the image, and subtract off the average bias frame:

   - **ccdproc *.imh ccdtype="" overscan+ trim+ zerocor+ zero=Zeron3 flatcor-**

   Although specifying ccdtype="" means we must sit through the processing of the 13 individual bias frames, it at least assures us that the flats are processed. We will see questions such as those shown in Fig. 29, and be confronted with a plot like that shown in the same figure. Note that we are leaving the order at 1 (scalar) despite the slight gradient; this will be taken out by the average bias frame. When we are satisfied that the overscan fitting is working fine, answer "NO" to the "Fit overscan... interactively?" question.

6. Combine the flat-field exposures:

   - **flatcombine *.imh reject=crreject gain=gain scale=mode rdnoise=rdnoise**

```
cc> ccdlist *.imh c0001.imh[2080,2048][short][zero][3]:bias 3rd afternoon
c0002.imh[2080,2048][short][zero][3]:bias 3rd afternoon
c0003.imh[2080,2048][short][zero][3]:bias 3rd afternoon
(more)
c0012.imh[2080,2048][short][zero][3]:bias 3rd afternoon
c0013.imh[2080,2048][short][zero][3]:bias 3rd afternoon
c0014.imh[2080,2048][short][flat][3]:domeR 3rd afternoon
c0015.imh[2080,2048][short][flat][3]:domeR 3rd afternoon
c0016.imh[2080,2048][short][flat][3]:domeR 3rd afternoon
c0017.imh[2080,2048][short][flat][3]:domeR 3rd afternoon
c0018.imh[2080,2048][short][flat][1]:domeB 3rd afternoon
c0019.imh[2080,2048][short][flat][1]:domeB 3rd afternoon
c0020.imh[2080,2048][short][flat][1]:domeB 3rd afternoon
c0021.imh[2080,2048][short][flat][1]:domeB 3rd afternoon
c0022.imh[2080,2048][short][flat][1]:skyB 3rd night
c0023.imh[2080,2048][short][flat][1]:skyB 3rd night
c0024.imh[2080,2048][short][flat][1]:skyB 3rd night
c0025.imh[2080,2048][short][flat][1]:skyB 3rd night
c0026.imh[2080,2048][short][object][3]:100_280R
c0027.imh[2080,2048][short][object][3]:100_280R
c0028.imh[2080,2048][short][object][1]:100_280B
c0029.imh[2080,2048][short][object][3]:G163_50
(more)
c0068.imh[2080,2048][short][object][1]:110_450B
c0069.imh[2080,2048][short][object][3]:110_450R
c0070.imh[2080,2048][short][flat][3]:skyR 3rd morning
c0071.imh[2080,2048][short][flat][3]:skyR 3rd morning
c0072.imh[2080,2048][short][flat][3]:skyR 3rd morning
c0073.imh[2080,2048][short][flat][3]:skyR 3rd morning
c0074.imh[2080,2048][short][flat][3]:skyR 3rd morning
c0075.imh[2080,2048][short][flat][3]:skyR 3rd morning
c0076.imh[2080,2048][short][flat][3]:skyR 3rd morning
c0077.imh[2080,2048][short][flat][3]:skyR 3rd morning
c0078.imh[2080,2048][short][flat][3]:skyR 3rd morning
cc>files c0022,c0023,c0024,c0025,c007* > skies
cc>hedit @skies IMAGETYP "object" verify- show+ update+
c0022,IMAGETYP: flat -> object
c0022 updated
c0023,IMAGETYP: flat -> object
c0023 updated
c0024,IMAGETYP: flat -> object
c0024 updated
c0025,IMAGETYP: flat -> object
c0025 updated
c0070.imh,IMAGETYP: flat -> object
c0070.imh updated
c0071.imh,IMAGETYP: flat -> object
(more)
cc> ccdlist c0070
c0070[2080,2048][short][object][3]:skyR 3rd morning
```

Figure 27: . Running **ccdlist** allows us to substantiate that the image types and filter numbers are being picked up correctly. We decide to change the imagetype of the twilight sky exposures to be that of “object” rather than “flat” using **hedit**, and then test that this worked by running **ccdlist** on one of them.

```
cc> zerocombine *.imh output=Zeron3

May 29 11:35: IMCOMBINE
  combine = average
  reject = minmax, nlow = 0, nhigh = 1
  blank = 0.
                Images
              c0001.imh
              c0002.imh
              c0003.imh
              c0004.imh
              c0005.imh
              c0006.imh
              c0007.imh
              c0008.imh
              c0009.imh
              c0010.imh
              c0011.imh
              c0012.imh
              c0013.imh

  Output image = Zeron3, ncombine = 13
```

Figure 28: Combining the bias exposures.

We can see from Fig. 30 that it combined the correct dome-flat exposures.

7. Flatten all the program and sky frames:

    - **ccdproc *.imh ccdtype="" flatcor+ flat=Flat***

    As shown in Fig. 31 the appropriate flat-field is matched with each program frame based upon the filter number.

8. Evaluate and do flattening correction if necessary:

    (a) Combine the twilight or blank-sky exposures:

        - **combine c0022,c0023,c0024,c0025,c007* Sky subset+ scale=mode weight=mode reject=crreject gain=gain rdnoise=rdnoise**
        - Examine the combined images to make sure that stars have been filtered out. (See Figs. 32 and 33.)

```
cc>ccdproc *.imh ccdtype="" overscan+ trim+ zerocor+ flatcor- zero=Zeron3
Zeron3.imh: May 29 14:29 Trim data section is [1:2046,1:2048]
Fit overscan vector for Zeron3.imh interactively (yes):
Zeron3.imh: May 29 14:29 Overscan section is [2051:2080,1:2048] with mean=746.4677
c0001.imh: May 29 14:29 Trim data section is [1:2046,1:2048]
Fit overscan vector for c0001.imh interactively (yes):
c0001.imh: May 29 14:32 Overscan section is [2051:2080,1:2048] with mean=746.5007
c0002.imh: May 29 14:32 Trim data section is [1:2046,1:2048]
Fit overscan vector for c0002.imh interactively (yes): NO
c0002.imh: May 29 14:33 Overscan section is [2051:2080,1:2048] with mean=747.1658
c0003.imh: May 29 14:33 Trim data section is [1:2046,1:2048]
c0003.imh: May 29 14:33 Overscan section is [2051:2080,1:2048] with mean=747.2908
(more)
```

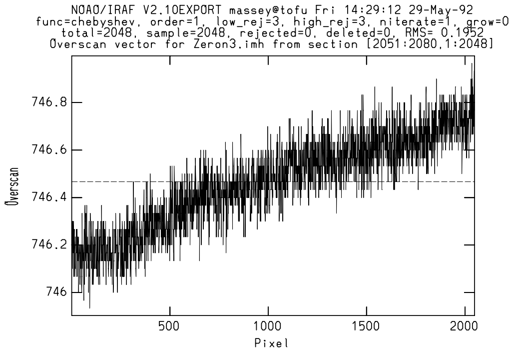


Figure 29: Making the first pass through **ccdproc** in order to subtract the overscan, trim the images, and subtract off the average bias.

```
cc>latcombine *.imh reject=crreject gain=gain rdnoise=rdnoise

Jun  2  8:14: IMCOMBINE
  combine = average
  reject = crreject, mclip = yes, rdnoise = rdnoise, gain = gain, hsigma = 3.
  blank = 0.
                Images    Mode Rdnoise   Gain  Scale
              c0014.imh  7854.      4.    4.2  0.988
              c0015.imh  7724.      4.    4.2  1.004
              c0016.imh  7854.      4.    4.2  0.988
              c0017.imh  7602.      4.    4.2  1.021

  Output image = Flat3, ncombine = 4

Jun  2  8:17: IMCOMBINE
  combine = average
  reject = crreject, mclip = yes, rdnoise = rdnoise, gain = gain, hsigma = 3.
  blank = 0.
                Images    Mode Rdnoise   Gain  Scale
              c0018.imh  5436.      4.    4.2  0.985
              c0019.imh  5377.      4.    4.2  0.996
              c0020.imh  5205.      4.    4.2  1.028
              c0021.imh  5394.      4.    4.2  0.992

  Output image = Flat1, ncombine = 4
```

Figure 30: The B (filter=1) and R (filter=3) dome-flat exposures are combined separately by **flatcombine**, with the final flats called **Flat1** and **Flat3**, respectively.

```
cc> ccdproc *.imh ccdtype="" flatcor+ flat=Flat*
c0022.imh: Jun  2  8:35 Flat field image is Flat1.imh with scale=5297.933
c0023.imh: Jun  2  8:36 Flat field image is Flat1.imh with scale=5297.933
c0024.imh: Jun  2  8:36 Flat field image is Flat1.imh with scale=5297.933
c0025.imh: Jun  2  8:36 Flat field image is Flat1.imh with scale=5297.933
c0026.imh: Jun  2  8:37 Flat field image is Flat3.imh with scale=7755.521
c0027.imh: Jun  2  8:37 Flat field image is Flat3.imh with scale=7755.521
c0028.imh: Jun  2  8:38 Flat field image is Flat1.imh with scale=5297.933
c0029.imh: Jun  2  8:38 Flat field image is Flat3.imh with scale=7755.521
c0030.imh: Jun  2  8:39 Flat field image is Flat1.imh with scale=5297.933
c0031.imh: Jun  2  8:39 Flat field image is Flat3.imh with scale=7755.521
c0032.imh: Jun  2  8:40 Flat field image is Flat1.imh with scale=5297.933
c0033.imh: Jun  2  8:40 Flat field image is Flat1.imh with scale=5297.933
c0034.imh: Jun  2  8:41 Flat field image is Flat3.imh with scale=7755.521
c0035.imh: Jun  2  8:41 Flat field image is Flat1.imh with scale=5297.933
c0036.imh: Jun  2  8:42 Flat field image is Flat3.imh with scale=7755.521
c0037.imh: Jun  2  8:42 Flat field image is Flat1.imh with scale=5297.933
c0038.imh: Jun  2  8:43 Flat field image is Flat1.imh with scale=5297.933
c0040.imh: Jun  2  8:43 Flat field image is Flat3.imh with scale=7755.521
c0041.imh: Jun  2  8:43 Flat field image is Flat1.imh with scale=5297.933
c0042.imh: Jun  2  8:44 Flat field image is Flat3.imh with scale=7755.521
c0043.imh: Jun  2  8:44 Flat field image is Flat1.imh with scale=5297.933
c0044.imh: Jun  2  8:45 Flat field image is Flat1.imh with scale=5297.933
c0045.imh: Jun  2  8:45 Flat field image is Flat3.imh with scale=7755.521
c0046.imh: Jun  2  8:46 Flat field image is Flat3.imh with scale=7755.521
c0047.imh: Jun  2  8:46 Flat field image is Flat1.imh with scale=5297.933
c0048.imh: Jun  2  8:47 Flat field image is Flat3.imh with scale=7755.521
c0049.imh: Jun  2  8:47 Flat field image is Flat1.imh with scale=5297.933
c0050.imh: Jun  2  8:48 Flat field image is Flat1.imh with scale=5297.933
c0064.imh: Jun  2  8:48 Flat field image is Flat3.imh with scale=7755.521
c0065.imh: Jun  2  8:49 Flat field image is Flat3.imh with scale=7755.521
(more)
```

Figure 31: The correct flat is chosen for each program frame based upon the filter number.

```
cc> combine c0022,c0023,c0024,c0025,c007* Sky subset+ scale=mode
                  weight=mode reject=crreject gain=gain rdnoise=rdnoise

Jun  2  9:00: IMCOMBINE
  combine = average
  reject = crreject, mclip = yes, rdnoise = rdnoise, gain = gain, hsigma = 3.
  blank = 0.
                Images     Exp   Mode Rdnoise   Gain  Scale Weight
                  c0022    1.0  2671.      4.    4.2  1.664  0.196
                  c0023    3.0  3919.      4.    4.2  1.134  0.237
                  c0024   10.0  6090.      4.    4.2  0.730  0.296
                  c0025   20.0  5099.      4.    4.2  0.872  0.271

  Output image = Sky1, ncombine = 4

Jun  2  9:05: IMCOMBINE
  combine = average
  reject = crreject, mclip = yes, rdnoise = rdnoise, gain = gain, hsigma = 3.
  blank = 0.
                Images     Exp   Mode Rdnoise   Gain  Scale Weight
              c0070.imh   30.0   177.      4.    4.2 34.711  0.023
              c0071.imh   30.0   272.      4.    4.2 22.588  0.029
              c0072.imh   30.0   520.      4.    4.2 11.815  0.040
              c0073.imh   30.0  1111.      4.    4.2  5.530  0.058
              c0074.imh   30.0  2606.      4.    4.2  2.358  0.089
              c0075.imh   30.0  6391.      4.    4.2  0.961  0.139
              c0076.imh   30.0 16212.      4.    4.2  0.379  0.221
              c0077.imh   15.0 19611.      4.    4.2  0.313  0.243
              c0078.imh    3.0  8395.      4.    4.2  0.732  0.159

  Output image = Sky3, ncombine = 9
```

Figure 32: Combining the sky exposures.

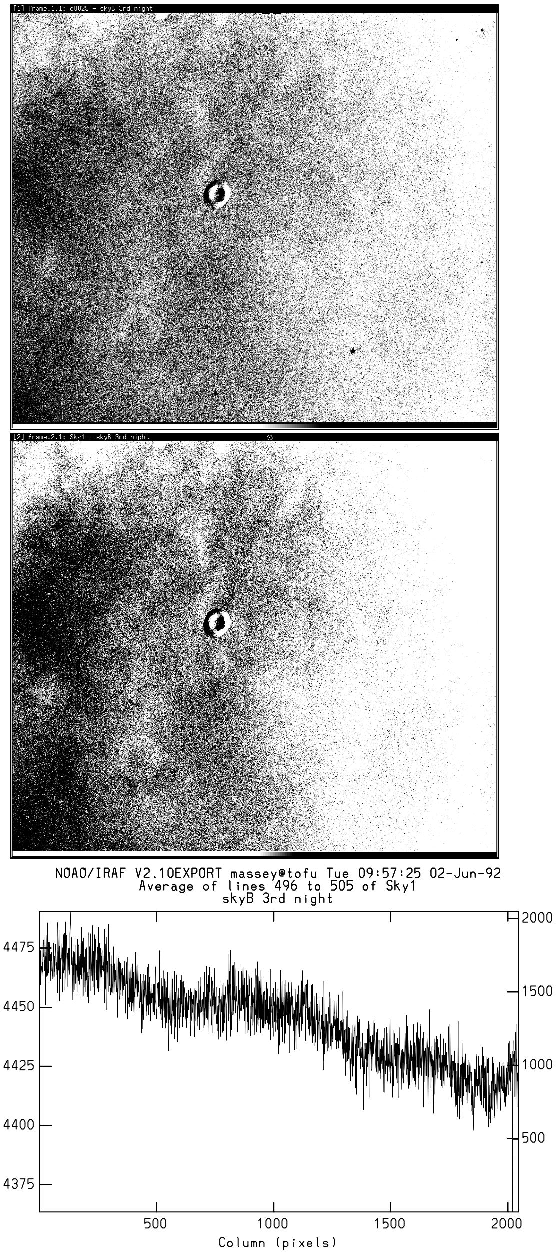


Figure 33: The image at the top is one of the individual sky exposures; the image in the middle is the final combined exposure. Note that the stars have disappeared in doing the combining, but also noticed that this flat-fielded twilight exposure shows a large residual donut near the center, and a gradient from left-to-right that is $\approx 1\%$.

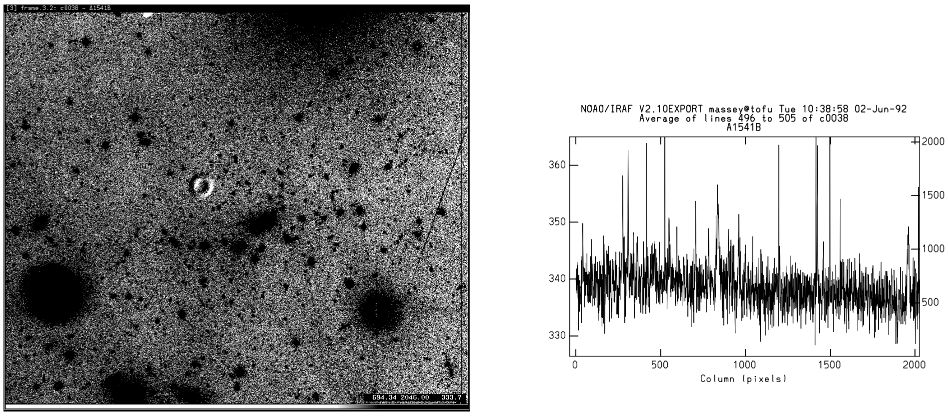


Figure 34: The top figure sures the flat-fielded program frame. Compare to the previous figure and one sees that the gradient from right to left is similar to that shown in the flat-fielded twilight exposure. The plot in the middle shows that the gradient, although harder to see, is of similar amplitude (4/335, or about 1%).

(b) Examine the longest program exposure (or exposure with the most sky) in each filter. Are there signs of any large-scale gradients left by the flat-fielding? We show in Fig. 34 that there *are* some indications of a problem: the large residual dust speck is there, and the frame *is* a little bit lighter on the right than on the left. Using **implot** to examine the same lines as on the sky exposure confirms that the gradient is also of the same order as before (i.e., 1%), although it is harder to make this out given the smaller number of counts.

(c) Having found that the twilight-flats would have done a better job of flattening our data than the dome flats (although the latter were not bad), we would like to be able to correct for this large scale gradient. How to proceed depends upon what sort of correction data you have:

- If you had "blank-sky" exposures, with few counts, you would want to first smooth the flat-fielded sky exposures. In this case we would do:
  - **files Sky*.imh > Skies**

- **mkskycor @Skies n//@Skies** This will produce images called **nSky1** and **nSky3** in this case which are smoothed versions of the sky.
- **ccdproc *.imh illumcor+ illum=nSky*** This will apply the smoothed sky exposures to each of the frames as an illumination correction.

- However, in the case here with well-exposed twilight sky frames, we have plenty of counts, and have no need to smooth. In fact, smooth would remove the residual "donut", making it impossible to remove from the sky exposures. Instead, what we would like to do is to go back and perform the equivalent of simply "redoing" the flat-fielding. We can do this by cheating every so slightly:
  - **hedit Sky*.imh MKILLUM "fake" add+ ver- show+** This will add the keyword "MKILLUM" to the Sky image headers.
  - **ccdproc *.imh illumcor+ illum=Sky*** This will now use the combined, flat-fielded twilight sky exposures as if they were an illumination correction.

  Note that had we realized that the twilight flats were more suitable as flat-fields than the dome-flats we could simply have skipped using the dome-flats entirely. The next night we might choose to alter the procedure by simply declaring the sky exposures as the flat-field images. (Note they must be of type "FLAT", though!)

We show in Fig. 35 the same program frame now corrected by using the twilight flat. The residual donut is gone, and the sky is nice and uniform. Enjoy!

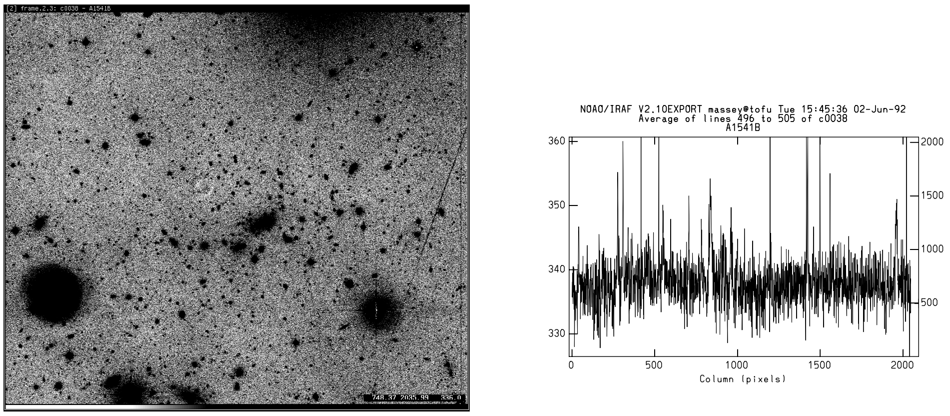


Figure 35: We see here that the residual donut is nearly eaten, and that the slight gradient previously present is gone.