SC/5.3

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Starlink Cookbook 5.3

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The 2-D CCD Data Reduction Cookbook

Abstract

This cookbook presents simple recipes and scripts for reducing direct images acquired with optical CCD detectors. Using these recipes and scripts you can correct un-processed images obtained from CCDs for various instrumental effects to retrieve an accurate picture of the field of sky observed. The recipes and scripts use standard software available at all Starlink sites.

The topics covered include: creating and applying bias and flat-field corrections, registering frames and creating a stack or mosaic of registered frames. Related auxiliary tasks, such as converting between different data formats, displaying images and calculating image statistics are also presented.

In addition to the recipes and scripts, sufficient background material is presented to explain the procedures and techniques used. The treatment is deliberately practical rather than theoretical, in keeping with the aim of providing advice on the actual reduction of observations. Additional material outlines some of the differences between using conventional optical CCDs and the similar arrays used to observe at infrared wavelengths.

Who Should Read this Cookbook?

This cookbook is aimed firmly at people who are new to reducing CCD observations. Typical readers might have a set of CCD observations to reduce (perhaps for the first time) or be planning to observe with a CCD camera. No prior knowledge of CCD data reduction is assumed.

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Revision history

(1) 17th March 1997: Version 1. Original version (GJP).

(2) 8th June 1999: Version 2. Added material for infrared arrays and the section describing the processing of large images (contributed by MBT). Also revised and re-arranged much of the existing material (ACD).

(3) 16th August 2001: Version 3. A few minor changes. Added an additional label to allow external hyper-links to the section on the FITS format. Also revised the references and URLs (ACD).

1 Introduction

> What are the roots that clutch, what branches grow
> Out of this stony rubbish? Son of man,
> You cannot say, or guess, for you know only
> A heap of broken images
>
> *The Waste Land*,
> T.S. Eliot, 1922.

Two-dimensional optical CCDs (Charge-Couple Devices) and the infrared arrays which are their close kin are now the type of detectors usually used to produce direct astronomical images (that is, simple pictures of a region of sky) at optical and infrared wavelengths. These arrays are much more sensitive and have a much larger useful dynamic range than the panoramic detectors used hitherto (principally the photographic plate) and it is hardly an overstatement to say that their widespread adoption in the past two decades has effected a revolution in astronomy. However, the un-processed images, as they are obtained from CCDs, are affected by a number of instrumental effects which must be corrected before useful results can be obtained. This cookbook is concerned with removing these instrumental effects in order to recover an accurate picture of the field of sky observed. This process is normally called 'CCD data reduction' though, figuratively at least, it can just as well be thought of as repairing a 'heap of broken images'.

The cookbook is primarily concerned with reducing direct images observed with optical CCDs. However, it contains additional material covering reducing direct images obtained with infrared arrays. Also, much of the material is relevant for reducing spectra recorded with two-dimensional CCDs or infrared arrays: the preliminary stages of reducing CCD spectra are the same as those for reducing direct images. The techniques for reducing CCD data are now well established and suitable software is readily available. However, the procedures must be applied with care if accurate results are to be obtained.

The cookbook includes a set of recipes for reducing CCD data and a set of scripts which automate some parts of the process. It also presents sufficient background material to allow you to use the recipes and scripts effectively. No prior knowledge of CCD data reduction is assumed. The structure of the cookbook is:

Part I – background material,

Part II – the recipes,

Part III – the scripts.

It is not necessary to read the cookbook sequentially from beginning to end. If you are already familiar with the principles of CCD data reduction you can simply skip Part I and go straight to the recipes or scripts. Similarly, you do not need to follow all the recipes or use all the scripts: just try the ones appropriate for your purposes.

The final product of CCD data reduction is an image which accurately reproduces the brightness distribution in the field of sky observed (subject to the limits on spatial resolution imposed by atmospheric seeing and the instrumental profile, of course). This image is in entirely arbitrary units. Such images are adequate for some sorts of programme (for example, for comparing the surface brightness of different parts of a nebula or galaxy). However, for other sorts of programme you will need to calibrate the arbitrary brightness of objects in the image into a known photometric system. This calibration (which can be quite involved) is beyond the scope of this cookbook, but is covered in the companion document SC/6: *The CCD Photometric Calibration Cookbook*[26]. It is not considered further here.

2 Further Reading

The literature on the use of CCDs in astronomy is extensive. However, there are several articles and books which provide convenient and accessible introductions. The articles by Newberry[23, 24, 25] in the amateur astronomy magazine *CCD Astronomy* are a straightforward, accessible and readable introduction to CCD data reduction techniques. The documentation included on the CD-ROM *Astronomical Images* by Jaffe[14] includes a useful introduction to the instrumental effects present in CCD images and the data reduction techniques used to correct them (document *Reducing CCD Images* in file `reduce.ccd`). Both Newberry's and Jaffe's articles are good starting points for beginners.

McLean's *Electronic and Computer-Aided Astronomy*[19] and the more recent *Electronic Imaging in Astronomy*[20] are, their titles notwithstanding, mostly about the construction and use of CCD instruments and, in the latter case, infrared arrays. *Electronic Imaging in Astronomy* is a particularly thorough, modern introduction to the subject.

Another useful book is *CCD Astronomy* by Buil[2]. The conference proceedings *Astronomical CCD Observing and Reduction Techniques*[13] contains several useful papers. In particular, the contribution 'CCD Data: the *Good*, the *Bad*, and the *Ugly*' by Massey and Jacoby[17] is an excellent introduction to the acquisition, processing and evaluation of CCD data. It is probably most useful if read before your observing trip. Brief descriptions of CCD techniques are included in Walker's *Astronomical Observations*[30], pp300-307 and in *Astrophysical Techniques*[16], pp20-30 by Kitchin.

A User's Guide to CCD Reductions with IRAF[18] describes the reduction of CCD data. It is particularly concerned with reducing observations using the IRAF software environment (see SG/12[22]). However, many of the techniques that it describes are equally applicable irrespective of whether you are using IRAF or some other software package. Finally, the glossary to SUN/139[10] (the manual for the CCDPACK package for processing CCD data) gives clear definitions of many of the technical terms used in CCD data reduction.

The Department of Physics at the University of Oregon provides a useful on-line introduction to the construction and use of CCDs at URL:

`http://zebu.uoregon.edu/ccd.html`

Finally, a word of warning: most of the uses of CCDs are not astronomical. Furthermore, the CCD chips used in astronomy are usually somewhat different to their non-astronomical kin. You should be aware of the existence of these differences if you read any non-astronomical literature about CCDs.

3 Typographic Conventions

Technical terms are shown in a **bold font like this** the first time that they are used. Also:

```
Anything that is to be typed into a computer program via the keyboard,
or output from one via the screen, is indicated by a ‘typewriter’ or
‘courier’ font like this.
```

However:

> items appearing in graphical windows, such as those used by GAIA or xreduce, are shown in a sans serif font like this.

Part I

Background Material

4 Overview of CCD Detectors

Before the introduction of photography to astronomy the only way of recording images of extended objects seen through a telescope was to sketch them. This approach worked moderately well for the planets, which are illuminated by reflected light, but was much less successful for nebulæ and other objects beyond the solar system, both because they are much fainter and because of the inherent difficulty in reproducing the gradations in brightness of an extended luminous object using drawing techniques. Photographic plates were first used to record images of regions of the sky around the middle of the nineteenth century. The techniques proved successful and photographic plates were ubiquitous in astronomy for more than a century. The advantages that they offered were basically threefold:

- unlike the eye they were an **integrating detector**: fainter objects could be detected by making longer exposures to accumulate more light,
- the images were objective and reproducible (unlike a sketch),
- the photographic image constituted a quantitative measure of the light distribution across the luminous object (at least in principle).

Nonetheless there were problems with photographic plates: they had only a limited dynamic range and their response to the brightness of the illuminating light was non-linear, leading to persistent calibration problems. In the middle years of the twentieth century **photoelectric photometers** were developed: electronic devices which were more sensitive, accurate, linear and had a wider dynamic range than the photographic plate. However, they were not imaging devices: they merely produced a single output corresponding to the brightness of one point on the sky.

In many ways CCDs (**Charge-Couple Devices**) combine the advantages of both photographic plates and photoelectric photometers, though their principles of operation are very different from either. They have a high sensitivity, linear response, large dynamic range and are imaging devices which record a picture of the region of sky being viewed. (Imaging devices are sometimes called, perhaps somewhat grandiloquently, **panoramic detectors**.)

The CCD was invented in 1969 by W.S. Boyle and G.E. Smith of the Bell Laboratory. They were not interested in astronomical detectors (and were, in fact, investigating techniques for possible use in a 'picture-phone'). Indeed, most of the applications of CCDs are not astronomical. CCDs were first used in astronomy in 1976 when J. Janesick and B. Smith obtained images of Jupiter, Saturn and Uranus using a CCD detector attached to the 61-inch telescope on Mt Bigelow in Arizona. CCDs were rapidly adopted in astronomy and are now ubiquitous: they are easily the most popular and widespread imaging devices used at optical and near infrared wavelengths.

A CCD is best described as a semiconductor chip, one face of which is sensitive to light (see Figure 1). The light sensitive face is rectangular in shape and subdivided into a grid of discrete

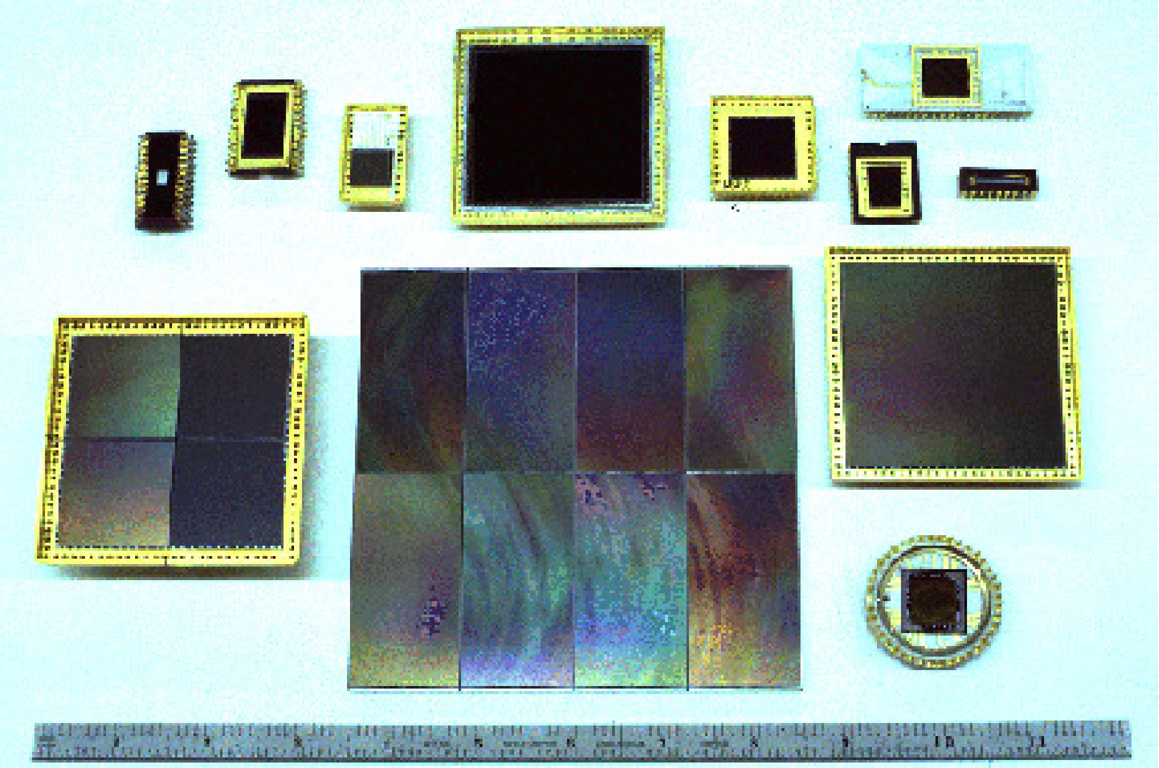


Figure 1: Examples of various CCD chips

rectangular areas (picture elements or **pixels**) each about 10-30 micron across. The CCD is placed in the focal plane of a telescope so the the light-sensitive surface is illuminated and an image of the field of sky being viewed forms on it. The arrival of a photon on a pixel generates a small electrical charge which is stored for later read-out. The size of the charge increases cumulatively as more photons strike the surface: the brighter the illumination the greater the charge. This description is the merest outline of a complicated and involved subject. For further details see some of the references in Section 2 or the web pages on CCD construction maintained by the University of Oregon. The CCD pixel grids are usually square and the number of pixels on each side often reflects the computer industry's predilection for powers of two. Early CCDs used in the 1970s often had 64×64 elements. 256×256 or 512×512-element chips were typical in the 1980s and 1024×1024 or 2048×2048-element chips are common now.

A CCD in isolation is just a semiconductor chip. In order to turn it into a usable astronomical instrument it needs to be connected to some electronics to power it, control it and read it out. By using a few clocking circuits, an amplifier and a fast analogue-to-digital converter (ADC), usually of 16-bit accuracy, it is possible to estimate the amount of light that has fallen onto each pixel by examining the amount of charge it has stored up. Thus, the charge which has accumulated in each pixel is converted into a number. This number is in arbitrary 'units' of so-called '**analogue data units**' (ADUs); that is, it is not yet calibrated into physical units. The **ADC factor** is the constant of proportionality to convert ADUs into the amount of charge (expressed as a number of electrons) stored in each pixel. This factor is needed during the data reduction and is usually included in the documentation for the instrument. The chip will usually be placed in an insulating flask and cooled (often with liquid nitrogen) to reduce the noise level and there will be the usual appurtenances of astronomical instruments: shutters, filter wheels *etc*. The whole instrument is often referred to as a **CCD camera**. Other synonyms sometimes encountered are **area photometer**, **panoramic photometer** or **array photometer**.

The electronics controlling the CCD chip are interfaced to a computer which in turn controls them. Thus, the images observed by the CCD are transferred directly to computer memory, with no intermediate analogue stage, whence they can be plotted on an image display device or written to magnetic disk or tape. Normally you will return from an observing run with a magnetic tape cartridge of some sort containing copies of the images that you observed.

4.1 Advantages and disadvantages of CCDs

The principal advantages of CCDs are their sensitivity, dynamic range and linearity. The sensitivity, or **quantum efficiency**, is simply the fraction of photons incident on the chip which are detected. It is common for CCDs to achieve a quantum efficiency of about 80%. Compare this figure with only a few percent for even sensitised photographic plates. CCDs are also sensitive to a broad range of wavelengths and are much more sensitive to red light than either photographic plates or the photomultiplier tubes used in photoelectric photometers (see Figure 2). However, they have a poor response to blue and ultra-violet light.

CCDs are sensitive to a wide range of light levels: a typical **dynamic range** (that is, the ratio of the brightest accurately detectable signal to the faintest) is about 10^5, corresponding to a range of about 14.5 magnitudes. The corresponding figures for a photographic plate are a range of less than about 1000 corresponding to 7.5 magnitudes. Furthermore, within this dynamic range the response is essentially linear: the size of the signal is simply proportional to the number of photons detected, which makes calibration straightforward.

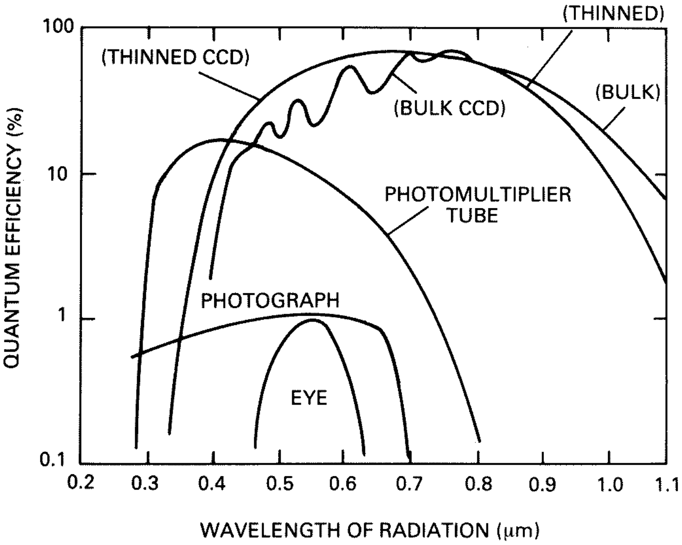


Figure 2: The sensitivity or quantum efficiency as a function of wavelength for various types of detectors. The quantum efficiency is simply the fraction of incident photons which are detected. Thinned and bulk CCDs are simply different types of CCDs. Photomultiplier tubes are used in photoelectric photometers. Note that the quantum efficiency is plotted on a logarithmic scale. Adapted from McLean[19, 20]

The principal disadvantage of CCDs is that they are physically small and consequently can image only a small region of sky. Typical sizes are 1.0 to 7.5 cm across, much smaller than photographic plates. There is a practical limit to the size of CCDs because of the time required to read them out. Thus, in order to image a large area of sky it is usual to place several chips in a grid (or **mosaic**) in the focal plane rather than fabricating a single enormous chip. The large CCD in the foreground in Figure 1 is actually a mosaic of eight chips.

4.2 Pixel size and field of view

In images observed close to the optical axis of a well-designed telescope an angular displacement on the sky is simply proportional to a linear displacement in position in the focal plane. The constant of proportionality is usually called the **plate scale** (a name which betrays its origin in photographic techniques) and is traditionally quoted in units of seconds of arc / mm. That is:

$$p = \Delta''/\Delta\mathrm{mm} \tag{1}$$

where p is the plate scale in seconds of arc / mm, Δ'' is a displacement on the sky in seconds of arc and Δmm is the corresponding displacement in the focal plane in mm. If you know the plate scale and the size of either a single pixel in the grid or the linear size of the CCD then it is trivial to use Equation 1 to work out either the angle on the sky subtended by a single pixel or the field of view of the CCD respectively. For example, the sample data used in Part II of the cookbook were obtained with the Jacobus Kapteyn Telescope (JKT) on La Palma. The CCD detector used has pixels which are 24×24 micron in size. The plate scale of the JKT is 13.8 seconds of arc / mm. Thus, each pixel subtends an angle of 0.331×0.331 seconds of arc on the sky.

The manual for the instrument or telescope that you are using will usually quote a value for the plate scale. However, if necessary it can be calculated from other parameters for the telescope. By simple geometry the plate scale is the reciprocal of the effective focal length of the system:

$$p' = 1/f \tag{2}$$

where f is the effective focal length of the system and p' is the plate scale in units of 'radians / whatever units f is in'. Thus, for f in metres and applying the factor for converting radians to seconds of arc:

$$p = 206.26/f \tag{3}$$

f is itself related to the diameter of the primary mirror, D, and the focal ratio, F:

$$f = F.D \tag{4}$$

At larger distances from the optical axis there is no longer a simple linear relation between angular displacement on the sky and displacement in position in the focal surface. That is, p varies as a function of position in the focal surface. This effect is usually not important in instruments containing a single chip because of the small size of individual CCDs. However it may be important if a grid of chips is used.

5 Instrumental Effects in CCD Detectors

The raw images returned by a CCD contain a number of instrumental effects which must be removed before the image can be used for scientific purposes. This section summarises some of these effects. It is largely based on the document *Reducing CCD Images* (file `reduce.ccd`) included on the CD-ROM *Astronomical Images* by Jaffe[14]. The instrumental effects are usually corrected by taking various sorts of calibration frames in addition to the images of the astronomical objects observed. In this cookbook the objects observed will be called **target objects** and the observations of them correspondingly called **target images** or **target frames**.

5.1 Bad pixels

Some of the pixels making up the light sensitive grid may be faulty and return signals which are grossly inaccurate. Such pixels are often referred to as being 'hot', 'cold' or '**bad**'. Because of the way that CCDs are read-out, in some circumstances a bad pixel will contaminate all the pixels in its row or column in the grid, leading to entire bad rows or columns. Fabrication techniques have improved markedly in recent years, though bad pixels are still regularly encountered.

The software to process CCD images must contain facilities to handle individual bad pixels, bad rows and bad columns. Typically it will either contain options to recognise and ignore them or to replace them with artificial but reasonable values, usually computed from neighbouring pixels.

5.2 Read-out signal; bias

Usually the amplifier which boosts the signal prior to its digitisation by the ADC will also generate an offset, false signal or **bias**, which is imposed in addition to the real signal generated by the illuminating light (there are sound reasons for doing this). This bias varies slightly with position on the chip, can vary slowly with time (though this is minimised if the chip is kept at a constant temperature) and inevitably has noise associated with it. There are two techniques for estimating and correcting the bias.

Bias strips Here the CCD controller software is written in such a way that the images generated contain regions (usually two narrow strips on either side of the chip) that are created by reading out the CCD without sampling any of its stored charge (see Figure 3). These regions are called **bias strips** or **overscan pixels**. The values of pixels within these strips consist only of the bias and its noise. Usually for each row in the image the pixels in the corresponding row of the bias strips are averaged and the resulting value is subtracted from all the pixels in the row. The bias strips serve no further purpose and can then be discarded, thus reducing the size of the images.

Bias frames Here the entire CCD array is read-out without sampling any stored charge (that is, no light is incident on the detector) so that any small scale structure in the noise is detected and can subsequently be corrected for. Such frames are called **bias frames**. In practice bias frames are acquired by taking short exposures with the shutter closed before or after each night of observing. Typically in order to reduce read-out noise several frames are taken and averaged. The resulting 'master' bias frame is then simply subtracted from the genuine image frames.

Which method is preferable depends on the quality and stability of the chip. If the chip and amplifier are stable during the observing session them observing separate bias frames is straightforward and gives satisfactory results. Conversely, using bias strips can be more convenient because you do not have to acquire, store and process separate bias frames. Of course, if the CCD controller software does not generate bias strips then you must use separate bias frames.

However you make the bias correction, you need to apply it to all the other frames acquired: target objects, flat fields (see below) *etc*. Often making the bias correction is the first stage of CCD data reduction.

5.3 Non-linearity

As mentioned above, CCD chips have a wide dynamic range within which their response is essentially linear. However, if the illuminating light is sufficiently bright the response will become non-linear and will ultimately saturate (that is, an increase in the intensity of the illumination produces no change in the recorded signal). In principle the response in the non-linear region can be calibrated. However, in practice, the onset of saturation is sufficiently rapid that it is more sensible to limit exposures to the linear region. In order to prevent saturation it is usual to a take a series of short exposures rather than a single long exposure of equivalent duration. The individual short exposures can then simply be added during the data reduction. This technique offers other advantages, for example in the detection and removal of cosmic-ray events (see below). Usually the documentation for the instrumentation that you are using will include the range of intensities over which the response is linear.

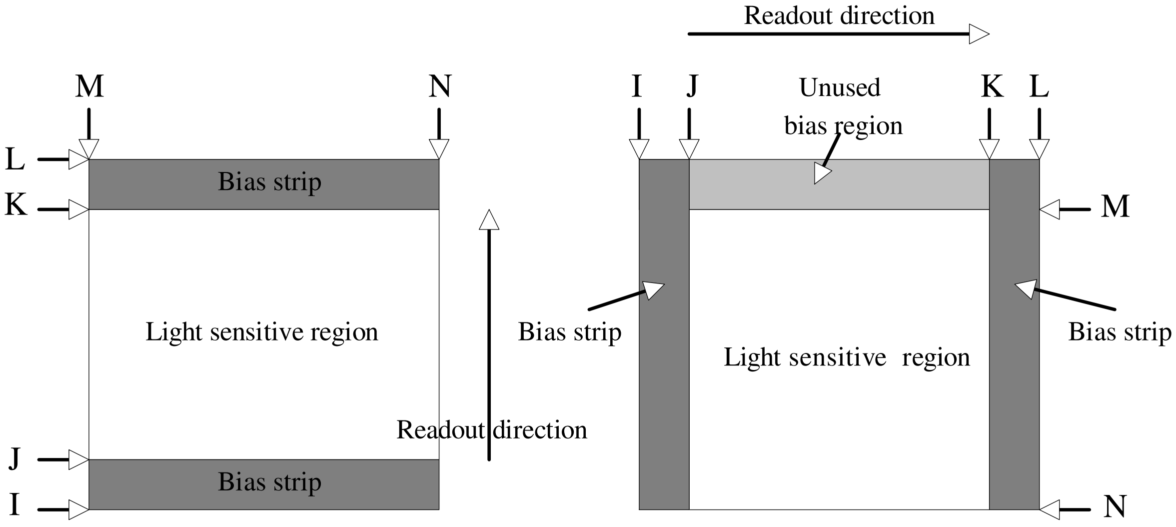


Figure 3: Typical CCD geometries. In the figure on the left the readout direction is ‘Y’, the bias strips are located with bounds I,J,K,L and the useful CCD area is M,J+1,N,K−1 (approximately; you should probably allow a gap of more than ±1 pixel between the bias and light-sensitive regions). In the figure on the right the readout direction is ‘X’, the bias strips are located with bounds I,J,K,L and the useful CCD area is N,J+1,K−1,M−1. (Note that some observatories recommend that you only use the left-hand strip; if you use the right-hand one too, check that it is not contaminated by residual charge)

5.4 Thermal noise; dark current

Another effect which is sometimes present is an offset from zero that is generated thermally within the CCD, even when no light is present. This offset is termed the **dark current** because it is present whether the shutter is open or closed. It varies somewhat from pixel to pixel and slowly with time (as long as the chip is kept at a constant temperature). It is usually minimised by cooling the CCD to the temperature of liquid nitrogen.

If necessary, the dark current can be measured by taking long exposures with the shutter closed, removing the bias, correcting for cosmic-ray events (see below) and dividing by the exposure time. The dark current response is then scaled to the exposure time of each target image and subtracted from the target image. However, the dark current is usually insignificant (and ignored) for visible light CCDs, but is important for infrared arrays.

5.5 Pixel sensitivity; flat fielding

Due to imperfections in the manufacturing process the sensitivity of the pixels will vary slightly (usually by a few percent) across the grid. This effect is essentially random, and is not a function of, for example, position on the grid. The relative sensitivities of the pixels can be calibrated by imaging an evenly illuminated source, such as the twilight sky, and examining the variation in values recorded. Once this calibration is known, astronomical images of the sky can be corrected to the values they would have had if all the pixels had been uniformly sensitive. This correction is known as **flat fielding** and images of evenly illuminated sources, such as the twilight sky, are known as **flat fields**. The pixel-to-pixel sensitivity variations change with wavelength, so the flat fields should always be acquired using the same filter as the observations of the target objects. The flat fielding procedure also corrects for several other effects:

- small sharp dark features with the same percentage absorption on all flat fields. These come from dust particles on the CCD chip,
- vague ring or torus-shaped features. These come from dust on the filters, which are out of focus as seen from the chip. They are the same on all exposures with the same filter, but obviously differ from filter to filter, and can differ from time to time,
- **vignetting**, the dimming of objects observed towards the edge of the telescope field of view. Vignetting is caused by various out-of-focus obstructions in the light path, such as the support for the secondary mirror.

Two types of flat fields are usually used: **dome flats** and **sky flats**. Brief details are as follows.

Dome flats are images of the inside of the telescope dome, illuminated by a bright continuum source free of emission lines. The interior surface of the dome is usually a smooth, diffuse reflector and is completely out of focus for the telescope optics. Consequently the image recorded is completely featureless. Dome flats are convenient because they can be taken in unlimited numbers during the day, rather than at night or during twilight when time is short. However, they have two disadvantages:

- light reflected from the dome is incident on the telescope at a slightly different angle to light from the sky. This difference does not affect the pixel-to-pixel sensitivity variations but can affect the vignetting and the shape of the images caused by dust particles,
- the colour (that is the wavelength distribution) of the lamp is not the same as that of the night sky. This effect is more important for observations made through a broad band filter than a narrow band one and can lead to fringing (see below).

Sky flats are images of the sky taken during twilight when it is relatively bright. The sky should be much brighter than any stars which happen to be in the field of view, but not bright enough to saturate the chip. The optimum time to acquire the flat field depends on the filter. A narrow filter, a filter corresponding to a wavelength for which the chip is insensitive, or to a wavelength range where the Sun emits little light (such as the *U* band), can be taken nearer to sunrise or sunset than a broadband filter at the peak of the chip's sensitivity. In an optimally exposed flat field the photon noise (see below) is negligible but the image is not saturated. However, it can sometimes be difficult to judge the exposure time correctly, particularly for frames acquired close to sunrise or sunset. Also, in such frames the interior of the dome is illuminated by sunlight and this light reaches the chip by internal reflections in the telescope. Thus sky flats show some of the vignetting and dust effects seen in dome flats. De-focussing the telescope to make any star images present less prominent is usually not viable because it may change the vignetting function.

An alternative to taking flat fields during twilight is to take then during the night. This approach is particularly common for infrared observations because at these wavelengths the sky is relatively bright.

It is possible to combine different sorts of flat fields to obtain the advantages of each. For example, you could use dome flats to correct pixel-to-pixel sensitivity variations and twilight flats to correct large-scale effects such as vignetting.

In outline, you use the flat fields to correct the target exposures as follows. Choose several correctly exposed flat fields, de-bias them and combine them into a single 'master' flat field. The de-biassed images of the target objects are simply divided by this master flat field. You should always calibrate target images using flat fields obtained through the same filter (that is, in the same colour) and on the same night. Flat fields acquired with a 16-bit camera should ideally have a mean pixel count which averages around 20,000 in order to allow high accuracy to be obtained.

5.5.1 Fringing

In the case of observations made through a narrow filter, or where the incident light contains a strong component at a single wavelength, multiple reflections within the CCD chip, or the filters in front of it, can cause wave-like patterns across the image. These patterns are called **fringes**. The precise pattern depends strongly on the exact wavelength of the illuminating light. Consequently, correcting for fringing requires a flat field whose wavelength corresponds closely to that of the image.

The emission from the night sky usually includes narrow emission lines originating in the terrestrial atmosphere. These lines will often fall within the bandwidths of broad band filters.

However, they are not present in the featureless spectra of dome flats. Consequently dome flats may not be appropriate when fringing due to night-sky lines is present.

The fringe pattern is an additive effect and must be subtracted. To remove fringes it is necessary to obtain several exposures of either a region of night sky containing no objects or, alternatively, remove all the contaminating objects from data frames which otherwise contain large areas of night sky. These frames should then be combined to give complete spatial coverage and to reduce the noise contribution. The resulting **fringe-frame** should be scaled to the fringes present in the data frame (after normalisation) and *subtracted*.

5.6 Cosmic-ray events

Astronomers usually refer to spurious signals in CCD frames caused by ionising radiation as **cosmic-ray hits** or **cosmic-ray events**. However, these terms are slightly misleading as the ionising events are as likely to be due to background terrestrial radiation as cosmic-rays. When a cosmic-ray particle hits a CCD pixel it causes an increase in charge which is indistinguishable from the arrival of photons. These spurious signals are usually (though not always) confined to a single pixel. Cosmic-ray hits appear as a set of pixels with intense values sparsely scattered over the CCD frame. Typically an exposure of a few minutes might have about a hundred cosmic-ray hits. The location of the hits within the chip is random. If several frames of the same target object or flat field have been acquired (for example to avoid saturation, see above) then the cosmic-ray hits will occur at different positions in each frame and it is possible to detect and remove them by comparing corresponding pixels in the different images and rejecting those with aberrantly large values.

5.7 Photon noise

The final, irreducible, source of noise is the **photon noise** due to the poissonian nature of counting photons. The error in the signal is proportional to the square root of the signal.

6 Reducing CCD Data

The previous section listed some of the instrumental effects which must be corrected during the reduction of CCD data. The reduction procedure is non-trivial and it must be carried out carefully if it is not to go awry. The various stages typically involved in CCD data reduction are:

(1) read your data from disk or tape,

(2) convert your data to a format compatible with your software,

(3) inspect the original images and discard those that are faulty,

(4) flag all the known faulty pixels as 'bad' or replace them with invented, reasonable values,

(5) create master bias and dark images for subsequent use in removing the dark and bias signal from raw images of target astronomical objects,

(6) for each filter, create a master flat field frame defining the pixel-to-pixel sensitivity variations and then flat field each of the images,

(7) for each filter, align and add the individual images of each target astronomical object to produce a master image of the object.

You would normally carry out the stages in the order listed, as you progress from copies of the raw images to reduced images. However, in some cases some of the stages can be omitted. The recipes given in Part II together constitute an example of working through these stages.

6.1 Software available

The principal Starlink software for reducing CCD images is CCDPACK (see SUN/139[10]). It provides extensive specialised facilities for reducing CCD data. A considerable advantage of CCDPACK is that it is optionally able to estimate and propagate an error estimate for each individual pixel in the CCD frames through the data reduction process. CCDPACK should be used in conjunction with the KAPPA package (see SUN/95[6]), which provides general image display, examination and processing facilities. KAPPA and CCDPACK are completely and seamlessly inter-operable and, indeed, intended to be used together. It is possible to make a reasonable attempt at reducing CCD data using KAPPA alone, though it is less convenient and gives less good results than CCDPACK.

The image processing and spectroscopy package Figaro (see SUN/86[27]) includes some facilities for reducing CCD data, though these are less comprehensive than CCDPACK. Again, Figaro is inter-operable with KAPPA and CCDPACK. In addition to CCDPACK, KAPPA and Figaro there are various other Starlink packages which are relevant to some aspects of CCD data reduction and CCD photometry. The various packages available, their uses and their inter-relations, are conveniently summarised in the 'Road-Map for CCD Photometry'[8] which has appeared in the *Starlink Bulletin*.

The IRAF software environment includes the powerful and extensive package CCDRED for reducing CCD data. The use of IRAF on Starlink systems is described in SG/12[22]. CCDRED is fully documented in:

- *User's Guide to the CCDRED Package* by F. Valdes[28],
- *The IRAF CCD Reduction Package – CCDRED* by F. Valdes[29].

Additional useful material may be found in:

- *A User's Guide to CCD Reductions with IRAF* by P. Massey[18],
- *Rectifying and Registering Images Using IRAF* by L.A. Wells[35],
- *Cleaning Images of Bad Pixels and Cosmic Rays Using IRAF* by L.A.Wells and D.J. Bell[36].

The early stages of reducing spectra recorded with CCD detectors are similar to those for direct images, though the later stages differ. There is a thorough and accessible introduction to reducing spectroscopic data in the cookbook SC/7: *Simple Spectroscopy Reductions*[3].

6.2 Data formats

Virtually any format might be used to initially write observations to magnetic disk following their acquisition at the telescope. The choice will simply be whatever is practical and convenient for the observatory concerned. Similarly, most software packages for reducing astronomical data have a preferred or 'native' format on which they operate. For most Starlink software it is the NDF (*n*-dimensional Data Format; see SUN/33[31]) and for IRAF it is the OIF (Old Image Format). However, most well-established packages are able to import data in various different formats and, in some cases, may be able to process data which are not in their native format, albeit with some loss of efficiency.

This proliferation of different and incompatible data formats is no longer a substantial problem. The FITS format is ubiquitous in astronomy for transferring data between institutions and between software packages. Howsoever the data were originally written when they were acquired at the telescope they will almost invariably be exported from the observatory in the FITS format. That is, the magnetic tape cartridge with which you return from your observing run will almost always contain FITS files. Similarly, observations extracted from data archives are likely to be in FITS format. All the major packages for reducing astronomical data can import files in the FITS format.

6.2.1 FITS

The original FITS (Flexible Image Transport System) format was proposed by Wells *et al.*[33] in 1981. However, it has been developed and enhanced over the years. The FITS standard is now maintained and documented by the FITS Support Office of the Astrophysics Data Facility at the NASA Goddard Space Flight Center (see URL: `http://fits.gsfc.nasa.gov/fits_home.html`). Though FITS is basically an astronomical format it is sometimes mentioned in books about standard image formats. See, for example, *Graphics File Formats* by Kay and Levine[15]. The development of the FITS standard since its inception has recently been reviewed by Wells[34].

FITS was originally a standard for files on magnetic tape. However, nowadays it is just as often used as a format for files on magnetic disk. Its primary rôle is the interchange of data between different institutions and software packages, though some packages can process data in the FITS format directly.

Even a brief description of the FITS format is not appropriate here (if you are interested you can retrieve a document prescribing the standard for the FITS format from the FITS Support Office). However, a few comments might be useful. A FITS file is a sequence of records, each of which must be exactly 2880 bytes long. Two types of information are included in a FITS file: the basic data (comprising the image or spectra read from the CCD or whatever) and header information describing and annotating it. Typical header information for an observation might be the instrument and telescope used, the date and time of observation, details of the instrumental set up *etc.* In the jargon of computer science such header information is often called **metadata**, though this term is rarely used in astronomy.

A given record may contain header information or data but not both. A record of header information is divided into thirty-six eighty-byte 'logical records' (older readers will recognise these as card images). The data are often stored as binary numbers, but the header records always comprise ASCII characters. Header records can occur throughout the file, though there is always at least one at its start.

Figure 4 lists the first few header records from a FITS file. The details are not germane here (and, indeed, the example is not typical; it is for a FITS file which contains no array of data). However, it illustrates the important point that there are two types of FITS header records: keywords and comments.

Keywords A keyword record consists of a named keyword, an equals sign, the value of the keyword and optionally a comment. For example, in the figure the keyword `SIMPLE` has the value '`T`' (for true in this instance) and the keyword `BITPIX` has the value 8. There are some additional rules about the position and length of these items, but they are not important here. Keywords are the principal mechanism used to associate auxiliary information with a dataset. Programs which process FITS files will often search the file for appropriately named keywords to give them the information that they need. The keywords in the figure are mandatory (their meanings are not important here). Others, if present have a specified meaning.

Comment A comment header record starts with the string '`COMMENT`' and the rest of the record consists of free text which is intended to be read by a human. Typically it is used to annotate the dataset.

```
SIMPLE  =                    T / file does conform to FITS standard
BITPIX  =                    8 / number of bits per data pixel
NAXIS   =                    0 / number of data axes
EXTEND  =                    T / FITS dataset may contain extensions
COMMENT   FITS (Flexible Image Transport System) format defined in Astronomy and
COMMENT   Astrophysics Supplement Series v44/p363, v44/p371, v73/p359, v73/p365.
COMMENT   Contact the NASA Science Office of Standards and Technology for the
COMMENT   FITS Definition document #100 and other FITS information.
END
```

Figure 4: A minimal header for a FITS file. The example is atypical in that it is for a FITS file which contains no data array

A consequence of the header information always being ASCII characters and some always occurring at the start of the file is that it is possible to examine it with the Unix command `more`. The resulting display is perfectly readable, though perhaps not very æsthetic. This technique works best with a window which is eighty characters wide. A disadvantage of using `more` is that it is usually not practical to examine any header information which does not occur at the start of the file. Most data reduction packages have more sophisticated means for examining FITS header information: see, for example, the recipe in Section 9 and the script in Section 21. These mechanisms usually allow you to examine header information which is embedded in the file as well as that at the front.

6.3 Illustration of data reduction

Despite marked improvements in CCD manufacturing techniques in recent years, the bias and pixel-to-pixel sensitivity variations found in raw CCD images are not small effects. This section briefly illustrates the effects and shows the improvement which careful calibration can yield. The images used here were generated by Matthew Trewhella using the WIRO CCD operating in the *K* band in the near infrared. The images are all of 128×128 pixels and were taken as part of a project to mosaic the M51 galaxy and its companion NGC 5194. Several hundred images were taken and they were all reduced, aligned and stacked using CCDPACK.

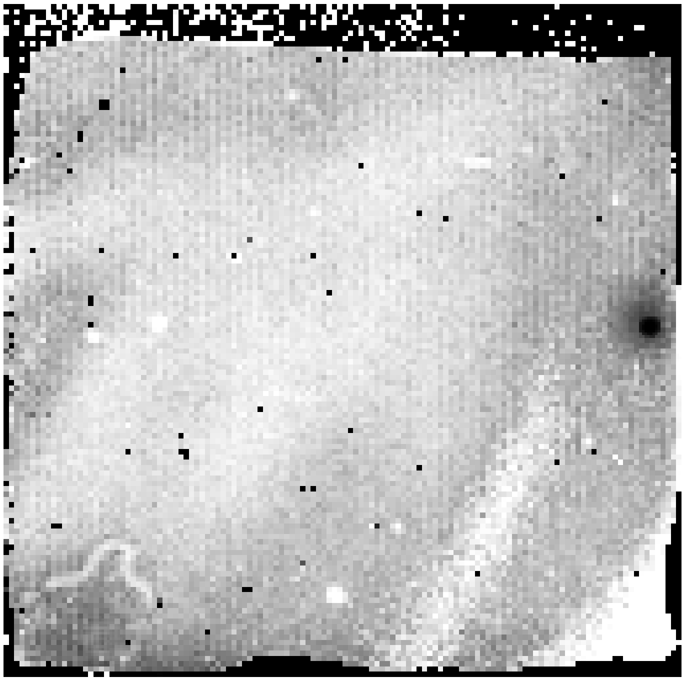


Figure 5: A raw WIRO *K* band image of part of M51

Figure 5 shows a raw, unprocessed target image, as read-out from the CCD. An astronomical object is visible in the middle of the right-hand edge of the image, but any other features are swamped by the instrumental signature.

Figures 6 and 7 are respectively a bias and a flat field frame. They clearly show the origin of the instrumental effects seen in Figure 5. For the sake of clarity the contrast of the flat field frame has been enhanced using a histogram-equalisation technique in order to make subtle changes in intensity easier to see.

Figure 8 shows the final mosaic of M51. The boxed area indicates the part of the mosaic to which the raw image shown in Figure 5 contributed. Over 2Gb of raw images, darks, flats and biases were used to construct this mosaic.

7 Infrared Arrays

This section summarises the differences between reducing data acquired with arrays sensitive to infrared (IR) wavelengths and those acquired with conventional CCDs. The purpose here is not to describe the principles of the construction and operation of infrared arrays; see McLean's

Figure 6: The bias frame associated with the WIRO CCD

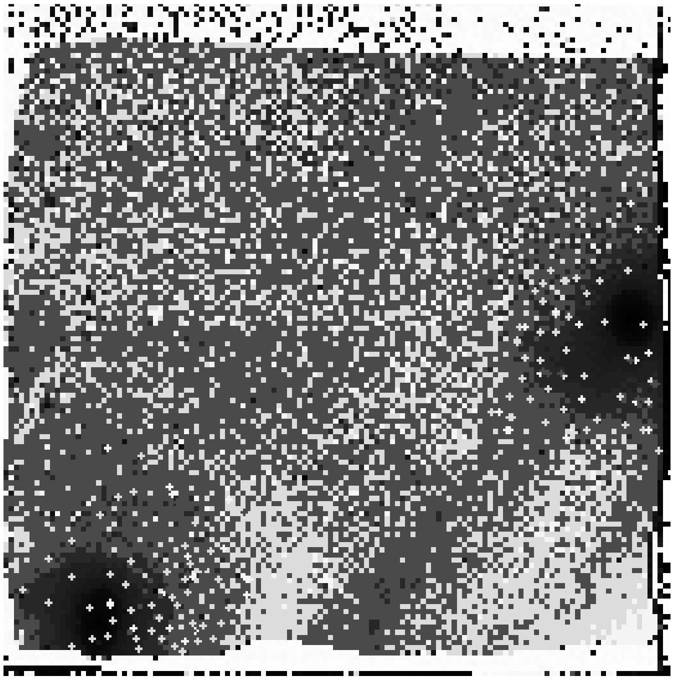


Figure 7: The WIRO CCD flat field (contrast enhanced)

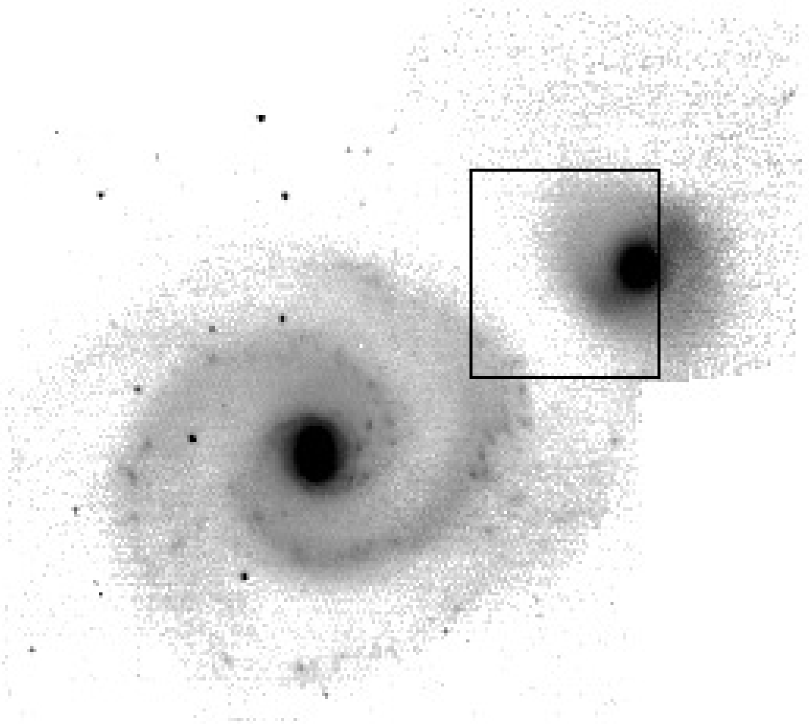


Figure 8: The final WIRO *K* band mosaic of M51 and NGC 5194

Electronic Imaging in Astronomy[20], especially Chapters 8 and 9 (pp195-263) for a thorough introduction to these topics. Infrared cameras were introduced into astronomy in the mid to late 1980s. The instruments are more technically demanding to construct than optical CCD cameras, largely though not entirely, because of the additional cryogenics required. The arrays are 'similar but different' to CCDs. They are usually smaller than CCDs and the quantum efficiency may be less. Like CCDs, infrared array instruments are entirely electronic, and the images are copied directly into computer memory without any intermediate analogue stage.

The data reduction procedures for infrared arrays are very similar to those for CCDs. However, some of the differences are outlined below. The following notes are largely based on practices at UKIRT (United Kingdom Infrared Telescope) on Mauna Kea, Hawaii and the procedures at other observatories may differ somewhat.

Observing modes In practice infrared arrays saturate very quickly. Consequently they are read-out very frequently in order to produce a stack of frames (or **co-adds**) which are subsequently added. You will not necessarily see the individual frames: they may be co-added before you receive them, either by bespoke circuitry in the instrument or by the instrument control software.

Also the instrument and telescope may be 'chopping' and 'nodding' during the observation: rapidly switching between observing the target object and neighbouring sky in order to allow the otherwise dominant contribution from the sky background to be estimated and and subtracted. This effect is usually achieved by oscillating some component of the optical system, often the telescope secondary mirror. See *Electronic Imaging in Astronomy*[20], pp201-203 for further details. Chopping and nodding were the usual modes of operation with earlier single-element photometers, but are less common with modern array detectors.

Bad pixels Though infrared arrays contain individual bad pixels the way that they are read-out means that they are unlikely to contain bad rows or bad columns.

Bias Infrared array data may appear to have no bias strips or bias frames. This absence may be due to the bias having already been automatically subtracted or it may be because the bias correction is subsumed into the dark current correction (see below).

Dark current Unlike optical CCDs, the dark current correction is important for infrared arrays. Dark frames should be taken frequently throughout the observing session.

Flat fields At infrared wavelengths the night sky is sufficiently bright that it can be used to construct flat field frames and this is the usual procedure, rather than acquiring twilight or dome flat fields. A particular disadvantage of dome flats is that they may contain a blurred image of the telescope reflected off the dome because the telescope glows at these wavelengths.

In order to generate the flat field a series of **jittered** frames will be acquired. Here **jittering** means slightly shifting the position of the telescope between exposures, typically by about ten seconds of arc[1]. At least three frames are required. The region of sky observed may be either offset from the target object and contain only field stars (a **sky flat**) or be centred on the object and have background sky and field stars around the periphery of the frame (a **self flat**). The dark current is subtracted from the individual frames, which are then

---

[1] The jitter offset may be larger, depending on the array size and target characteristics. For example, the UFTI instrument on UKIRT can have an offset of up to forty-five seconds of arc.

combined by computing the median or clipped median for each corresponding pixel. The median for some pixels may still be biased by the presence of field stars (and the target object in a self flat) so it may be necessary to locate any objects in the frames and mask them out prior to combination.

The frequency with which flat fields need to be taken depends (amongst other things) on the type of coating on the array detector. Arrays with an indium antimonide (InSb) coating, such as IRCAM on UKIRT, require frequent flat fields at intervals of about every half an hour. Arrays with a mercury-cadmium-telluride (HgCdTe) coating, such as UFTI on UKIRT, are more stable and taking only a few flat fields throughout the night may be adequate.

7.1 Reduction procedure

Infrared images of target objects are dominated by the large, additive sky background. Various reduction schemes are possible. One common approach is as follows.

1. subtract the dark current from all the frames (both flat fields and target objects),
2. create a master flat field,
3. apply the flat field to the target frames,
4. resample the target images onto the same pixel grid and assemble them into a mosaic,
5. optionally any remaining residual non-zero sky can be subtracted later, if required.

Obviously observations made with different filters and on different nights are reduced separately. An alternative, though less usual, approach is to subtract the sky background before making the flat field and dark correction:

$$\text{Final target frame} = \frac{\text{Raw target frame} - \text{Sky frame}}{\text{Flat frame} - \text{Dark frame}} \tag{5}$$

The flat field will usually be normalised. The sky frame should have been acquired at a similar time to the target frame, have the same co-adds and be an average of several frames taken before and after the target observation. Median filtering and pixel masking can be used to remove cosmic-ray hits and bad pixels, respectively.

The dark frame includes the bias offset. It should have the same exposure time and co-adds as the flat field and both should be averaged from numerous individual frames. Although in principle it is possible to combine exposures of different duration by scaling, there may be subtle effects which do not scale, so it is better to ensure that the exposures are of the same duration.

For some further details see Section 6.3, *IR data reduction*, of SUN/139[10].

Part II

The Recipes

8 Introduction

This part of the cookbook provides a set of simple recipes for reducing CCD images and performing various related auxiliary tasks. The recipes are:

- importing data (Section 9),
- displaying images (Section 10),
- calculating image statistics (Section 11),
- simple removal of instrumental effects (Section 12),
- advanced removal of instrumental effects (Section 13),
- combining target images (Section 14),
- reading FITS files from tape (Section 15),
- handling large images (Section 16).

The first three recipes (Sections 9 to 11) demonstrate preliminary, auxiliary tasks. Two alternative recipes are provided for removing the instrumental effects from CCD images. Section 12 is a very simple recipe using software operated from an easy-to-use GUI (Graphical User Interface). Section 13 is a more advanced recipe using software operated from the Unix command line. Though more complicated than the preceding recipe it offers more flexibility and perhaps greater insight into the operations being performed on the data. Section 14 is an example of combining reduced images.

Recipes 9 to 14 form a natural sequence and are intended to be worked through in the order in which they are given. Each of these recipes consists of a set of numbered steps which you can follow and example data are provided with the cookbook so that you can work through them yourself. On Starlink systems these example data are kept in directory:

```
/star/examples/sc5/data
```

These data are *R* band images of the spiral galaxy NGC 2336 obtained with the Jacobus Kapteyn Telescope (JKT) on La Palma. They were obtained from the CD-ROM *Astronomical Images* by Jaffe[14]. However, the same data are publicly available from the ING (Isaac Newton Group) data archive maintained at the Institute of Astronomy, University of Cambridge. See URL:

```
http://archive.ast.cam.ac.uk/
```

For technical reasons there are some differences in the arrangement of the FITS headers in the archive and CD-ROM versions of the files but both contain identical astronomical information.

The final two recipes, *Reading FITS Files from Tape* (Section 15) and *Handling Large Images* (Section 16) are rather different. They contain material which could not be presented conveniently as a set of numbered steps which you can follow, but rather are given as a set of hints and tips.

The packages used in the recipes in this cookbook are GAIA (see SUN/214[11]), CCDPACK (see SUN/139[10]), KAPPA (see SUN/95[6]) and ESP (see SUN/190[12]). These items should all be available at all Starlink sites. If you have any difficulty in accessing them then see your site manager in the first instance. In all cases on-line hypertext versions of the manuals are available via the command `showme`. For example, to display the CCDPACK manual, SUN/139, you would simply type:

```
% showme sun139
```

IRAF examples equivalent to the recipes for displaying images (Section 10) and calculating statistics (Section 11) are included in SG/12[22], the introduction to IRAF on Starlink systems. IRAF includes the powerful and flexible package CCDRED for reducing CCD data; see Section 6.1 for a list of the documentation for it.

8.1 Getting started

In order to work through the recipes you should use a colour display capable of receiving X-output (typically an X-terminal or a workstation console). Before starting you should ensure that your display is configured to receive X-output.

To work through the recipes as they are presented you should take a copy of the example data provided with the cookbook. Proceed as follows.

(1) Create a new subdirectory, perhaps called `sc5`, in some convenient location and make it your current directory:

```
% mkdir sc5
% cd sc5
```

(2) Copy the example data files into this subdirectory:

```
% cp -r /star/examples/sc5/data .
```

Note that the data files are kept in various subdirectories of `/star/examples/sc5/data` and a recursive copy (the '`-r`' option) is used to preserve this structure. Each subdirectory contains a different type of file, as follows:

`bias` – bias frames,

`flats` – flat fields,

`targets` – images of target astronomical objects.

Keeping the different types of files in separate subdirectories makes them easier to manage.

As an alternative to using the data supplied with the cookbook you could use data of your own. Suitable data are available on the CD-ROM *Astronomical Images*[14] or from the ING data archive. However, if you substitute your own data you will need to ensure that you know the extent of any bias strips on the CCD frames and similar auxiliary information. For data from *Astronomical Images* these details are given in file `descript.ccd` included on the CD-ROM.

9 Importing Data

> *Note that this section describes KAPPA FITSDIN rather than CONVERT FITS2NDF because at the time of writing the latter aborts when presented with an ING nearly-FITS file. The underlying problem is with the ING file rather than FITS2NDF. It may be possible to switch to using FITS2NDF when it has been enhanced to handle ING nearly-FITS files.* ACD, 11/5/99.

The CCD images that you plan to reduce may be available as FITS files (see Section 6.2) which are already resident on magnetic disk, as is the case for the examples provided with this cookbook. Most Starlink software can read data files in a variety of formats, including FITS. However, it is most simple, convenient and efficient to convert the files to Starlink's NDF (*n*-dimensional Data Format; see SUN/33[31]) format at the outset.

If you have not already done so, you should copy the example data to a convenient directory where you can work on them, as described in Section 8.1. Make this directory your current directory, then proceed as follows.

(1) First you must start the KAPPA package (see SUN/95[6]). Simply type:

```
% kappa
```

(2) Move to the subdirectory containing the astronomical images:

```
% cd targets
```

(3) You can list the header records in a FITS file using KAPPA application `fitshead`. Type:

```
% fitshead ngc2336_r_1.fit
```

The header records will be listed to the terminal. This output should look similar to Figure 9.

(4) A FITS file can be converted to the NDF format using KAPPA application `fitsdin`. Type:

```
% fitsdin ngc2336_r_1.fit ngc2336_r_1 fmtcnv=yes
```

The option `fmtcnv=yes` specifies that INTEGER data arrays in the input files will be converted to REAL arrays in the output NDF files. The keywords in the FITS file will be listed to the terminal and NDF file `ngc2336_r_1.sdf` should be created in your current directory.

(5) You can examine the contents of this file using the `hdstrace` utility. Simply type:

```
% hdstrace ngc2336_r_1
```

(note that the '`.sdf`' file-extension can be omitted). `hdstrace` is fully documented in SUN/102[5].

```
SIMPLE  =                    T
BITPIX  =                   16
NAXIS   =                    2
NAXIS1  =                 1124
NAXIS2  =                 1124
DATE    = '13/02/96'                    /Date tape file created

PACKTYPE= 'OBSVATON'                    /Packet type
PACKVERS=                    2          /Packet Version Number
PACKDATE= '96/02/13'                    /Date of packet creation
PACKTIME= '22:57:02'                    /Time of packet creation
PACKNAME= 'JOB44209'                    /Packet name
PACKPDAT= '96/02/13'                    /Date of previous packet of this type
PACKPTIM= '22:51:54'                    /Time of previous packet of this type
PACKPNAM= 'JOB44208'                    /Name of previous packet of this type
ORIGIN  = 'ING La Palma'                /Tape writing institution
OBSERVER= 'WJJ     '                    /Name of the Observer
TELESCOP= 'JKT     '                    /Name of the Telescope
INSTRUME= 'AGBX    '                    /Instrument configuration
OBSTYP  =                   40          /Observation type
OBJECT  = 'N2366 R '                    /Name of the Object
RA      = '07:18:22.50'                 /RA of the source
DEC     = '+80:16:26.0'                 /Declination of the source
        .
        .
        .
```

Figure 9: The first few FITS header records for file `ngc2336_r_1.fit`

(6) Now convert the remaining files. Type:

```
% fitsdin ngc2336_r_2.fit ngc2336_r_2 fmtcnv=yes
% cd ../flats
% fitsdin files='*.fit' auto fmtcnv=yes
% cd ../bias
% fitsdin files='*.fit' auto fmtcnv=yes
```

Note the use of the asterisk (‘`*`’) as a wild card: all the files in the directory with names ending in ‘`.fit`’ are converted without having to explicitly specify their file names. The file specification ‘`*.fit`’ is enclosed in quotes to ensure that the asterisk is passed to `fitsdin` rather than being trapped and interpreted by the Unix shell. The use of Starlink applications from Unix shell scripts is discussed further in SC/4: *C-shell Cookbook*[4]. The `auto` option specifies that the output file name is to be constructed automatically from the input file name.

10 Displaying Images

Having converted the images to the NDF format it is usually sensible to have a look at them before you proceed with the reductions. Any gross defects in the data will often be readily apparent and a quick check before you start may save you a great deal of wasted effort. Similarly, it is often prudent to display intermediate images created during the reductions to check that nothing has gone awry.

Several image display programs are available. One of the simplest to use, yet most powerful and flexible, is GAIA (see SUN/214[11]), which will be used in this recipe. Proceed as follows.

(1) Move to subdirectory `targets`.

(2) Start GAIA by typing:

```
% gaia &
```

The ampersand (‘`&`’) is, of course, simply to run GAIA as a detached process, so that you can continue to issue Unix commands from the command line. The GAIA window should appear. Load file `ngc2336_r_2.sdf` by clicking the File menu (rightmost of the options in the menu bar at the top of the window), selecting Open. . . and using the file-picker which appears to choose the appropriate file.

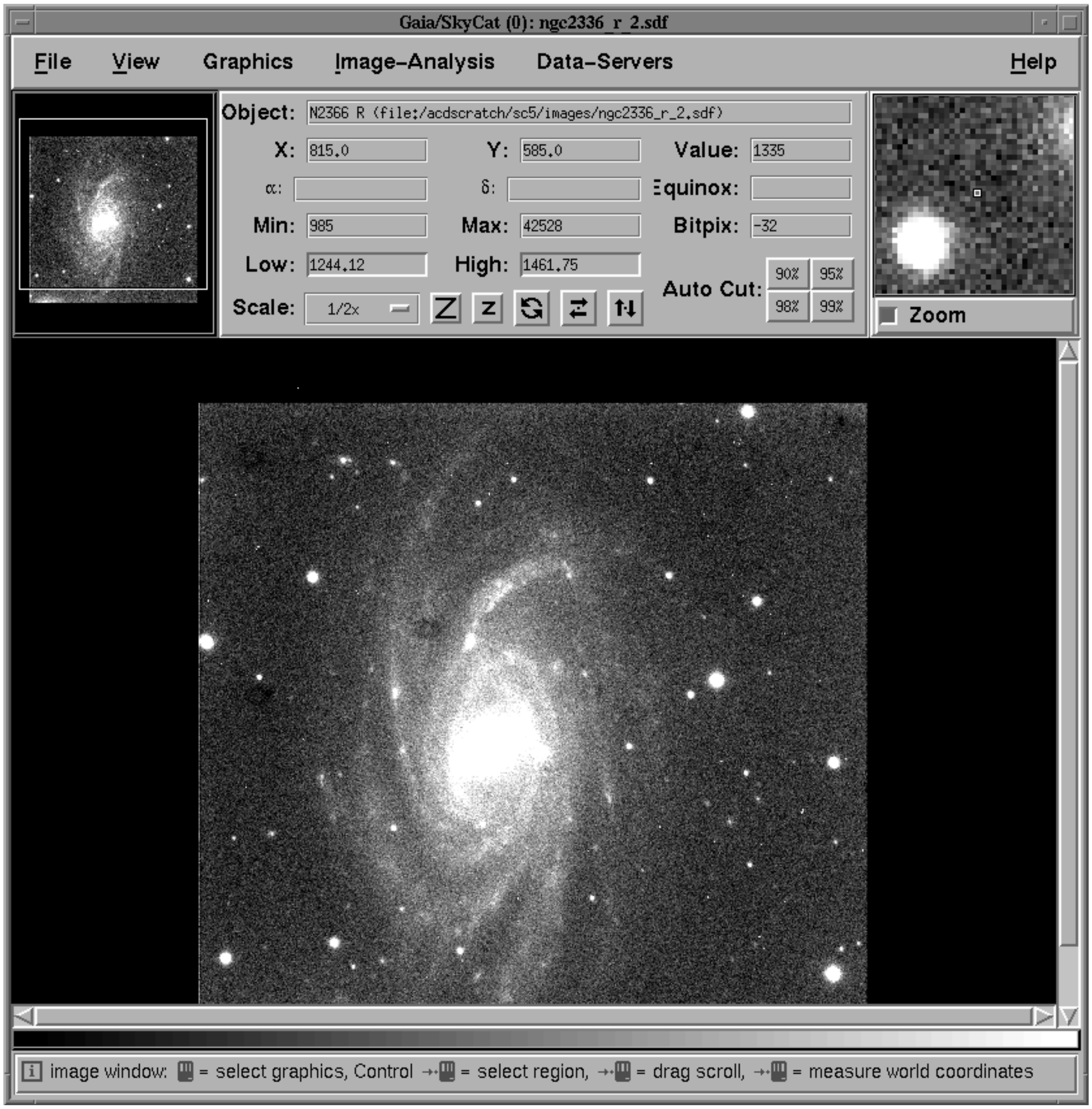
(3) The file should open, but the main display window will probably be mostly dark, with just a few white dots corresponding to the brightest parts of the image. Set some of the display options as follows:

   (a) click the Auto Cut: button for 90% (in the bottom right of the control panel in the centre top of the window),
   (b) click the View menu (second left in the menu bar at the top of the window), select Magnification and set it to 1/2x,
   (c) click View again, select Colors. . . (sic) and choose the heat colour table.

The display should now look something like Figure 10.

(4) GAIA has many other functions and options and you may want to spend a while exploring some of them. On-line help is available from the Help menu at the extreme right of the menu bar at the top of the window. Similarly, you might also like to examine the other target image and the flat field and bias frames included in the example.

(5) When you have finished close GAIA by clicking on the File menu and choosing the Exit option.



Gaia/SkyCat (0): ngc2336_r_2.sdf

Object: N2366 R (file:/acdscratch/sc5/images/ngc2336_r_2.sdf)

X: 815.0 Y: 585.0 Value: 1335

α: δ: Equinox:

Min: 985 Max: 42528 Bitpix: -32

Low: 1244.12 High: 1461.75

Scale: 1/2x

image window: = select graphics, Control → = select region, → = drag scroll, → = measure world coordinates

Figure 10: An unprocessed *R* band image of NGC 2336 displayed with GAIA. The apparently asymmetric positioning of the image in the GAIA windows is caused by the bias strips along some of the edges of the CCD frame which appear black in this plot

11 Calculating Statistics

In the same way that it was useful to display images at intermediate stages in the data reduction, it is often useful to be able to calculate and list gross statistics (mean value, standard deviation *etc.*) for images as they are processed. There are a couple of applications which provide this facility. Proceed as follows.

(1) Assuming that KAPPA is loaded (see the recipe in Section 9), move to the subdirectory containing the target astronomical images and type:

```
% stats ngc2336_r_2
```

The following information should be displayed:

```
Pixel statistics for the NDF structure /acdscratch/sc5/targets/ngc2336_r_2

   Title                      : N2366 R
   NDF array analysed         : DATA

      Pixel sum               : 1.6012529E9
      Pixel mean              : 1267.44
      Standard deviation      : 279.5582
      Minimum pixel value     : 166
         At pixel             : (1, 547)
         Co-ordinate          : (0.5, 546.5)
      Maximum pixel value     : 50963
         At pixel             : (1023, 146)
         Co-ordinate          : (1022.5, 145.5)
      Total number of pixels : 1263376
      Number of pixels used  : 1263376 (100.0%)
```

(2) The statistics can also be written to a log file. Type:

```
% stats ngc2336_r_2 logfile=ngc2336_r_2.log
```

Text file `ngc2336_r_2.log` will be created containing a copy of the output.

(3) `stats` has a 'κ-sigma clipping' option which allows outlying values, such as star images, to be rejected when computing the statistics. If a clipping level is given, `stats` will compute statistics using all the available pixels, reject all those pixels whose values lie outside κ standard deviations of the mean and then re-evaluate the statistics. An array of up to five clipping levels may be given, which are applied sequentially. For example, to reject values outside two standard deviations type:

```
% stats ngc2336_r_2 clip=2
```

The statistics will again be displayed, but this time the clipping will have been applied before they were computed.

(4) Often the information generated by `stats` will be adequate. However, application `histpeak` in the ESP package (see SUN/180[12]) gives further details. To load ESP type:

```
% esp
```

then type `histpeak` and respond to the prompts:

```
% histpeak

ESP HISTPEAK running.

IN - Image NDF filename /@ngc2336_r_2/ > ngc2336_r_2
Filename:   /acdscratch/sc5/targets/ngc2336_r_2
Title:      N2366 R
Shape:      1124 x 1124  pixels
Bounds:     x = 1:1124  y = 1:1124
Image size: 1263376 pixels

USE - Use the whole image or an ARD file /'w'/ >

SFACT - Smoothing width you wish to use /0/ >

DEVICE - Display device code or name /@xwindows/ >
```

Output similar to the following should be produced:

```
HISTPEAK Results: /acdscratch/sc5/targets/ngc2336_r_2

Pixels (used):           1263376     Pixels (bad):               0
Lowest count:            166.000     Highest count:      50963.000
Skewness:                 63.680     Kurtosis:            7114.975

Mean:                   1267.440     Median:              1294.776

Histogram modal values:
Unsmoothed:             1298.000     Smoothed:            1298.000
Projected:              1296.511     Interpolated:        1298.696

Absolute dev.:            90.361     Variance:              78153.
Standard. dev.:          279.558     Back. st. dev.:        33.353

Smoothing filter radius:
Radius request:                0     Radius actual:              0

Contents of the most occupied histogram bin:
Unsmoothed:            21104.000     Smoothed:           21104.000
Interpolated:          12126.075
```

and a plot similar to Figure 11 should appear. For the purpose of determining the sky background level it is probably best to use either `histpeak` or `stats` with the clipping option. Also note that the `histpeak` pre-amble contains the dimensions and bounds of the image.

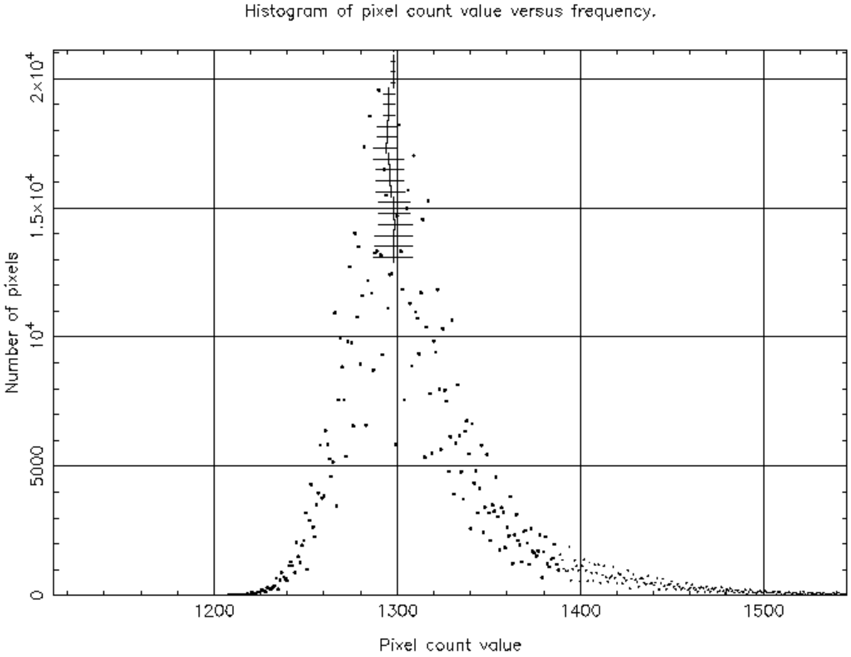


Figure 11: Example of histogram produced by `histpeak`

12 Simple Removal of Instrumental Effects

This recipe is a simple example of reducing CCD data. It uses the `xreduce` easy-to-use GUI (Graphical User Interface) to the CCDPACK package (see SUN/139[10]). `xreduce` makes the reduction of CCD observations very straightforward. Using `xreduce` you can follow various routes to reduce your data. However, most of them are fairly similar and involve the following steps:

(1) set up the package (probably using both the General Options and CCD Characteristics windows; see Figure 12),

(2) identify the various frames, and types of frames, which are to be processed (probably using one of the Manual Organization or Using FITS Headers windows),

(3) specify how the data are to be de-biassed (which is done in the Setup and Run window; your choice will be restricted to options which are valid for the given data).

The recipe given here corresponds to one simple route through the data reduction. `xreduce` is described further in SUN/139, especially Section 4, *How to reduce your data now*. Some additional illustrated examples have appeared in the *Starlink Bulletin*[9].

If you have not already set up for working through the recipes then you should do so now. The procedure is described in Section 8.1. Then proceed as follows.

(1) Move to the directory to which you have copied the example data. Then type:

```
% ccdpack
% xreduce &
```

The first command starts CCDPACK, the second starts the `xreduce` GUI. The ampersand (‘`&`’) runs `xreduce` as a detached process, so that you can continue to issue Unix commands from the terminal window.

The main `xreduce` window should appear, as shown in Figure 12. Extensive on-line help information is available from most of the `xreduce` windows, to the extent that it is virtually an ‘interactive cookbook’ in itself. Simply click on the Help menu in the top right of the window. Several options are available: for assistance on using the current window choose the On Window option. The help information is presented as hypertext displayed with a Web browser (Netscape by default).

The underlying purpose of `xreduce` is to gather sufficient details of your data to define how they are to be reduced. Basically it needs to know: which of the CCDPACK options you plan to use, a few details about your CCD frames (such as the extents of any bias strips) and the names and directory specifications of each of your various types of data frames (bias frames, flat fields, target frames *etc*). In order to make specifying the details of the CCD frames easier `xreduce` has a list of commonly-used chips which you can choose from. If the instrument that you used is not included in this list then you can enter the requisite details manually.

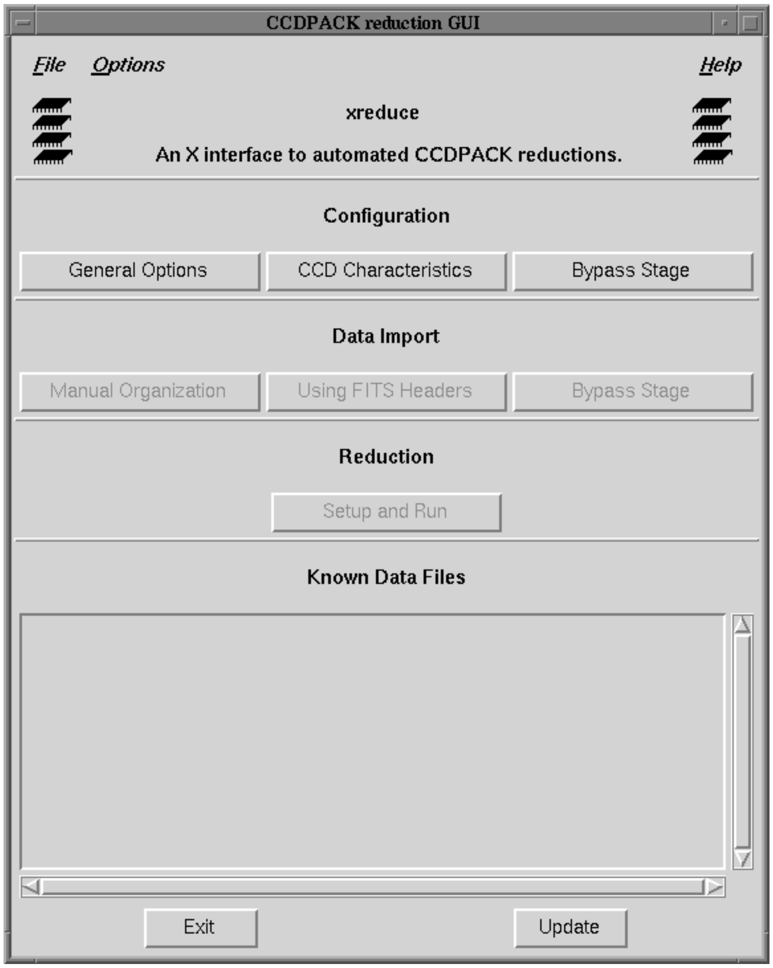
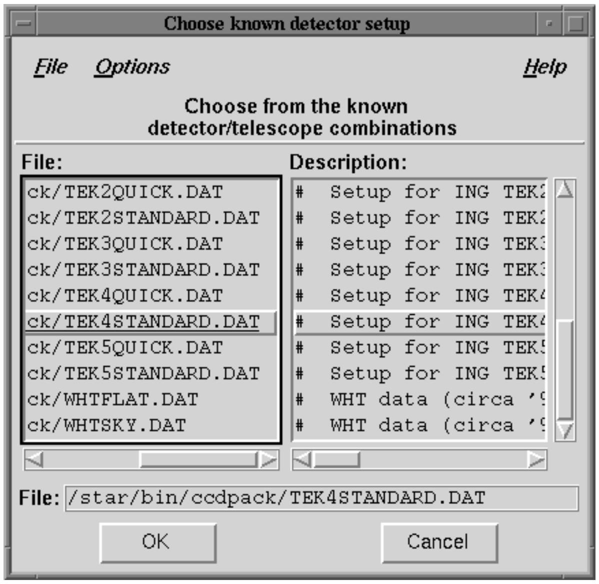


Figure 12: Main window for the `xreduce` GUI

(2) Click on the Options menu (rightmost of the two options in the top left corner of the window: see Figure 12) and choose the Set detector... option. A window similar to Figure 13 should appear. This window lists the various CCD detectors known to `xreduce`. Click on the entry `TEK4STANDARD.DAT` (as shown) which was the detector used to acquire the example data.



Choose from the known detector/telescope combinations

File:	Description:
ck/TEK2QUICK.DAT	# Setup for ING TEK
ck/TEK2STANDARD.DAT	# Setup for ING TEK
ck/TEK3QUICK.DAT	# Setup for ING TEK
ck/TEK3STANDARD.DAT	# Setup for ING TEK
ck/TEK4QUICK.DAT	# Setup for ING TEK
ck/TEK4STANDARD.DAT	# Setup for ING TEK
ck/TEK5QUICK.DAT	# Setup for ING TEK
ck/TEK5STANDARD.DAT	# Setup for ING TEK
ck/WHTFLAT.DAT	# WHT data (circa '
ck/WHTSKY.DAT	# WHT data (circa '

File: /star/bin/ccdpack/TEK4STANDARD.DAT

Figure 13: CCD detectors known to `xreduce`

Figure 13 shows the window as it is created by default. A useful trick is to expand it horizontally so that the file names and descriptions are more easily visible. Some of the CCD descriptions end in '`(setup)`' and others in '`(table)`'. `xreduce` knows more about the former than the latter. The option chosen here ends in '`(setup)`', so full details are available.

Once you have selected the detector click on the OK button.

(3) Next you need to set the configuration options. Click on the General Options button in the main window. For the example data all the defaults are acceptable, so simply click on the OK button.

Now click on the CCD Characteristics button in the main window. Again the defaults are acceptable, so click on OK.

(4) You need to specify the types of files (bias frames, flat fields, target objects, *etc*) present in your data and the name and directory specification of each file of each type. You specify these details using the buttons in the Data Import section of the main window.

Click on the Manual Organization button and a window similar to Figure 14 should appear. The example data comprise only bias frames, flat fields and images of target objects, so click the three corresponding buttons in the list of Frame types present: in the top half of the window. Ensure that these three are the only data types for which the buttons are set.

The defaults can be accepted for the other options in the lower half of the window. Simply click the OK button.

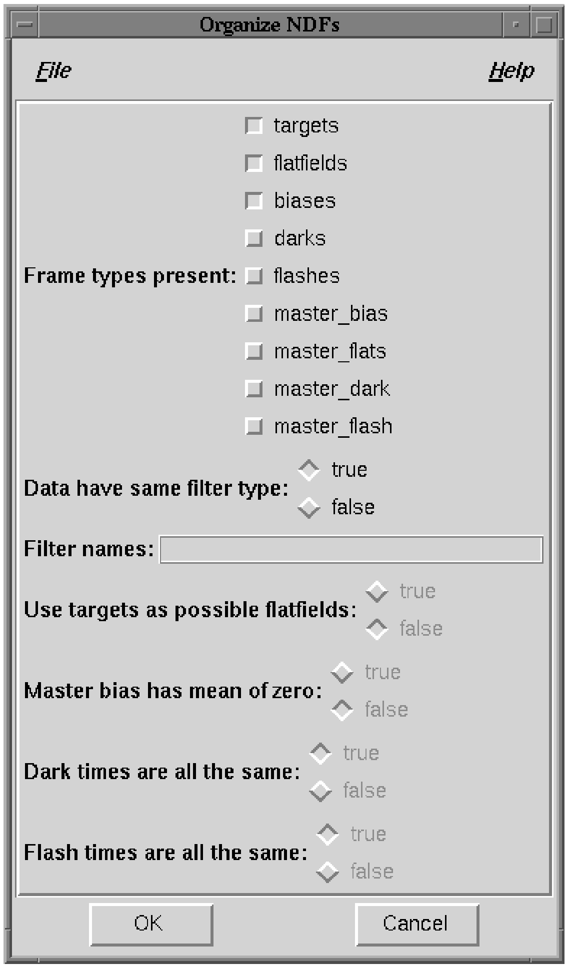
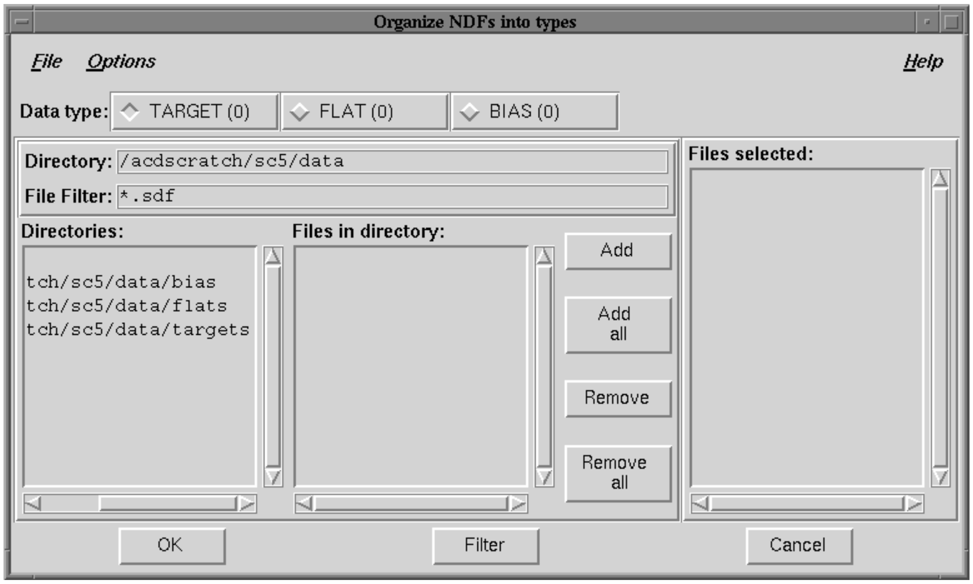


Figure 14: `xreduce` window to specify the types of file present

(5) A window similar to Figure 15 should appear. This window allows you to specify the individual files which are to be reduced. First specify the target object frames. Proceed as follows.

   (a) Click the TARGET button in the row towards the top left of the window.
   (b) In the Directories: box (on the left side of the window) double-click on the `targets` subdirectory. This directory should become the current directory and the two target frames should appear in the Files in directory: box.
   (c) Click on the Add all button and the files should appear in the Files selected: box (on the right side of the window).

Repeat the procedure for the flat field and bias frames by clicking on the FLAT and BIAS buttons (in the row towards the top left of the window) respectively and proceeding as before. The flat fields are in subdirectory `flats` and the bias frames in `bias`.



Directory: /acdscratch/sc5/data

File Filter: *.sdf

```
tch/sc5/data/bias
tch/sc5/data/flats
tch/sc5/data/targets
```

Figure 15: `xreduce` window to specify the files to be reduced

Once you have specified the files for the three types of frame click the OK button. A window should appear briefly showing the message:

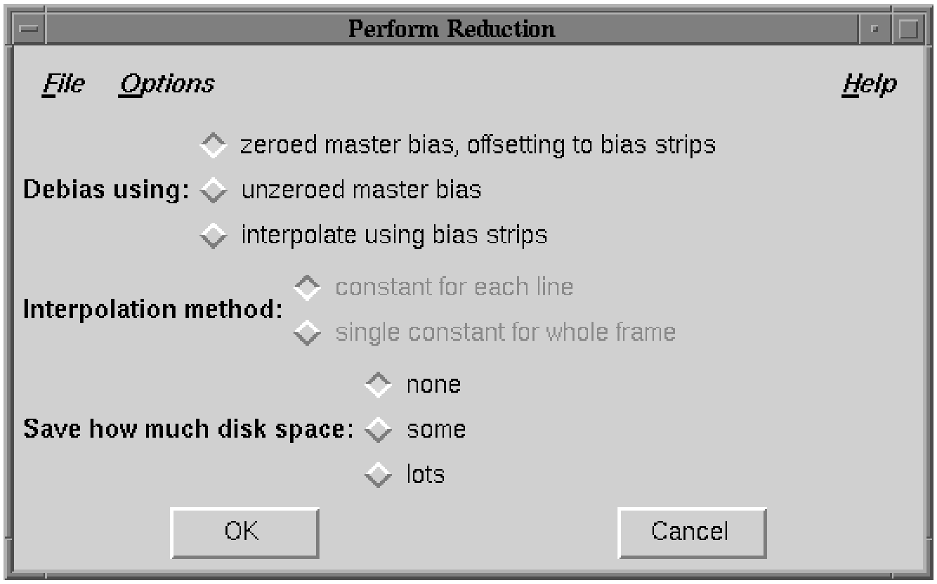
> Setting data descriptions, please wait

and you will be returned to the `xreduce` main window.

(6) Now click the Setup and Run button. A window should appear briefly showing the message:

> checking possible debiassing methods please wait

and then be replaced by a window similar to Figure 16. For the example data all the defaults can be accepted, so just click the OK button.



Debias using:
- ◇ zeroed master bias, offsetting to bias strips
- ◇ unzeroed master bias
- ◇ interpolate using bias strips

Interpolation method:
- ◇ constant for each line
- ◇ single constant for whole frame

Save how much disk space:
- ◇ none
- ◇ some
- ◇ lots

Figure 16: `xreduce` window to specify the reduction options

(7) A window showing the message:

> performing reduction scheduling please wait

should appear briefly and be replaced by one saying:

> Reduction started. The output will be logged in file "xreduce.log".

Click on the OK button.

(8) A further window showing the progress of the reductions appears. From this point the reductions proceed autonomously. You can either watch their progress by leaving the window running or close it by clicking the Exit button. You will be asked for confirmation and then be returned to the main window. Click on the Exit button (at the bottom of the window, towards the left) to close down `xreduce`: again you will be asked for confirmation.

(9) Various files have been created during the reduction process. The new files in the top level data directory are:

`CCDPACK.LOG`	CCDPACK log file
`MASTER_BIAS.sdf`	master bias frame
`MASTER_FLATNONE.sdf`	master flat field frame
`xreduce.csh`	`xreduce` reduction script
`xreduce.log`	`xreduce` log file

Some files have also been created in the `targets` subdirectory:

```
ngc2336_r_1_db.sdf
ngc2336_r_2_db.sdf
```

are the de-biassed target images and:

```
ngc2336_r_1_db_fl.sdf
ngc2336_r_2_db_fl.sdf
```

are the de-biassed, flat fielded images: the final product of the data reduction. They can be examined, for example, with GAIA. Type:

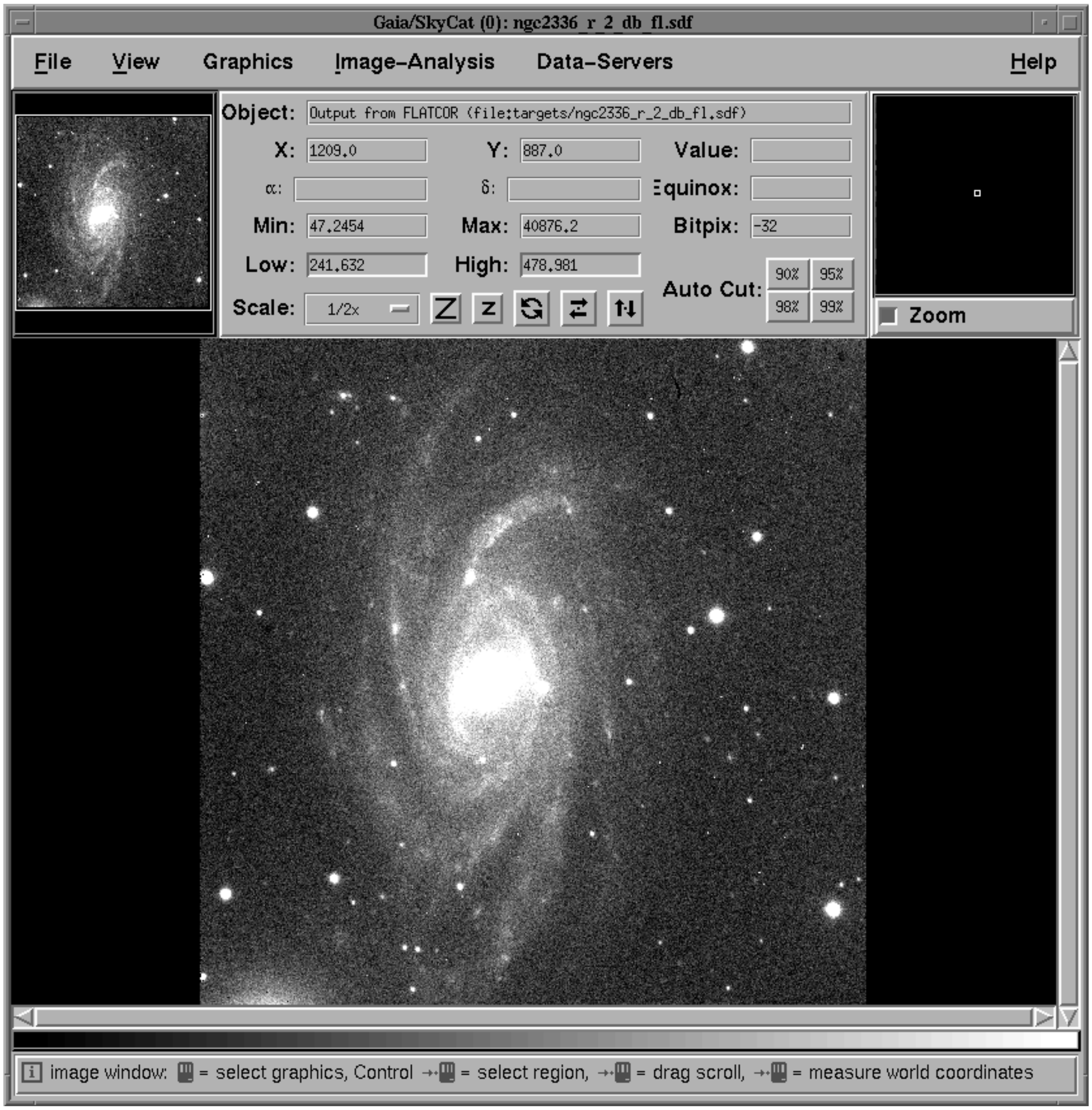
```
% gaia  targets/ngc2336_r_2_db_fl.sdf &
```

After setting the Auto Cut level, Magnification and colour table (see the recipe in Section 10) the image should look something like Figure 17.

(10) Once you have examined all the files you should delete them prior to trying the next recipe. Return to the top level data directory and type:

```
% delete_xreduce_files.csh
```

Note that script `xreduce.csh` is not deleted because it is interesting to compare it with the commands issued in the following recipe.



Object: Output from FLATCOR (file:targets/ngc2336_r_2_db_fl.sdf)

X: 1209.0 Y: 887.0

Min: 47.2454 Max: 40876.2 Bitpix: -32

Low: 241.632 High: 478.981

Scale: 1/2x

image window: = select graphics, Control → = select region, → = drag scroll, → = measure world coordinates

Figure 17: GAIA displaying a fully reduced image of NGC 2336. Note that the image no longer appears to be positioned asymmetrically (as it did in Figure 10) because the bias strips have been removed

13 Advanced Removal of Instrumental Effects

This recipe is an example of reducing CCD data by using CCDPACK from the command line. The full functionality of CCDPACK is available when it is used in this way. However, not all the facilities are used in this recipe and you should see the CCDPACK manual, SUN/139[10], for a full description. Figure 18 shows typical data reduction routes for CCDPACK.

Using CCDPACK from the command line is less intuitive than using the `xreduce` GUI introduced in the previous recipe (see Section 12). However, it is more flexible and, perhaps, gives greater insight into the data reduction process. If you have worked through the previous recipe `xreduce` will have produced the Unix shell-script `xreduce.csh` which actually performed the reductions. This file contains a sequence of CCDPACK commands. You might find it interesting to print out a copy and 'compare and contrast' it with the commands issued interactively in the current recipe.

If you have not already set up for working through the recipes then you should do so now. The procedure is described in Section 8.1. If you have tried the previous recipe using `xreduce` (Section 12) then you should ensure that the intermediate and reduced files are deleted by running script `delete_xreduce_files.csh`. Then proceed as follows.

(1) Move to the directory to which you have copied the example data. If you have not already started CCDPACK then type:

```
% ccdpack
```

to start it . Various on-line help is available. Typing `ccdwww` or `showme sun139` will cause a hypertext version of SUN/139 to be displayed using a Web browser (Netscape by default). Typing `ccdhelp` invokes an hierarchical help system in the Unix command window.

(2) The first step in using CCDPACK is to enter the details of the CCD detector that you are using. The sort of details which have to be specified are the extents of any bias strips (and consequently the extent of the image region on the CCD chip), the ADC factor *etc*. Type:

```
% ccdsetup adc=0.75 saturation=61440 rnoise=6.1 bounds='[11,40]' \
    extent='[51,1074,1,1024]' accept
```

Here the ADC factor is being set to 0.75, columns 11 to 40 are being used as a bias strip and the image proper comprises columns 51 to 1074 and rows 1 top 1024. Note how the ranges for the `bounds` and `extent` are specified inside single quotation marks in order to prevent the square brackets ('`[`' and '`]`') used to define the ranges from being interpreted by the Unix shell. The use of such 'special characters' is described in SC/4: *C-shell Cookbook*[4]. The `accept` option causes `ccdsetup` to accept default values rather than issue additional prompts.

(3) The next step is to make a single, 'master' bias frame from the various individual bias frames that are available. Type:

```
% makebias in='bias/*' out=master_bias zero=true accept
```

The points to note here are:

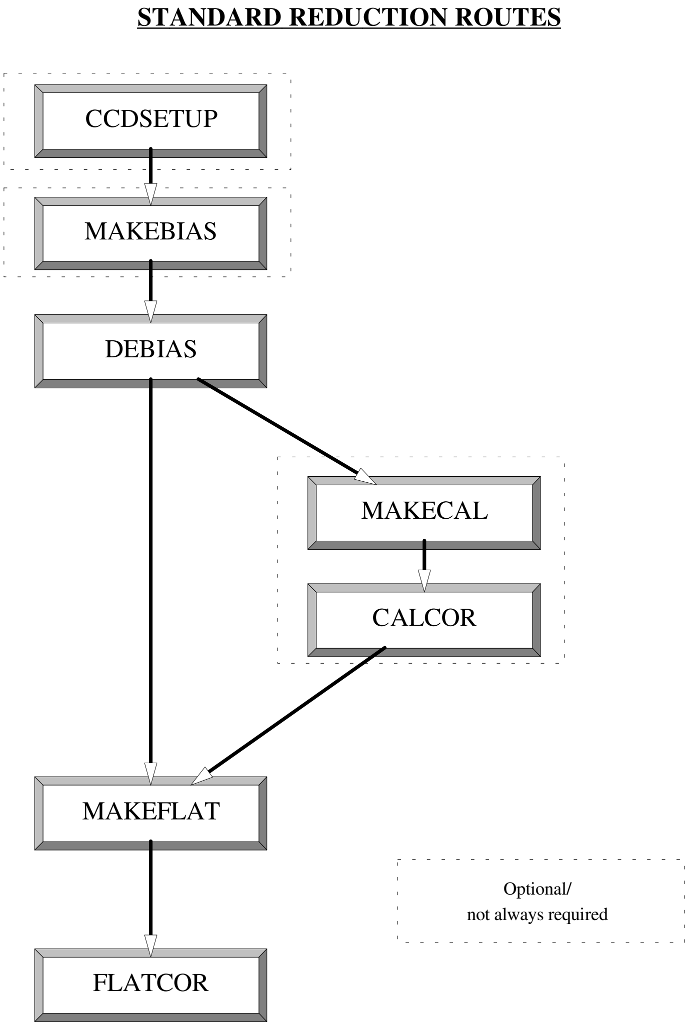


Figure 18: Typical data reduction routes for CCDPACK

- the input files are specified as `'bias/*'`. Here the asterisk (‘`*`’) is being used as a ‘wild card’ and all the files in subdirectory `bias` will be read. Again note the use of single quotes to prevent ‘special characters’ from being interpreted by the Unix shell,
- the master bias frame will be written to file `master_bias.sdf` in the current directory,
- the option `zero=true` specifies that the mean values of the pixels in the input images are to be adjusted to zero prior to combining them. This option is the preferred method and normal default. However, it can only be used if the CCD chip has bias strips which were specified using `ccdsetup`. If your data do not have bias strips you will need to set `zero=false`. See SUN/139 for further details,
- again the `accept` option is used to suppress additional prompts.

(4) Once you have created a master bias frame you need to apply it to your flat field and target image frames. First consider the flat field frames. Type:

```
% debias in='flats/sky*' out='*_deb' bias=master_bias accept
```

Some points to note here are:

- the asterisk is again being used as a ‘wild card’. The input flat fields will be all the files in subdirectory `flats` with file names beginning in ‘`sky`’,
- output de-biassed flat fields will be created in the same subdirectory as the input ones and with the same basic file name, but with ‘`_deb`’ appended. That is, the following files will be created:

```
flats/sky_r_6_deb.sdf
flats/sky_r_7_deb.sdf
```

Now repeat the procedure to de-bias the target images:

```
% debias in='targets/ngc2336*' out='*_deb' bias=master_bias accept
```

If you have a non-zeroed master bias frame or you are using only bias strips rather than bias frames then you need to specify different options for `debias`. Section 13.1 introduces some of the alternatives.

(5) The next step is to combine the individual de-biassed flat fields to create a single ‘master’ flat field. CCDPACK provides application `makeflat` for this purpose. The algorithm used by `makeflat` ensures that the master flat field it creates contains the minimum possible contribution from spurious sources, such as stars still faintly visible in twilight flats, by comparing each flat field with a smoothed version of itself and rejecting pixels that deviate from the local mean by more than a given number of standard deviations. It also ensures that flat field frames of different exposures are combined using an appropriate weight when the ‘median stacking’ option is used.

To invoke `makeflat` simply type:

```
% makeflat in='flats/*_deb' out=master_flat accept
```

Here the de-biassed flat fields in subdirectory `flats` are being used as input and the master flat field created will be saved as file `master_flat.sdf` in the current directory.

(6) The final stage is to use the master flat field to make a flat field correction to the target images. Type:

```
% flatcor in='targets/ngc2336*_deb' out='*_flt' flat=master_flat accept
```

The input files are the two de-biassed target images in subdirectory `targets`. The flat fielded images will be created in the same directory and with the same basic file names but with '`_flt`' appended. That is, the following two files will be created:

```
targets/ngc2336_r_1_deb_flt.sdf
targets/ngc2336_r_2_deb_flt.sdf
```

These images should be a true representation of the brightness distribution in the region of sky observed (subject to the constraints of atmospheric seeing and instrumental resolution, of course). The images can, for example, be displayed with GAIA. Type:

```
% gaia targets/ngc2336_r_2_deb_flt.sdf &
```

After setting the Auto Cut level, Magnification and colour table (see the recipe in Section 10) the reduced image should appear similar to the ones in the previous recipe (see Figure 17).

(7) You can delete the intermediate files at this point if you wish. Return to the top level data directory and type:

```
% delete_clfiles.csh
```

Note that the two reduced images are not deleted because they are used in the next recipe.

13.1 Additional options

This section introduces some additional options available in CCDPACK which were not used in the preceding recipe. It merely gives an outline of what is available. For full details see SUN/139[10].

13.1.1 Specifying bad pixels; ARD files

You can use ARD (ASCII Region Description) files to specify the location of any bad pixels, rows or columns in your images. ARD files are simple text files which contain a series of directives defining the defective parts of the CCD. Their syntax is very simple and is fully documented in SUN/183[1].

The observatory where your data were acquired may provide an ARD file for the instrument that you used. However, if one is not available it is straightforward to create one. There are several ways of doing so. Perhaps the simplest is to plot the image with GAIA. The defective region can then be specified with the Image regions... option and saved as an ARD file. Another method is to plot the image using application `display` in KAPPA and then use `ardgen` to identify the bad regions. Section 14.1.1, *Doing it the ARD Way*, of SUN/95 gives an example of the procedure. Alternatively, ARD files can be created with a simple text editor.

Once you have created an ARD file you specify it as a mask for `ccdsetup`. In this context a **mask** is simply a set of defective pixels in the image. For example:

```
% ccdsetup adc=1.5 bounds='[2,10,400,416]' extent='[11,399,1,576]' \
    mask=badpix.ard
```

where `badpix.ard` is the ARD file. Once you have specified the ARD file to `ccdsetup` all subsequent stages in the data reduction will automatically ignore all the image regions identified as containing bad pixels. This approach can save you a lot of time later.

For infrared images a different approach is common; use application `thresh` in KAPPA to directly identify pixels with aberrant values and mark them as 'bad', without the intermediate stage of an ARD file. KAPPA applications `stats` or `histat` can be used to find suitable thresholds.

13.1.2 De-biassing options

In the preceding recipe de-biassing was performed using a zeroed master bias frame. Various other options are available.

Non-zeroed MAKEBIAS frame To subtract a non-zeroed `master_bias` frame type:

```
% debias in='targets/ngc2336*' out='*_deb' bias=master_bias offset=false
```

As before, file `master_bias.sdf` in the current directory is subtracted from all the files with names beginning in '`ngc2336`' in subdirectory `targets`. The option `offset=false` specifies that the master bias frame has not been zeroed.

No bias frames available If you do not have bias frames, but do have images with bias strips, it is still possible for CCDPACK to approximately de-bias the images. In this case, `debias` will estimate values of the bias for each pixel of the image on the basis of information taken from the bias strips. For many purposes this approach will work very well. The options for `debias` are slightly different because no master bias frame is specified:

```
% debias in='targets/ngc2336*' out='*_deb'
```

More about `debias` In most cases `debias` will change the size of the images because it removes the bias strips (compare Figures 10 and 17). Once the frames have been de-biassed they serve no further purpose and merely increase the size of the files.

`debias` has a number of additional features which are beyond the scope of this cookbook, including:

- error estimation,
- deferred charge correction,
- saturated pixel correction.

See SUN/139[10] for the full details.

13.1.3 Dark current subtraction; `makecal` and `calcor`

Though the correction for dark current is usually insignificant, there can be circumstances where it is not and it is necessary to correct for it (see Section 5). In particular, it is often significant for arrays operating at infrared wavelengths. The correction is usually made using **dark frames**: images taken with the shutter closed but of the same length as your normal exposures. These frames are used to create a master calibration frame.

`makecal` can be used to combine a number of calibration frames (assumed to be stored in subdirectory '`darks`'):

```
makecal in='darks/*' expose=1 out=master_dark
```

Correcting the data for the dark current is performed by the application `calcor`, which subtracts a scaled calibration frame from a list of target frames:

```
% calcor in='targets/ngc2336' out='*_dark' cal=master_dark expose=1
```

This command will generate a series of dark current subtracted files that have names ending in '`_dark`'.

The correction is slightly more complicated if your calibration frames are not the same exposure length as your normal exposures: the *Flash or dark calibration* section of SUN/139[10] gives the details.

13.1.4 Large-scale structure in dome flats

Dome flats which are not evenly illuminated may show large-scale structure which must be removed. This correction can be made by modelling the structure using `fitsurface` in KAPPA and then subtracting the resulting fitted surface from the flat field.

14 Combining Target Images

Having produced several reduced images of a target object in a given colour, as in the previous two recipes, often the next step is to combine them into a single 'master' image of the object in that colour. Such a combined image will have an effective exposure time equivalent to the sum of the individual exposure times of the constituent images and hence will have an improved signal to noise ratio and fainter features will be visible. Indeed, this improvement in signal to noise ratio over the individual images is the principal reason for combining them. The reasons for taking several short exposures and then combining them, rather than taking one long exposure, are basically twofold: firstly to avoid saturation in the CCD and secondly to allow cosmic-ray hits to be detected and removed. Cosmic-ray hits occur randomly over the frame and in general will occur in different places in different frames. Therefore, by combining two images and looking for pixels where the signal is greatly different it is possible to locate and remove the hits.

In addition to combining images of the same patch of sky, a related technique is to combine images of partly overlapping regions of sky in order to build up a **mosaic**[2] of a larger area. This method is quite important for CCD data because of the limited field of view of CCDs. Figure 8 is an example of an image built up in this way.

In general, separate images notionally centred on the same object will not line up perfectly because of pointing imperfections in the telescope. That is, corresponding pixels in two images will not be viewing exactly the same area of sky. Such misalignments are inevitable if images taken on different nights are being combined and will occur to some lesser extent even if consecutive images are being combined. In other circumstances the frames may be deliberately offset slightly (or **jittered**) in order to compensate for the CCD pixels under-sampling the image or to reduce the effect of flat field errors. Before misaligned images can be combined they need to be lined-up. Conceptually, they are aligned by using stars (and other objects) in the frames as fiducial marks.

The displacement between the various images means that a region of sky which was imaged on a 'bad' pixel in one image may well have been imaged on a good pixel in the other images. Consequently the combined image may well contain significantly fewer 'bad' pixels than the individual images. However, it should be remembered that the amount of statistical noise present in any part of the combined image will be related to the total exposure time of the pixels which contributed to it. If part of the final image was visible on only one of the input images then it will have rather more noise associated with it than a part of the final image to which twenty input images contributed. This effect is often particularly noticeable around the edges of mosaics or combined images.

CCDPACK has various facilities for aligning (or **registering**) and combining images: they are illustrated in Figure 19. Which route is appropriate depends basically on how badly the images are misaligned and how crowded the fields being imaged are (that is, how many objects they

---

[2] Note that the term 'mosaic' is used in two similar but different ways in connection with CCD instruments. One usage is to denote images of a region of sky larger than the CCD camera's field of view which have been constructed by combining partly overlapping image frames, as introduced here. The other usage, introduced in Section 4.1, is to describe a CCD camera in which several abutting CCD chips are arranged in a grid in the focal plane. To complicate matters further, an instrument with a mosaic of CCD chips will often be used to observe a series of partly overlapping images which are subsequently combined to form a mosaic of a larger region of sky, not least because it is often necessary to partly overlap images from a mosaic of CCD chips in order to 'fill in' the regions surrounding the edges of the chips which cannot be observed.

contain). The usual techniques correct for the misalignment completely automatically. However, manual techniques are available as a fall-back for cases where the automatic ones fail.

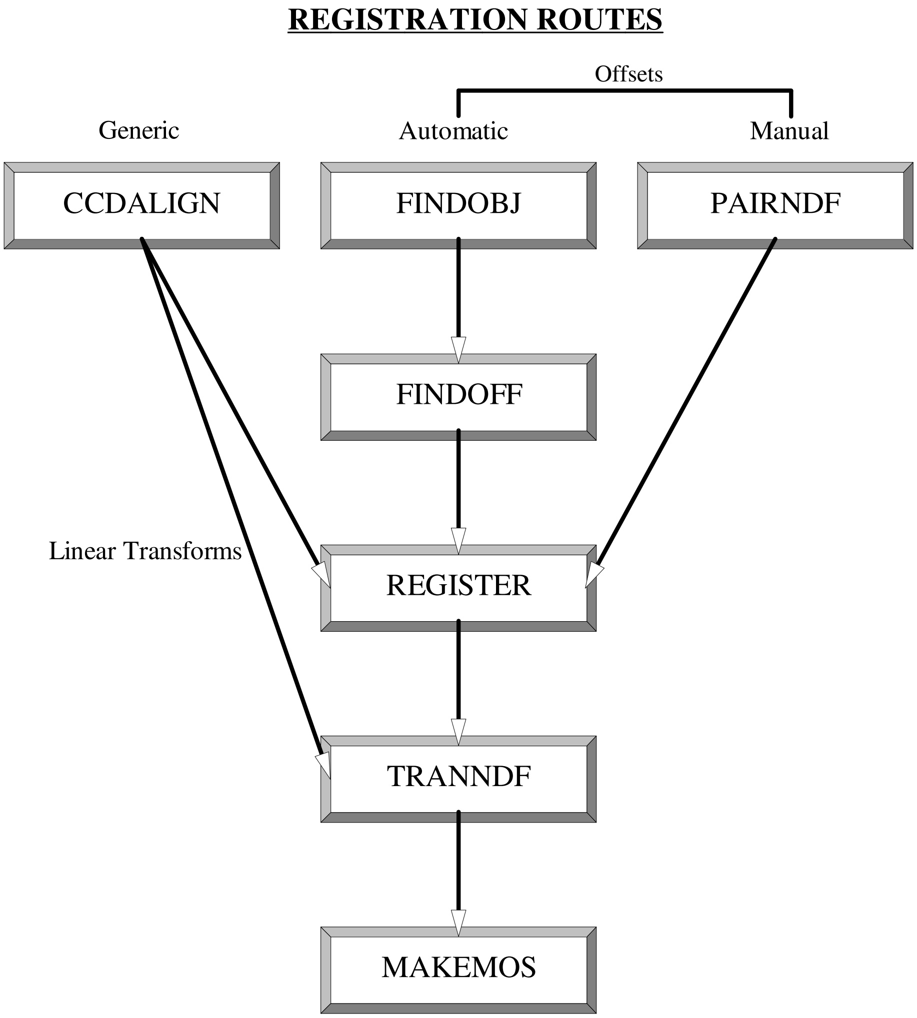


Figure 19: Routes for registering images with CCDPACK

In this recipe a simple x, y transformation is applied to align the two reduced images produced in the previous recipe. Consequently the following two files should be available:

```
ngc2336_r_1_deb_flt.sdf
ngc2336_r_2_deb_flt.sdf
```

Then proceed as follows.

(1) First find all the objects in each of the two images. Type:

```
% findobj in='targets/*_flt' outlist='*.find' accept
```

The lists of objects found in each frame will be written to files in the same directory with names derived from the corresponding input frame and file type '`.find`'. These files are simple text files and, if you wish, you can examine them with Unix commands such as `more`.

(2) The next steps are to identify corresponding objects in the two images, calculate the offset between the images and transform the input images so that they align. Type:

```
% findoff inlist='targets/*_flt' outlist='*.off' error=3 accept
% register inlist='targets/*_flt' fittype=1
% tranndf  in='targets/*_flt' out='*_reg'
```

Two transformed, registered images are created, called:

```
ngc2336_r_1_de\_flt_reg.sdf
ngc2336_r_2_deb_flt_reg.sdf
```

This sequence of steps should work correctly with the example data. However, with other data `findobj` or `findoff` may sometimes fail because they find an insufficient number of stars which are common to the two datasets. In this case the transformation must be defined manually using `pairndf`; see SUN/139 for further details.

(3) The final step is to combine these aligned images into a single master (or mosaic). Type:

```
% makemos in='targets/*_reg' out=targets/mosaic scale zero
```

All the images in subdirectory `targets` with names ending in '`_reg`' are combined into a single image called `mosaic.sdf`. The `scale` and `zero` options ensure that `makemos` correctly handles images of different exposure time, air mass and atmospheric transparency. The application will run somewhat faster if `scale` and `zero` are omitted, but if they are given it should produce sensible output from almost any input images.

For (UKIRT) infrared data the `scale` option does not work well. As the frames being combined are usually nearly contemporaneous and have the same integration time it is better to omit `scale` and just use the `zero` option.

By default `makemos` combines images using a method known as 'median stacking'. This technique involves extracting all the input pixel values that contribute to an output image pixel and sorting them into rank order. The median value is computed from this sorted list and adopted as the value of the output pixel. This technique both suppresses image noise and removes cosmic-ray hits. Other methods, such as the 'clipped mean', are available. See SUN/139[10] for full details.

(4) The combined image can be displayed in the usual fashion with GAIA. Type:

```
% gaia targets/mosaic.sdf &
```

Because it was created from just two input images the improvement in signal to noise over the individual images is modest.

(5) Finally, to delete the intermediate files created by the recipe move to the top level data directory and type:

```
% delete_combine_files.csh
```

15 Reading FITS Files from Tape

This recipe gives some hints about reading FITS files from magnetic tape. Often you will return from an observing run with one or more exabyte tapes, or similar, containing the data you have acquired. Before you can reduce and analyse these observations you need to copy them from tape on to a magnetic disk on your local Starlink computer system. The files are usually written on the tapes using the FITS format (see Section 6.2) and this is the only alternative considered here.

Before you can start you will need to find the name and physical location of a suitable tape drive and determine which computers can access it; your site manager should be able to advise. The next step is to physically load the tape into the drive; again see your site manager for details.

The simplest way to read the files from tape is to use application `fitsin` in KAPPA. It is fully documented in SUN/95[6]. However, briefly, each FITS file is converted to a disk file in the Starlink NDF (*n*-dimensional Data Format; see SUN/33[31]) format. The NDF format is the most convenient for subsequent processing with CCDPACK and other Starlink applications. The details are not particularly germane here, but all the auxiliary information in the original FITS keywords is preserved in the 'FITS' extension to the NDF.

You need to start KAPPA prior to running `fitsin`. Simply type:

```
% kappa
```

First example One example of using `fitsin` might be:

```
% fitsin mt=/dev/rmt/1n file='[2-4,9]' auto prefix=ccd nofmtcnv
```

Some points to note here are:

- files will be read from device `/dev/rmt/1n`,
- only files 2, 3, 4, and 9 will be read (files occur sequentially on the tape, the first file is numbered 1, the second 2 *etc*),
- NDF files will be created called '`ccd2.sdf`', '`ccd3.sdf`', '`ccd4.sdf`' and '`ccd9.sdf`',
- the `nofmtcnv` option specifies that data type conversion is not required: the NDF files will be created with the same data types (REAL, INTEGER or whatever) as the original FITS files.

Second example Another example might be:

```
fitsin mt=$TAPE files='*' auto prefix=ccd fmtcnv logfile=jkt.log
```

Points to note here are:

- prior to running the command, Unix shell variable `TAPE` should have been set to the name of the tape drive,

- `files='*'` indicates that all the files on the tape are to be read: here the asterisk is being used a 'wild-card',
- the NDF files created will have the prefix '`ccd`',
- a record of the headers and the names of the output files are written to the text file `jkt.log`,
- the `fmtcnv` option specifies that INTEGER data arrays in the input files will be converted to REAL arrays in the output NDF files. Standard keywords in the FITS file can be used to supply a zero point and scale factor for this conversion.

  Note that '`nofmtcnv`' is equivalent to and inter-changeable with '`fmtcnv=false`' or '`fmtcnv=no`' and similarly '`fmtcnv`', '`fmtcnv=true`' and '`fmtcnv=yes`' are equivalent.

If you experience problems reading FITS tapes then Section 17.10, *I've Got This FITS Tape*, of SUN/95[6] may contain some useful hints.

16 Handling Large Images

This recipe gives some hints about reducing large images with CCDPACK (see SUN/139[10]). Starlink data reduction applications, such as CCDPACK, do not on the whole have formal limits on image size. However, reducing very large sets of data can make heavy demands on system resources, which can lead to long run times, degradation of the performance (especially interactive response time) of the machine being used, failure of the applications, or in extreme cases system crashes. Even if you are of a patient disposition, these effects could make you unpopular with other users, so it is worth giving some additional thought to this sort of work.

16.1 How large is large?

What is and is not a problem large enough to require special care will depend on what is being done and on the computer being used. As a very rough indication, images smaller than 1000x1000 in most cases do not count as large, and ones larger than 5000×5000 in most cases (at the time of writing) do; for cases in-between it depends very much on the details.

The 'size' of a data reduction problem is some ill-defined function of, *inter alia:*

- **number of pixels per frame**,
- **number of objects**,
- **number of frames**: the number of bias and flat field frames to be processed will be important as well as the number of target object frames,
- **overlap of frames**: some parts of the reduction process which compare objects or backgrounds between frames will perform differently according to how much overlap in coverage there is between frames.

The principal resources which can fall into short supply during a data reduction process are as follows.

Memory: a computer has a fixed amount of real memory (RAM; Random Access Memory), and also a part of the disk called **swap space** which serves as an overflow if running processes need more memory than the available RAM. If there is insufficient real memory + swap space to run the program, it will fail. If there is insufficient real memory for the parts of the program and data which are used simultaneously to be loaded at once, a lot of time will be spent shifting data between RAM and disk, and the program (as well as other processes on the same machine) will run painfully slowly. Depending on the operating system and the way the machine is set up, either of these eventualities can lead to termination of other processes on the machine, or system crashes.

Disk space: if there is insufficient disk space the program will fail. If other processes are writing to the same disk partition they can fail too.

Input/Output: Input/Output (I/O) time, that is the time spent waiting for data to be read from and written to disk, will inevitably increase with large data sets. I/O speed is likely to be fairly similar between different low- or mid-range workstations and servers, except in the case where a resource is being used heavily by other processes at the same time; on a busy server this may be the norm.

CPU time: algorithms which are efficient with CPU (Central Processor Unit) time for small problems may become inefficient for large ones. Speed of execution varies quite a lot between different machines. Some guide is given by the nominal processor speed (in MHz or megaflops), but when processing large data sets on a modern workstation or server, the CPU time spent will normally be limited by memory bandwidth. Bandwidth is not usually quoted as prominently as processor speed, but is typically better on heavy duty servers than on smaller workstations.

Normally the statistic which will actually concern you is elapsed, or 'wall clock' time, that is the number of minutes or hours between starting a job off, and the results being available. For a large data reduction job most of this time will typically be spent in I/O, which may or may not include moving data between real memory and swap space. In a multi-user environment however it is important to consider how your use of the machine is affecting the elapsed times of other people's jobs, or other jobs of your own. As a general rule then, if your data reduction runs fast enough that it does not inconvenience you or other people then you do not have a 'large' problem. Otherwise, the rest of this recipe may provide some useful tips.

16.2 Limitation on NDF or HDS file sizes

The Starlink NDF format is a special case of the HDS (Hierarchical Data System; see SUN/92[32]) format. There is currently a fundamental limitation of HDS which will be corrected in a future release. Until then, there is a problem with HDS files longer than 512 Mbyte. Such files can result either from a user NDF file which is very long (for example, a 9000×9000 type _REAL frame with variances) or, more likely, from a file used as temporary workspace by CCDPACK or other applications.

This problem may not be reported as such by the software, but often manifests itself as an 'Object not found' error, which will cause the application to terminate. In this case there is not much which can be done apart from discussing the matter with the programmer responsible for supporting the package.

16.3 General tips

A full discussion of maximising performance for large jobs is beyond the scope of this document, but the following are good common-sense rules of thumb.

Run on a large machine: usually the more memory available the faster the job will run, since this reduces the amount of disk I/O needed.

Use local disks: disks attached to the machine running the job will be much faster than disks attached to another machine which are accessed remotely via the local network. It can also make a big difference to use a disk which no other process is making heavy use of at the time. Your system manager may be able to advise on choice of disk.

Be economical with disk space: while it may make sense to retain all intermediate files (for example, de-biassed, flat fielded, re-sampled frames) for small images, these can take up excessive disk space for large images. Scripts can be written to remove files as they go along, or appropriate options of the applications can be used (for example, `keepin=false` in CCDPACK's `debias` and `flatcor`). When thinking about disk space requirements, remember that large temporary files can be created by some of the applications. These files have names like `t123.sdf` and are created in the directory pointed to by the environment variable `HDS_SCRATCH`, or in the current directory if `HDS_SCRATCH` is not defined.

Discuss with your system manager and/or other users: if your job could have a serious effect on the system's performance it might be polite to ask if there are recommended ways of going about it, or to warn other users.

Run at off-peak times: if you can run your job at a time when few or no other processes are running on the machine in question it will run faster and inconvenience other users less. The Unix `at` command can be used to start a job at a given time, or there may be other queuing software installed at your site.

Be `nice` to other processes: on Unix the commands `nice` or `renice` should be used when running CPU-intensive jobs on multi-user machines. In the C shell typing:

```
% nice +18 reduce_script
```

would run the script `reduce_script` at a 'niceness' of 18. This setting means that the job will be less aggressive in requesting CPU time, thus making it run slower, but causing less disruption to other processes (presumably ones with more moderate requirements). The higher the niceness, the less demanding the job is, with 18 often a sensible maximum. Ask your system manager for more details; there may be locally recommended values for certain kinds of job. Note however that the only resource usage this affects is CPU time, so that even a maximally `nice`d job can cause major disruption.

Keep an eye on the job: if your job might push the system to its limits, especially if you have not run one of similar size before, it is a good idea to monitor its progress, for instance to check that the system's swap space or file system is not filling up (using, for example, `top` and `df` respectively).

16.4 Bottleneck applications in CCDPACK

Some parts of the data reduction process are much more expensive than others, and these are not always the same for large images as for small ones.

The maximum frame size which can be treated is determined mainly by the memory required. Exactly how this limitation manifests itself is quite dependent on the system, but if the size of the process is much bigger than available real memory it is likely to run very slowly. There may also be local guidelines about the largest processes which may be run on given machines. Table 1 gives a guide to how memory use of the most demanding CCDPACK applications scales with frame size.

Briefly, the heaviest users of resources are:

memory: `debias`; then `makebias`, `flatcor`, `makeflat` and `tranndf`,

	Variance		No variance	
	Mask	No mask	Mask	No mask
`debias` (with bias frame)	8.25	6.0	7.25	5.0
`flatcor`	5.5	5.5	2.75	2.75
`makeflat`	4.5	4.5	2.75	2.75
`makebias`	3.0	3.0	3.0	3.0
`tranndf`	2.75	2.75	2.75	2.75
`ardmask` (KAPPA)		4.0		4.0

Table 1: Words required per pixel for the largest CCDPACK applications. The memory usage of most CCDPACK applications scales with the number of pixels per image. This table gives the number of (4 byte) words required per pixel when the calculations are being done at _REAL (4 byte) precision. So, for example, `debiassing` a 4000×4000 frame with variances and a bad pixel mask at _REAL precision requires around $4000 \times 4000 \times 8.25 \times 4$ bytes ≈ 500 Mbyte. The values in this table are meant only as a rough indication; for some of the applications memory use is a more complex function of the details of the task than suggested here

CPU time: `makemos` (normalisation); then `tranndf`. Sometimes `findoff`,

I/O: `debias`; then `makeflat`, `makemos` (normalisation).

Elapsed time for a data reduction sequence will usually be dominated by `debias` or the normalisation part of `makemos`, or under some circumstances `findoff`. More detail is given for some of these in the next section.

16.5 Specific tips

The following tricks are applicable when using several of the Starlink applications. To use some of the commands in the examples you will need to start KAPPA (see SUN/95[6]) by typing `kappa` at the C shell prompt. These commands (`erase`, `ndftrace`, `parget`, `settype`, `ndfcopy`, `paste`, `ardmask`, `compave`, `compadd` and `compick`) are described fully in SUN/95; but by way of a quick explanation, the `ndftrace`, `parget` pair tells you one thing about the NDF being queried.

Omit variances: variance information doubles the size of NDFs on disk and for many of the applications substantially increases the CPU and memory usage. Often it is not required, or if it is can be satisfactorily estimated from the data themselves. If you do not need it, then do not generate and/or propagate it. To omit the variance set parameter `genvar=false` either in `ccdsetup` or in `debias` and `makebias`. If you wish to remove the VARIANCE component from a frame which already contains it, you can use the KAPPA command `erase`:

```
% ndftrace frame quiet
% parget variance ndftrace
TRUE
% erase frame.variance
OK - The HDS object FRAME.VARIANCE is to be erased. OK ? /NO/ > yes
% ndftrace frame quiet
% parget variance ndftrace
FALSE
```

Use an appropriate data type: possible data types for storage of the pixel values in NDFs are:

Data Type	Size (bytes)
_BYTE, _UBYTE	1
_WORD, _UWORD	2
_INTEGER, _REAL	4
_DOUBLE	8

The type _WORD is usually sufficient for storage of most of the intermediate NDFs required in a data reduction sequence (the exception is `makeflat` which always generates a master flat field of type _REAL or _DOUBLE). If your data type is _INTEGER, _REAL or _DOUBLE therefore it can be worth reducing it to one of the smaller types. The KAPPA programs `ndftrace` and `settype` can be used to determine and modify respectively the type of data in an NDF, as in this example:

```
% ndftrace frame quiet
% parget type ndftrace
_REAL
% settype frame _WORD
% ndftrace frame quiet
% parget type ndftrace
_WORD
```

Reducing the size of the data type may increase or reduce the CPU time requirements of the program, but should reduce the memory and I/O requirements. Under certain circumstances using a two-byte type can lead to overflow errors however, so some caution should be exercised.

Compact NDFs: sometimes applications generate or modify NDFs to contain additional empty space; you can tell if this is the case by examining the file using `ndftrace` to work out the approximate size it should be and comparing this with the size shown by `ls`. If disk space is very tight, and you do not want to delete files, such oversized NDFs can be compacted using the KAPPA application `ndfcopy`. For example, using the file of reduced data type created above:

```
% ls -s frame.sdf
2047 frame.sdf
% ndfcopy frame compacted_frame
% ls -s compacted_frame.sdf
```

```
1027 compacted_frame.sdf
% mv compacted_frame.sdf frame.sdf
```

Treat images in sections: when faced with really large images, the only way to process them may be by breaking them up into sections. This can be done using NDF sections as described in SUN/95[6], for example:

```
% flatcor in=huge"(:,:4000)" flat=master_flat"(:,:4000)" out=bottom
% flatcor in=huge"(:,4001:)" flat=master_flat"(:,4001:)" out=top
% paste bottom top out=huge_flatcor
```

Reduce image resolution: in the event that image resolution is better than required, the size of the frames can be reduced by using one of the KAPPA applications `compave`, `compadd` or `compick`. If the averaged pixels are still small enough to under-sample the image point spread function this approach will be ok; otherwise it is rather a waste of good data, but may be useful for taking a quick look at oversized frames.

Finally, we list the most demanding of the CCDPACK applications with some notes about each one.

`debias`**:** `debias` is the heaviest user of memory and so is where problems are most likely to arise. The following suggestions are possible ways of limiting the resources used:

Masking: if the `mask` parameter is set (to the name of an image or ARD file) then more memory is required. It can therefore be more efficient to apply the mask explicitly elsewhere in the reduction sequence, for example, to the bias frame prior to debiassing:

```
% ardmask in=master_bias out=masked_bias ardfile=mask.dat
% debias in="data?" out="debias_*" bias=masked_bias \
        getmask=FALSE
```

instead of:

```
% debias in="data?" out="debias_*" bias=master_bias \
        getmask=TRUE mask=mask.dat
```

Variances: using variances will also have a big impact on the requirements of `debias`, and so should be avoided (using `genvar=false`) if possible.

Bias frames: de-biassing using the bias strips rather than a master bias frame (see Sections 5.2 and 13.1) reduces the work done by `debias` and also makes it unnecessary to process the bias frames at all. This technique will lead to inferior de-biassing, but can represent significant savings, and using frames from modern CCDs may give quite satisfactory results.

`makemos`**:** the normalisation part of `makemos`, if performed, is usually the most CPU intensive part of the data reduction process, although this depends on how numerous and how large the regions of overlap between frames are. The process should therefore be omitted if it is not required. Normalisation is performed only if one or both of the parameters `scale` and `zero` is `true` (both default to `false`): set `scale=true` only if multiplicative corrections might be required (for example, if the individual input images have differing exposure times) and set `zero=true` only if additive corrections might be required (for example, if the images have different background levels). If it must be performed, the following measures may decrease execution time, possibly at the expense of accuracy:

- if `scale` but not `zero` is being used and the images have variance information then set `cmpvar=false`,
- if there are many multiply-overlapping frames then set the parameter `optov` (optimum number of overlaps) to a small number (such as one),
- the normalisation is usually an iterative process, so it is possible to tweak the parameters controlling the iteration (`maxit`, `tols`, `tolz`).

`findoff`: this application uses one of two algorithms to match objects between frames for determining their relative offset. The first algorithm scales as n^2 (where n is the number of objects found by `findobj`), but if this fails it normally falls back on a more reliable algorithm which scales as $n^3 \ln n$. In this case, and if there are many objects, `findoff` can be very slow indeed and come to dominate the whole reduction process. Failure of the fast algorithm is also more likely when there are very many objects. For both these reasons it can be a good idea to limit the number of objects found by `findobj` – a few tens of objects in the overlap region is about right. You can control the number of objects found by by modifying the `minpix` parameter: the higher this threshold is set the fewer objects `findobj` will identify in the image.

More detailed information on each of these applications can be found in SUN/139[10].

Part III

The Scripts

17 Introduction

This part of the cookbook provides a set of scripts to assist with various aspects of reducing CCD images. The scripts embody some of the 'tricks of the trade' of reducing CCD data and either automate part of the process by allowing you to process a set of files or string several individual applications together to provide some useful functionality. The scripts are written for the Unix C-shell and should be run from the Unix command line. They suffer from the usual limitation of scripts that they are neither as flexible nor as robust as an application program. However, they do provide additional useful functionality. Also, they have been deliberately kept simple and commented in order to make it easy for you to modify them for your own purposes. The use of Starlink applications from shell scripts is discussed further in SC/4: *C-shell Cookbook*[4].

The scripts available are:

- convert files to a new data format (Section 18),
- clip an image (Section 19),
- process compressed files (Section 20),
- examine specified FITS keywords (Section 21),
- automatically scale an image display (Section 22).

On Starlink systems the scripts are kept in directory:

```
/star/examples/sc5/scripts
```

You should copy the scripts to your current directory before using them. The examples included in the following descriptions of the scripts assume that your current directory is the subdirectory `targets` of the example data directory used in the recipes in the previous part of the document and that you have worked through the previous recipes for reducing CCD observations (Sections 9 to 14). The examples should work as given in this case.

The current collection of scripts is not comprehensive. If you have a script which you think could usefully be included in this document then please contribute it. Similarly, suggestions for additional scripts which we could provide are welcome. In both cases contact the Starlink Software Librarian (e-mail `starlink@jiscmail.ac.uk`) in the first instance. New versions of the cookbook including additional scripts will be issued from time to time.

18 Convert to a New Data Format

Script `changetype.csh` converts one or more input files to a new data format. The formats available include: NDF, FITS and IRAF OIF: see SUN/55[7] for a full list. The actual format conversion is carried out by KAPPA application `ndfcopy` and most of the rest of the script is concerned with checking that the file names are valid and generating suitable input and output names. You give the script a list of one or more input files and the output file type required.

Example

(1) To convert a single file to the GIF image display format type:

```
% changetype.csh ngc2336_r_2.sdf gif
```

File `ngc2336_r_2.gif` will be generated. It can be displayed with, for example, the `xv` utility. (If you do display the image with `xv` it will appear mostly black because the dynamic range is dominated by a few very bright pixels. Use the histogram equalisation option to show more details.)

(2) As a second, and perhaps more useful, example, to convert all the NDF files in the directory to FITS type:

```
% changetype.csh '*.sdf' fit
```

19 Clip an Image

Script `clipim.csh` ‘clips’ an image. That is, the image is displayed, you choose a sub-image with the cursor and this selected region is saved as a separate file. The script uses the KAPPA applications `display`, `cursor` and `ndfcopy`.

Example

To clip the file `ngc2336_r_2.sdf` type:

```
% clipim.csh ngc2336_r_2.sdf ngc2336_small.sdf}
```

The clipped image will be saved in file `ngc2336_small.sdf`. Note that to avoid ambiguity the ‘`.sdf`’ file type must be included in the file name here. Also note that you must follow the instructions carefully if the script is to work correctly.

20 Process Compressed Files

Script `doapp.csh` allows you to apply an application to a series of compressed files. It is useful if disk space is scarce. The files are assumed to have been compressed with the Unix utility `compress`. Each file is, in turn, decompressed, processed and recompressed. In the script provided application `histpeak` in ESP is used to determine the median value of the image and this value is output to a text file. This effect is achieved by writing `histpeak`'s output to a temporary file and then using the Unix utilities `grep` and `awk` to extract the details required.

It is relatively straightforward to change `doapp.csh` to perform some other processing. For example, script `dostats.csh` is a modified version which uses KAPPA application `stats` to find the mean of each image. Using the Unix command `diff` on scripts `doapp.csh` and `dostats.csh` will show the lines that need to be changed to produce a modified script which performs some other processing.

The input for either script consists of the names of one or more files to be processed (wild-cards are permitted) and the name of the output text file.

Example

(1) Before giving an example of using the script it is necessary to create some compressed files for it to work on. Type:

```
% compress *.sdf
```

The compressed files retain their original name but have the additional file type '`.Z`'.

(2) To examine a single file type:

```
% doapp.csh ngc2336_r_2.sdf.Z result.txt
```

File `ngc2336_r_2.sdf.Z` will be decompressed, examined, and recompressed. The result will be written to file `result.txt`.

(3) Alternatively, all the compressed files can be processed. Type:

```
% doapp.csh '*.Z' results.txt
```

Here the results are written to file `results.txt`.

(4) The use of `dostats.csh` is similar. Type:

```
% dostats.csh '*.Z' stats.txt
```

and the results will be written to file `stats.txt`.

(5) For the purpose of this example you will probably want to decompress the files once you have finished. Type:

```
% uncompress *.Z
```

Obviously you would omit this stage if you were using the scripts 'for real' and disk space was scarce.

21 Examine Specified FITS Keywords

Often you will want to know the value of a given FITS keyword for each of a set of FITS files. It is straightforward to find the value of a keyword for a single file, but doing so manually can be tedious if have dozens (or hundreds) of files. Script `fitsinfo.csh` addresses this problem and gives the value of a named keyword for each of a set of FITS files.

Each FITS file is examined in turn and KAPPA application `fitslist` is used to list the contents of the header cards to a text file. The Unix utility `grep` is then used to extract the line for the required keyword from the file and this line is appended to the output file.

You give the script a list of input files (wild-cards are permitted), the required keyword (which must be in upper case) and the name of the output file in which the results are to be written.

Example

To find the value of keyword `EQUINOX` for all the FITS files in the current directory type:

```
% fitsinfo.csh '*.fit' EQUINOX fitsdetails.txt
```

The values found are written to file `fitsdetails.txt`.

22 Automatically Scale Displays

A common problem with astronomical images is that a few pixels at the centre of a bright star or galaxy will dominate the dynamic range of the image. If the range of intensities displayed is simply set from the dynamic range the faint details close to the sky background will not be visible. Script `scaledisp.csh` addresses this problem and determines a range of intensities to be plotted which are closer to the background.

it uses `histpeak` in ESP to determine the sky background level and a measure of its variation. The measure used is the mean absolute deviation, α, defined as:

$$\alpha = \frac{1}{n} \sum_{i=1}^{n} \mid x_i - \overline{x} \mid \tag{6}$$

α is more robust than the more familiar standard deviation (because it is less sensitive to outlying values). It is also usually smaller. The image is plotted using KAPPA application `display`.

Script `saodisp.csh` is similar to `scaledisp.csh`, but uses the image display program SAOIMAGE (see SUN/166[21]).

The input for either script consists of the name of the image to be displayed and the minimum and maximum intensities to be displayed. The minimum intensity is specified as the number of α below the sky background and the maximum as the number of α above the sky background.

Example

(1) To display a scaled image with KAPPA's `display` type:

```
% scaledisp.csh ngc2336_r_2.sdf 1  5
```

File `ngc2336_r_2.sdf` is displayed. The minimum intensity is $1 \times \alpha$ below the sky background level and the maximum intensity is $5 \times \alpha$ above it.

(2) To display the same image with SAOIMAGE and similar scaling type:

```
% saodisp.csh ngc2336_r_2.sdf 1  5
```

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Any mistakes, of course, are our own.

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