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The CCD Photometric Calibration Cookbook

Abstract

This cookbook presents simple recipes for the photometric calibration of CCD frames. Using these recipes you can calibrate the brightness of objects measured in CCD frames into magnitudes in standard photometric systems, such as the Johnson-Morgan *UBV* system. The recipes use standard software available at all Starlink sites.

The topics covered include: selecting standard stars, measuring instrumental magnitudes and calibrating instrumental magnitudes into a standard system. The recipes are appropriate for use with data acquired with optical CCDs and filters, operated in standard ways, and describe the usual calibration technique of observing standard stars. The software is robust and reliable, but the techniques are usually not suitable where very high accuracy is required.

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 calibration of observations.

Who Should Read this Cookbook?

This cookbook is aimed firmly at people who are new to astronomical photometry. Typical readers might have a set of photometric observations to reduce (perhaps observed by a colleague) or be planning a programme of photometric observations, perhaps for the first time. No prior knowledge of astronomical photometry is assumed.

The cookbook is not aimed at experts in astronomical photometry. Many finer points are omitted for clarity and brevity. Also, in order to make the most accurate possible calibration of high-precision photometry, it is usually necessary to use bespoke software tailored to the observing programme and photometric system you are using.

Revision history

1. 25 April 1997: Version 1. Original version (JP).
2. 29 January 1998: Version 2. Added recipes for extracting standard stars from catalogues and calibrating instrumental magnitudes. Also re-arranged much of the existing material (ACD).
3. 8 June 1999: Version 3. Added material for infrared photometric systems and atmospheric transmission (ACD).
4. 31 August 2001: Version 4. Revised the recipes to correspond to GAIA version 2.6 and CURSA version 6.3. Added an additional label to allow external hyper-links to Appendix B.2. Also revised the references and URLs (ACD).

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1 Introduction

> For the **photographical magnitudes** much work has been done at Harvard College. In the Cape photographic Dm data about such magnitudes are contained for all the stars south of declination $-19°$, down to about 9.5, together with a great mass of fainter ones.
>
> The difficulty of reducing all these magnitudes to one and the same *homogeneous* and *rational* scale has however, not been altogether overcome.
>
> *Plan of Selected Areas*,
> J.C. Kapteyn, 1906.

Nearly a century has passed since Prof. Kapteyn made this remark and during the intervening period much effort has been devoted to developing techniques for the proper calibration of astronomical photographs and latterly CCD images. The techniques for calibrating CCD images are now well established. However, they must be applied carefully if accurate results are to be obtained.

In essence, astronomical photometry is concerned with measuring the brightness of celestial objects. CCD (Charge-Coupled Device) photometric calibration is concerned with converting the arbitrary units in which CCD images are recorded into standard, reproducible units. In principle the observed brightness could be calibrated into genuine physical units, such as W m^{-2}, and indeed this is occasionally done. However, in optical astronomy it is much more common to calibrate the observed brightness into an arbitrary scale in which the brightness is expressed relative to the brightness of well-studied 'standard' stars. That is, the stars chosen as standards are being used as 'standard candles' to calibrate an arbitrary brightness scale.

The reasons for wanting to calibrate CCD frames are virtually self-evident. Once an image has been calibrated it can be compared directly with other photometrically calibrated images and with theoretical predictions. The calibration of CCD frames is simplified because CCD detectors have a response which is usually for all practical purposes linear; that is, the size of the recorded signal is simply proportional to the observed brightness of the object.

This cookbook provides a set of simple recipes for the photometric calibration of CCD frames and sufficient background information about astronomical photometry to allow you to use these recipes effectively. The structure of the cookbook is:

Part I – background material,

Part II – the recipes.

You should not require any prior knowledge of astronomical photometry to use the cookbook. Part I gives the necessary background information. You should realise, however, that it only covers the basics of the subject and in sufficient detail to allow you to use the recipes effectively. Many of the finer points and details are deliberately omitted for clarity and brevity. However, references to additional details are given throughout and the next section gives some useful general references. In summary, the cookbook will not turn you into an expert in astronomical photometry, but it does give recipes which you can use for the photometric calibration of CCD frames.

It is not necessary to read the cookbook sequentially from beginning to end. You can skip some or all of the background material if you are already familiar with it. Similarly, the individual recipes are independent of each other and you can use just the ones appropriate for your purposes.

It is also worth noting that astronomical photometry is a diverse subject. There are many different ways of making and reducing photometric observations. Observations can be made for very different types of programmes and require very different standards of accuracy. The cookbook describes the most common method of calibrating observations using standard stars. This method is not the only one, nor always appropriate. You might, for example, only be interested in the relative brightness of two objects, or the brightness of an object relative to the night sky. Some of the recipes in the cookbook are not appropriate in these cases.

It is usually necessary to correct for various instrumental effects which are present in CCD images, such as bias signal, flat field sensitivity variations and cosmic-ray events, before they can be photometrically calibrated. These corrections are usually referred to as 'CCD data reduction' and should be carried out before you attempt the photometric calibration. CCD data reduction is not described in this cookbook, but is covered in the companion document SC/5: *The 2-D CCD Data Reduction Cookbook*[18], which is a good introduction. It is not considered further here.

2 Further Reading

There are a number of good introductory texts on astronomical photometry. For a gentle introduction to the use of CCDs in photometry, try some of the articles in 'amateur' astronomy magazines, such as the one by Kaitchuck, Henden and Truax[46].

A good, detailed introduction is *Astronomical Photometry* by Henden and Kaitchuck[38]. The similarly titled *Astronomical Photometry — A Guide* by Sterken and Manfroid[67] is a much more technical and rigorous treatment. Another useful and detailed text is Straižys' *Multicolor Stellar Photometry*[70]. There are also a number of good articles in the conference proceedings *Astronomical CCD Observing and Reduction Techniques*[39].

The chapter 'Photoelectric Reductions' by Hardie in *Astronomical Techniques*[35] is a classic treatment of the reduction of photometric observations. However, it predates the introduction of CCD detectors and seems a little dated now.

3 Typographic Conventions

The following typographic conventions are used in this cookbook.

```
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' font
like this.
```

Lines that are to be typed into the computer are shown beginning with a `%` sign, for example:

```
% photom
```

The % indicates the Unix 'shell prompt' and should not be typed in. However:

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

Finally:

> **items of particular importance are shown in bold and indented paragraphs like this one.**

Asides and points of interest are usually shown as footnotes.

Part I

Background Material

4 Introduction

This section briefly gives some background information about astronomical photometry. It starts with the basic definitions and equations of radiation theory. Subsequent topics include: the definition of the magnitude scale, photometric systems, atmospheric extinction, selecting and observing standard stars and finally techniques for measuring and calibrating the magnitudes of objects recorded in CCD frames.

You do not have to read the sections sequentially. You can skip some of the sections if you are already familiar with the material that they cover. Indeed, if you are already familiar with the background to astronomical photometry you can skip this part of the cookbook entirely and go straight to the recipes in Part II.

5 Intensity, Flux Density and Luminosity

This section recapitulates some of the basic concepts and equations of radiation theory. Further details can be found in any standard introductory textbook on astrophysics. One such classic text is Unsöld's *The New Cosmos*[74]. However, there are numerous suitable textbooks. Assume some radiation passing through a surface and consider an element of the surface of area dA (Figure 1). Some of the radiation will leave the surface element within a beam of solid angle $d\omega$ at an angle θ to the surface. The amount of energy entering the solid angle within a frequency range $[\nu, \nu + d\nu]$ in a time dt will be:

$$dE_\nu = I_\nu \cos\theta \, dA \, d\nu \, d\omega \, dt \tag{1}$$

where I_ν is the **specific intensity** of radiation at the frequency ν in the direction of the solid angle, with dimensions of W m^{-2} Hz^{-1} sr^{-1}.

The intensity including *all* possible frequencies, the **total intensity** I, can be obtained by integrating over all frequencies:

$$I = \int_0^\infty I_\nu \, d\nu \tag{2}$$

From an observational point of view we are generally more interested in the energy flux or **flux** (L_ν, L) and the **flux density** (F_ν, F)[1]. Flux density gives the power of the radiation per unit area and hence has dimensions of W m^{-2} Hz^{-1} or W m^{-2}. Observed flux densities are usually extremely small and therefore (especially in radio astronomy) flux densities are often expressed in units of the **Jansky** (Jy), where 1 Jy = 10^{-26} W m^{-2} Hz^{-1}.

If we consider a star as the source of radiation, then the flux emitted by the star into a solid angle ω is $L = \omega r^2 \, F$, where F is the flux density observed at a distance r from the star (it

[1] You should be aware - and beware - that different authors define the terms flux density, flux and intensity differently, and they are sometimes used interchangeably!

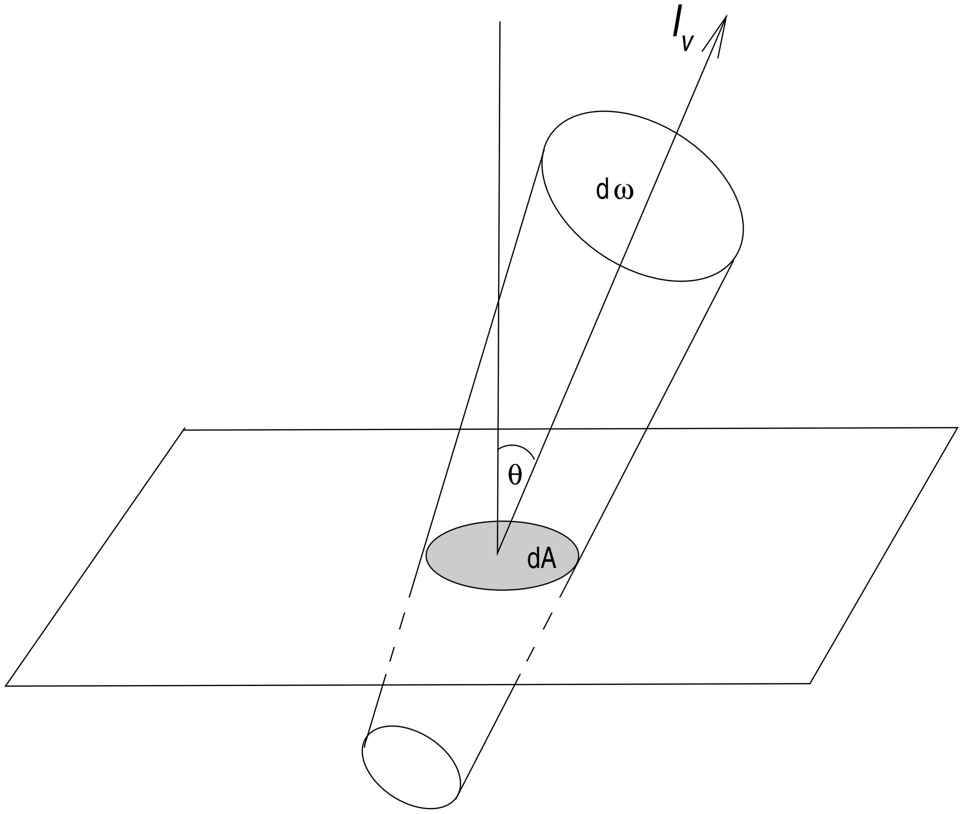

Figure 1: Relationship between radiation intensity, I_v, and energy passing through a surface element of area dA into a solid angle $d\omega$ at an angle of θ to the surface

is also usual to refer to the total flux from a star as the **luminosity**, L). If the star radiates isotropically then radiation at a distance r will be distributed evenly on a spherical surface of area $4\pi r^2$ and hence we get the relationship:

$$L = 4\pi r^2 \; F \tag{3}$$

The situation is slightly more complicated for an extended luminous object such as a nebula or galaxy. The **surface brightness** is defined as the flux density per unit solid angle. The geometry of the situation results in the interesting fact that the observed surface brightness is *independent* of the distance of the observer from the extended source. This slightly counter-intuitive phenomenon can be understood by realising that although the flux density arriving from a *unit* area is inversely proportional to the distance to the observer, the area on the surface of the source enclosed by a unit solid angle at the observer is *directly* proportional to the square of the distance. Thus the two effects cancel each other out.

6 Magnitudes

Traditionally in optical astronomy the brightness of stars is measured in **magnitudes**. This system has its origins in classical antiquity. In 120 BC Hipparchus classified naked-eye stars into six groups or magnitudes, with the first class comprising the brightest stars and the sixth the faintest. The scale was based on the progressive visibility of stars during the onset of twilight. The duration of twilight was divided into six equal parts and the stars that became visible during the first part were assigned the first magnitude, those that became visible during the second part the second magnitude and so on.

The response of the human eye to the brightness of light is not linear but more nearly logarithmic. In 1856 Norman Pogson defined the modern magnitude scale in a way which corresponded closely to the historical subjective classifications. He defined the ratio between two brightness classes n and $n+1$ as $\sqrt[5]{100} \simeq 2.512$. If we define an arbitrary 'standard' flux density F_0, then the **apparent magnitude**, m, of any source with an observed flux density F is defined by:

$$m = -2.5 \log \frac{F}{F_0} \tag{4}$$

So the magnitudes[2] of any two stars with observed flux densities of F_1 and F_2 are related by:

$$m_1 - m_2 = -2.5 \log \frac{F_1}{F_2} \tag{5}$$

The system discussed so far is reliant on flux density which is a function of distance from the star, and so says nothing of the intrinsic brightness of the star itself. The **absolute magnitude**, M, is defined as the apparent magnitude of a star that would be observed at a distance from it of 10 parsec[3]. Considering the flux density at 10 parsec and the observed distance r parsec we can say:

[2] Some magnitudes : Sirius = -1.5, full Moon = -12.5, Sun = -26.8

[3] Strictly speaking this is the apparent magnitude which would be observed in the absence of interstellar extinction (see Appendix A).

$$\frac{F(r)}{F(10)} = \left(\frac{10}{r}\right)^2 \tag{6}$$

So the relationship between apparent and absolute magnitudes is given by:

$$m - M = -2.5 \log \frac{F(r)}{F(10)} = -2.5 \log \left(\frac{10}{r}\right)^2 \tag{7}$$

or

$$m - M = 5 \log \frac{r}{10} \tag{8}$$

which is more usually written as:

$$m - M = 5 \log r - 5 \tag{9}$$

Though the use of the magnitude scale is ubiquitous in optical astronomy it is worth bearing in mind that it has three major drawbacks (see Hearnshaw[37]):

- it is an inverse scale, with fainter stars having larger magnitudes,
- it is a logarithmic scale,
- the base of the logarithm is 2.512.

7 Photometric Systems

The intensity of the light emitted by stars and other astronomical objects varies strongly with wavelength. Thus, the apparent magnitude, m, observed for a given star by a detector depends on the range of wavelengths to which the detector is sensitive; a detector sensitive to red light will usually record a different brightness than one sensitive to blue light.

The first estimates of stellar magnitudes were made either using the unaided eye or later by direct observation through a telescope. Magnitudes estimated in this way are referred to as **visual magnitudes**, m_v[4]. The sensitivity of the human eye peaks at a wavelength of around 5500Å.

The **bolometric magnitude**, m_{bol}, is the notional magnitude measured across *all* wavelengths. Clearly the bolometric magnitude cannot be measured directly, because of absorption in the terrestrial atmosphere (see Section 8) and the practical difficulties of constructing a detector which will respond to a sufficiently wide range of wavelengths. The **bolometric correction** is the difference between m_v and m_{bol}:

[4] The last major catalogues compiled using magnitudes estimated by direct observation are the great *Durchmusterungen* produced in the late nineteenth and early twentieth centuries: the *Bonner Durchmusterung*, the *Bonner Südliche Durchmusterung* and the *Cordoba Durchmusterung*. However, the visual system is still in use, particularly for variable-star work. The various extensive archives of variable-star data consist largely of visual observations, mostly contributed by amateurs.

$$m_{bol} = m_v - BC \tag{10}$$

Note, however, that sometimes the opposite sign is given to BC. The concept of a bolometric magnitude is only really applicable to stars, which to a first approximation emit thermal radiation as black bodies. The bolometric correction is used to derive an approximation to the bolometric magnitude from the observed one. It would clearly be absurd to try to apply a bolometric correction to the observed visual magnitude of some exotic object which was emitting most of its energy non-thermally in the X-ray or radio regions of the spectrum. Schmidt-Kaler[65] gives tables of stellar bolometric corrections.

Another type of magnitude which is sometimes encountered is the **photographic magnitude**, m_{pg}. Photographic magnitudes were determined from the brightness of star images recorded on photographic plates and thus are determined by the wavelength sensitivity of the photographic plate. Early photographic plates were relatively more sensitive to blue than to red light and the effective wavelength of photographic magnitudes is about 4200Å. Note that photographic magnitudes refer to early plates exposed without a filter. Using a combination of more modern emulsions and filters it is, of course, possible to expose plates which are sensitive to different wave-bands.

However, modern photometric systems are defined for photoelectric, or latterly, CCD detectors. In modern usage a **photometric system** comprises a set of discrete wave-bands, each with a known sensitivity to incident radiation. The sensitivity is defined by the detectors and filters used. Additionally a set of primary standard stars are provided for the system which define its magnitude scale. Photometric systems are usually categorised according to the widths of their passbands:

wide band systems have bands at least 300Å wide,

intermediate band systems have bands between 300 and 100Å,

narrow band systems have bands no more than a few tens of Å wide.

The optical region of the spectrum is only wide enough to accommodate three or four non-overlapping wide bands. A plethora of photometric systems have been devised and a large number remain in regular use. The criteria for designing photometric systems and descriptions of the more common systems are given by Sterken and Manfroid[67], Straižys[70], Lamla[49], Golay[32] and Jaschek and Jaschek[40]. Some of the more common ones are summarised below.

Johnson-Morgan *UBV* System The Johnson-Morgan UBV wide-band system[43, 44] is easily the most widely used photometric system. It was originally introduced in the early 1950s. The longer wavelength R and I bands were added later[42]. Table 1 includes the basic details of the Johnson-Morgan system and Figure 2 shows the general form of the filter transmission curves. Tabulations of these curves are given by Jaschek and Jaschek[40].

The Johnson-Morgan R and I bands should not be confused with the similar, and similarly named, bands in the Cousins VRI system[13, 14]. The Cousins V band (complemented by U and B) is identical to the Johnson-Morgan system. However, the Cousins R and I bands

respectively have wavelengths of 6700Å and 8100Å and thus both are bluer than the corresponding Johnson-Morgan bands. They are usually indicated by $(RI)_C$, where 'C' stands for 'Cape'. For further details see Straižys[70], pp294-296 and pp309-312.

The zero points of the UBV system are chosen so that for a star of spectral type A0 which is unaffected by interstellar reddening (see Appendix A) $U = B = V$. Despite its ubiquity the UBV system has some disadvantages. In particular, the short wavelength cutoff of the U filter is partly defined by the terrestrial atmosphere rather than the detector or filter. Thus, the cutoff (and hence the observed magnitudes) can vary with altitude, geographic location and atmospheric conditions.

System	Band	Effective Wavelength	Bandwidth (FWHM)
		Å	Å
visual	m_v	~ 5500	-
photographic	m_{pg}	~ 4250	-
Johnson-Morgan	U	3650	680
	B	4400	980
	V	5500	890
	R	7000	2200
	I	9000	2400
Strömgren	u	3500	340
	v	4100	200
	b	4670	160
	y	5470	240
		μm	μm
$JHKLM$	J	1.25	0.38
	H	1.65	0.48
	K	2.2	0.70
	L	3.5	1.20
	L'	3.8	0.6
	M	4.8	5.70

Table 1: Details of common photometric systems. The values are taken from *Astrophysical Quantities*[1], except those for the $JHKLM$ system which are taken from Sterken and Manfroid[67] and those for the L' band which are from the UKIRT on-line documentation

Strömgren System Another widely used system is the Strömgren intermediate-band *uvby* system[71, 72]. The details of this system are included in Table 1. Filter transmission curves for the Strömgren system are given by Jaschek and Jaschek[40]. Strömgren y magnitudes are well-correlated with Johnson-Morgan V magnitudes.

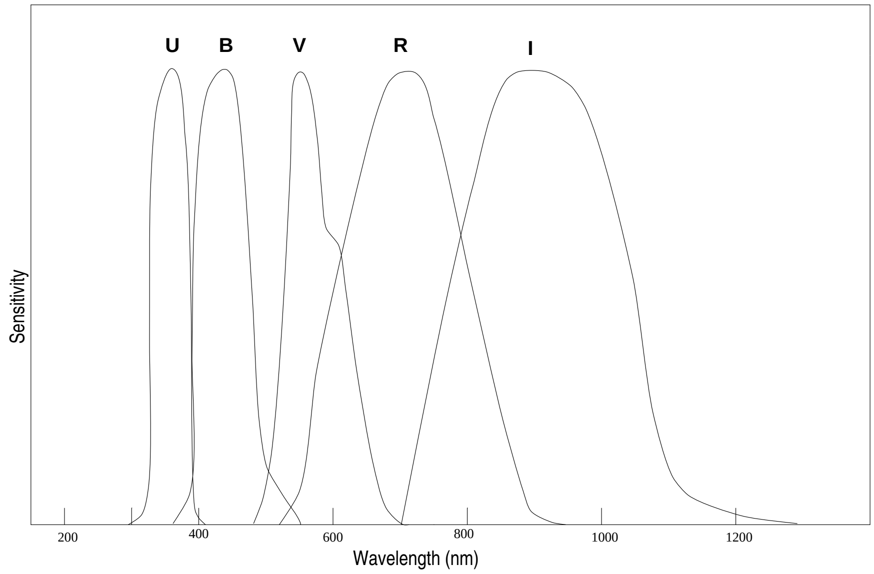

Figure 2: Relative transmission profiles of the $UBVRI$ filters. The transmission maxima have been normalized

$JHKLM$ **System** The $JHKLM$ system is an extension of the UBV system to longer wavelengths. It was originally introduced by Johnson and his collaborators though modern versions of it derive from the work of Glass[29]. Details of the system are included in Table 1. The bands are matched to, and share the same names as, the windows in which the terrestrial atmosphere is transparent at infrared wavelengths (see Section 8.1). The L' band is a later addition. It is better matched to the corresponding atmospheric window than the the original L band.

The $JHKLM$ system is less well-standardised than other systems and each observatory will often define its own system which differs slightly from the others. These differences arise because the atmospheric windows which are transparent at infrared wavelengths are themselves different at different observatories and, in particular, vary with altitude. Consequently, great care must be exercised in inter-comparing $JHKLM$ observations made at different observatories. Table 2 summarises some of the more common $JHKLM$ systems. For further details see Bersanelli *et al.*[4], Bouchet*et al.*[5] and Straižys[70], pp292-307. Leggett[54] gives details of the transformations between the various infrared systems. Simons and Tokunaga[66] have recently reported an attempt to standardise infrared photometric systems.

As for the original Johnson-Morgan system, the zero point of the *JHKLM* system is defined so that an unreddened A0 star has the same magnitude in all colours: $J = H = K = L = M (= U = B = V)$. The standard star used is Vega (α Lyræ).

Observing programmes which use a given photometric system need not necessarily observe in all the bands of that system. Often only some, or perhaps even only one, of the bands will be used. The choice of bands will be dictated by the aims of the programme and the observing time available.

System	Institute	Bands	Reference
Arizona	Lunar and Planetary Lab.	$JKLM$	Johnson[41]
SAAO	South African Astron. Obs.	$JHKL$	Glass[29]
		$JHKL$	Carter[6, 7]
ESO	European Southern Obs.	$JHKLM$	Wamsteker[76]
		$JHKL$	Engels *et al.*[26]
AAO	Anglo-Australian Obs.	$JHKL'$	Allen and Cragg[3]
MSO	Mount Stromlo Obs.	JHK	Jones and Hyland[45]
CIT	California Inst. Technol.	JHK	Frogel *et al.*[28]
		$JHKL$	Elias *et al.*[25, 24]
UNAM	Univ. Autonoma de Mexico	$JHKL'M$	Tapia *et al.*[73]
UKIRT	Joint Astron. Centre, Hawaii	JHK	Casali and Hawarden[8]

Table 2: Common *JHKLM* systems. Adapted from Bersanelli *et al.*[4]

7.1 Colour indices

A photometric system with more than one band is formally called a **multi-colour system** (though in practice most photometric systems are multi-colour). For any multi-colour system a series of **colour indices**, or colloquially **colours**, can be defined. A colour index is simply the difference between the magnitude of a given object in any two bands. For example, in the UBV system the $B - V$ index is simply the V magnitude subtracted from the B magnitude[5]. Multi-colour photometry is usually published as a single magnitude and a set of colours rather than a set of magnitudes.

7.2 Standard and instrumental systems

When a standard photometric system is first set up the detectors and filters used define its passbands. Also the originators of the system will typically observe and publish a set of standard stars which define the magnitude scale for the system.

Subsequently, instrumentation for observing in the system will be built at other observatories. There are, for example, many observatories with photometers and CCDs capable of observing in the Johnson-Morgan system. However, the original passbands can never be reproduced precisely, even if the original instrumentation is simply copied and similar filters are purchased from the same manufacturers. The system in which the new instrumentation actually observes is called its **natural** or **instrumental** system. In this cookbook the standard system to which a given instrumental system approximates is called the **target** standard system. Usually considerable effort is expended to make the instrumental system match the target standard system as closely as possible[6].

[5] *En passant*, for stars $B - V$ is primarily related to temperature (and hence spectral class) while $U - B$ is a more complex function of both luminosity and temperature.

[6] Clearly, instrumentation will be designed so that the combination of detector and filters matches the target system as closely as possible. However, there are a number of potential pitfalls. One is that most of the older photometric systems were originally set up using photoelectric detectors. Modern CCDs are usually relatively more sensitive in the red and less in the blue than photoelectric detectors (see Figure 3). Thus, a CCD detector

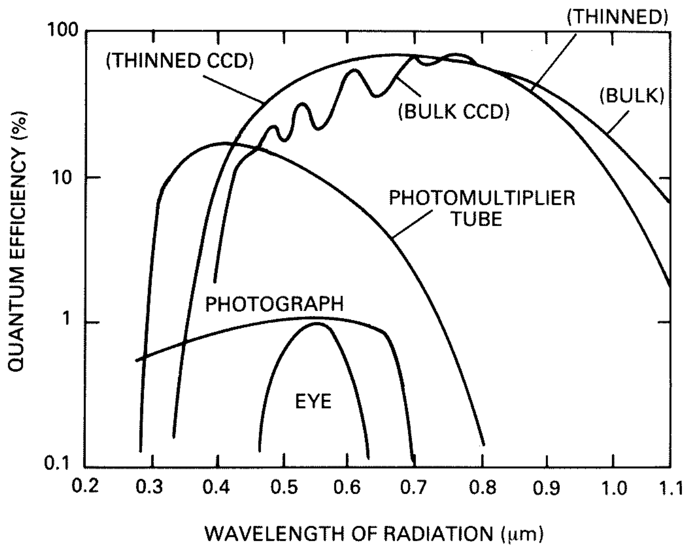

Figure 3: The sensitivity or quantum efficiency as a function of wavelength for various types of detectors. The quantum efficiency is simply the fraction of incident photons which are detected. Here it is plotted on a logarithmic scale. Thinned and bulk CCDs are simply different types of CCDs. Photomultiplier tubes are used in photoelectric photometers. Note that CCDs are more sensitive to red light than photomultiplier tubes. Adapted from McLean[56]

However, in order to make reproducible observations one of the calibrations which must be done is to convert instrumental to standard magnitudes. Conceptually this calibration is done be re-observing the standard stars for the system and comparing the instrumental and standard magnitudes. If the instrumental system is a good match to the standard system then it may be possible to compare just the corresponding bands in the two systems. Conversely, if the two systems are less well-matched or high precision is required then the standard magnitude may have to be computed from the corresponding band in the instrumental system with corrections using the colour indices.

7.3 Catalogues of standard stars

There are many catalogues of photometric standard stars. A catalogue of primary standards for a given photometric system is usually published when the system is defined. For widely used systems further catalogues of 'secondary' standards will often be compiled by making observations calibrated with the original primary standards. Recent catalogues of standards are usually available in a computer-readable form.

Johnson-Morgan system The primary standards for the Johnson-Morgan system are listed in various places, including the original publications. See, for example, Zombeck[81], p101. These standards are often too bright (and too few in number) for modern instrumentation and programmes, and catalogues of fainter (and more numerous) secondary standards are often more useful.

Some suitable catalogues of secondary standards are: Johnson and Morgan[44], Landolt[50, 51, 52, 53], Christian *et al.*[9], Graham[30] and Menzies *et al.*[57, 58]. Landolt's catalogues are, perhaps, the most useful.

Strömgren system For catalogues of standards in the Strömgren system see Grønbech and Olsen[34], Grønbech, Olsen and Strömgren[33] and references therein.

$JHKLM$ **system** For catalogues of standards in the $JHKLM$ system see Straižys[70], pp305-307 and also the references in Table 2.

7.3.1 Computer-readable catalogues

Some of the recipes in Part II of this cookbook use the CURSA package (see SUN/190[16]) for manipulating catalogues of standards. A small collection of photometric standard catalogues in a format accessible to CURSA is available by anonymous ftp. This collection includes most of Landolt's catalogues. The details are:

will usually use a different or additional set of filters to match a given system than a photoelectric detector. Another potential problem is that some filters are prone to 'leakage'. Here the filter correctly blocks light at wavelengths surrounding the required passband but becomes transparent again at very different wavelengths (so, for example, a filter which correctly defined the R band might also leak light at much shorter wavelengths, perhaps corresponding to the U or B bands). If leakage occurs it is necessary to use an additional filter, a so-called blocking filter, to remove the extraneous light. The choice of filters to match photometric systems is far beyond the scope of this cookbook and as an observer using CCD detectors neither will it normally concern you. However, it is useful to be aware of some of the potential problems.

Anonymous ftp to:	`ftp.roe.ac.uk`
Directory:	`/pub/acd/catalogues`
File:	`photostandards.tar.Z`

Remember to reply `anonymous` when prompted for a username and to give your e-mail address as the password. You should use ftp in binary mode. `photostandards.tar.Z` is a compressed tar file and should be de-compressed with `uncompress` (sic). See Section 13 for more details.

Other sources of computer-readable versions of catalogues of photometric standards are the Centre de Données astronomiques de Strasbourg (CDS) and the US Astronomical Data Center (ADC). These institutions now keep many of the catalogues in their collections permanently on-line and you can retrieve copies via anonymous ftp or the World Wide Web. Briefly, the CDS and ADC may be contacted as follows.

CDS URL: `http://cdsweb.u-strasbg.fr/CDS.html`

Electronic mail: `question@simbad.u-strasbg.fr`

Postal address: Centre de Données astronomiques de Strasbourg, Observatoire de Strasbourg, 11, rue de l'Université, 67000 Strasbourg, France.

ADC URL: `http://adc.gsfc.nasa.gov/`

Electronic mail: `request@nssdca.gsfc.nasa.gov`

Postal address: World Data Center A for Rockets and Satellites, NASA, Goddard Space Flight Center, Code 633, Greenbelt, Maryland 20771, USA.

8 Atmospheric Extinction and Air Mass

An effect which must be corrected when calibrating instrumental magnitudes is the **atmospheric extinction** or the dimming of starlight by the terrestrial atmosphere. The longer the path length the starlight traverses through the atmosphere the more it is dimmed. Thus, a star close to the horizon will be dimmed more than one close to the zenith, and the observed brightness of a given star will change throughout a night, as its zenith distance varies.

The path length through the atmosphere is known as the **air mass**. Consider an observation through the blanket of the atmosphere around the curved surface of the Earth. At any particular wavelength, λ, we can relate $m_0(\lambda)$, the magnitude of the observed object outside the atmosphere, to $m(\lambda)$, the magnitude of the observed object at the surface of the earth, by:

$$m(\lambda) = m_0(\lambda) + \kappa(\lambda)X(z) \tag{11}$$

where $X(z)$ is the air mass, $\kappa(\lambda)$ is the **extinction coefficient** at wavelength λ and z is the zenith distance (the angular distance of the object from the zenith at the time of observation). X is defined as the number of times the quantity of air seen along the line of sight is greater than the quantity of air in the direction of the zenith and will vary as the observed line of sight moves away from the zenith, that is, as z increases. Note that the air mass is a normalised quantity and the air mass at the zenith is one.

For small zenith angles $X = \sec z$ is a reasonable approximation, but as z increases, refraction effects, curvature of the atmosphere and variations of air density with height can become important. Hardie[35] gives a more refined relationship:

$$X = \sec z - 0.0018167(\sec z - 1) - 0.002875(\sec z - 1)^2 - 0.0008083(\sec z - 1)^3 \quad (12)$$

and Young and Irvine[80] propose:

$$X = \sec z \left(1 - 0.0012(\sec^2 z - 1)\right). \quad (13)$$

Both these equations imply the use of z_t, the *true* zenith angle, that is, the zenith angle to the observed object *in the absence of the atmosphere* as opposed to the *apparent* zenith angle z_a affected by refraction effects.

For purposes of illustration the approximate air mass is tabulated as a function of zenith distance in Table 3. Note that the air mass remains quite small for $z < 45°$, reaches 2.0 at $z = 60°$ and increases rapidly thereafter.

z	$X = \sec z$	z	$X = \sec z$
0°	1.00	40°	1.31
5	1.00	45	1.41
10	1.02	50	1.56
15	1.04	55	1.74
20	1.06	60	2.00
25	1.10	65	2.37
30	1.16	70	2.92
35	1.22		

Table 3: Approximate air mass, X, as a function of zenith distance, z

The atmospheric extinction coefficient, $\kappa(\lambda)$, can be determined by observing the same object (through an appropriate filter) at several times during the night at varying zenith angles. When the observed magnitudes of the object are plotted against computed air mass (see Figure 4), they should lie on a straight line with a slope equal to $\kappa(\lambda)$. It is important to note that the extinction is dependent upon wavelength, being greater for blue light than red.

8.1 Atmospheric transmission at infrared wavelengths

Traditionally the infrared region of the spectrum was considered to be wavelengths just longer than the reddest colours visible to the human eye, typically about 7000Å or (0.7μm). However, in modern astronomical usage wavelengths up to about 10,000Å (or 1μm) tend to be described as 'optical' and longer wavelengths as 'infrared'. This terminology reflects both a change in the type of detector used and the behaviour of the terrestrial atmosphere at about 10,000Å. It is cumbersome to quote infrared wavelengths in Ångström and they are usually given in micron. The infrared region stretches to about 350μm; longer wavelengths are referred to as the sub-millimetre part of the spectrum.

The terrestrial atmosphere is largely opaque at most infrared wavelengths longer than 1μm, largely due to absorption by water vapour and carbon dioxide. However, there are a series

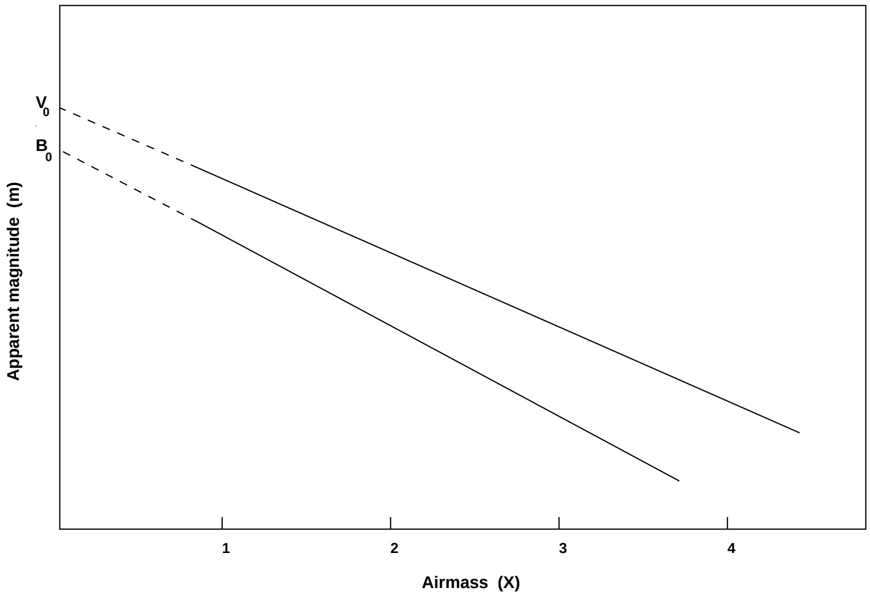

Figure 4: How to determine atmospheric extinction coefficients by plotting apparent magnitudes against air mass throughout the night

of wavelength ranges or **windows** where the atmosphere is mostly transparent (see Figure 5). Ground-based infrared observations must be made in these windows. Each window corresponds to a band in the $JHKLM$ system (see Section 7) and the corresponding band and window have the same name.

The width, maximum transmission and, to an extent, central wavelength of the windows vary with geographical location and in particular with altitude. They also vary with the current meteorological conditions. The windows are particularly sensitive to the amount of water vapour, which is why infrared observatories tend to be at high, dry sites. The variation in the infrared windows at different locations is the underlying reason for different versions of the $JHKLM$ system being used at different observatories, as mentioned in Section 7.

9 Selecting and Observing Standard Stars

This section describes some common practices for selecting and observing standard stars. To recapitulate: the purpose of observing standard stars is to allow the instrumental magnitudes measured for programme objects to be converted into calibrated magnitudes in the target standard photometric system. The effects which the calibration must remove are atmospheric extinction and the mismatch between the instrumental and standard systems.

Though the procedures described here are often good practice they are not always appropriate. Clearly you should tailor your choice of standards and observing practices to the aims of your programme. Indeed, there are some sorts of photometric programme for which it is un-necessary to observe standard stars at all.

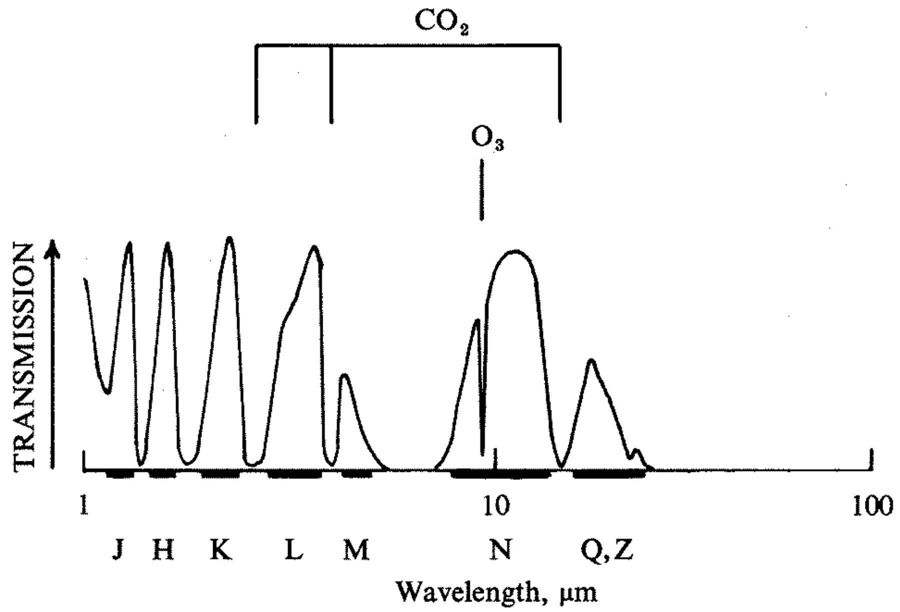

Figure 5: Atmospheric transmission at infrared wavelengths. The windows where the atmosphere is largely transparent are marked. The short-wavelength windows correspond to bands in the *JHKLM* photometric system. Note the additional N, Q and Z windows at longer wavelengths. Adapted from Allen[2]

9.1 Selecting standard stars

You will usually select standards from either the computer-readable or printed versions of catalogues of standard stars (see Section 7.3). If you are observing in the Johnson-Morgan system then Landolt's catalogues are probably the most useful.

You should not use catalogues of standards blindly. Rather, you should read the paper or other documentation accompanying the catalogue; it will contain details of the limitations, applicability and use of the catalogue which you should be aware of in order to use it effectively. Also, standards from different catalogues should not normally be mixed in a given observing programme.

The desirable properties for a set of standard stars include the following:

- a range of zenith distances (and hence air masses) similar to, but slightly larger than, those of the programme objects. Also the range in air mass should be at least 1.0. Since the air mass at the zenith is 1.0, to get a range of 1.0 you need to observe at an air mass of at least 2.0, corresponding to a zenith distance of 60° (see Table 3). A reasonable upper limit to the air mass for observing standards is about 2.5 (though this will depend on the site),
- a range of celestial coordinates similar to those of the programme objects (this criterion is, of course, related to the previous one),
- a range of colours and magnitudes which are similar to (or slightly larger than) those of the programme objects.

These criteria are really merely special cases of the usual requirement that calibrators should occupy a similar volume of parameter space as the things which they are calibrating.

The number of standard stars chosen will vary depending on the aims of your programme. However, for most purposes fifteen to twenty is probably adequate. The advantage of having this number of standards is that a representative range of air masses, magnitudes and colours can be sampled.

Section 13 gives a recipe for selecting standard stars from a computer-readable catalogue.

9.2 Observing standard stars

Because transient variations in atmospheric conditions can cause unpredictable variations in the atmospheric extinction it is necessary to regularly monitor the standard stars throughout a night's observing. When making photometric observations care and caution pay dividends. A typical strategy might be to start the night's observing with a series of observations of standard stars, covering a range of zenith distances. These observations can be used to make a preliminary estimate of the atmospheric extinction. Then as the night progresses observations of standards are regularly interspersed amongst the observations of programme objects.

Often modern observatories will have software which allows approximate 'rough and ready' reductions to be carried out in near real time, thus allowing instrumental magnitudes to be computed for the standard stars *pari passu* the continuing observations. This facility is extremely useful because it allows the atmospheric extinction to be monitored as the night progresses.

However, reductions carried out during the observing session are only approximate. They are useful for monitoring the atmospheric extinction, but are not the most accurate results obtainable from the observations.

> **You should always reduce your data after the observing session has finished, starting from the full set of observations.**

Passing clouds and light mist will obviously affect the atmospheric extinction. Furthermore, they can be difficult to detect by eye, even if you regularly look outside the telescope dome (it is difficult to see light cloud at night with eyes that are not dark-adapted). However, it is easy to spot any deterioration in the observing conditions if the atmospheric extinction is being monitored regularly. Observations of programme objects can be suspended until good conditions return. Using these techniques, and with good conditions and modern instrumentation, it is perfectly feasible to carry out photometry to an accuracy of 0.01 magnitude without resorting to any special tricks.

> **It is prudent to keep a note of the Right Ascension, Declination and UT or sidereal time of each observation (for both standard stars and programme objects) as it is made. Usually (though not always) the air mass or zenith distance will be calculated automatically and added to the header information for each observation as it is written. However, if you have kept your own notes you can calculate these quantities yourself if necessary, either as a check or because they are not otherwise available. (See Appendix B for further details of calculating the zenith distance.)**

10 Measuring Instrumental Magnitudes

The first step to producing a set of calibrated magnitudes for your list of programme objects is to measure the **instrumental magnitudes** of the programme objects and standard stars recorded in your CCD frames. Instrumental magnitudes are usually measured relative to the sky background in each CCD frame. Prior to measuring the instrumental magnitudes the various instrumental effects should be removed from the CCD frames. Typically you will need to de-bias and flat-field the frames and remove the effects of bad pixels (possibly including whole bad rows and columns) and cosmic-ray events. The CCDPACK package (see SUN/139[19]) is available for this task. The cookbook SC/5: *The 2-D CCD Data Reduction Cookbook*[18] gives a set of recipes for removing instrumental effects and is a good introduction to the topic. The support staff at the observatory where your observations were made should be able to advise about any peculiarities associated with the CCD detector that you were using.

Once the CCD frames have been corrected for instrumental effects they are ready to be used to measure instrumental magnitudes. There are two classes of techniques for measuring instrumental magnitudes in widespread use: **aperture photometry** and **point-spread-function fitting**. There are numerous variations on each technique, but the essentials of the two methods are as follows.

Aperture photometry The principle of aperture photometry is simple. For the star which is to be measured a circular region of the CCD frame (or 'aperture') is defined which entirely encloses the image of the star (that is, all the light from the star falls inside the aperture)[7]. The flux in all the pixels inside the aperture is added to give the total flux. A similar measurement is made of a region containing no stars to give the flux from the background sky. The two are then subtracted to yield the flux from the star. The same principle may be applied to extended objects such as galaxies or nebulæ, though here an elliptical aperture may be used. Packages for performing aperture photometry include PHOTOM (see SUN/45[22]) and GAIA (see SUN/214[20]).

Point-spread-function fitting This technique is used to measure images in crowded star fields, such as the central regions of a globular cluster. In such regions the images of individual stars overlap and it is impossible to position an aperture so that it simultaneously includes all the light from a given star and excludes all the light from its neighbours. Stars are, of course, unresolved by a conventional telescope and the star images recorded in a CCD frame simply trace out the point-spread function of the telescope. For a properly designed telescope the point-spread function will be independent of the position of the star in the focal plane, at least for positions close to the optical axis. The point-spread-function fitting technique makes the underlying assumption that all the star images have the same shape. Since CCD detectors are usually positioned on the optical axis and have a small field of view this assumption is usually valid. The light distribution in the CCD frame is modelled by assuming positions and brightnesses for the observed stars and knowing the point-spread function (it can be measured using isolated stars). The positions and brightnesses of the stars are iteratively varied until the observed light distribution in the CCD frame is reproduced. The actual mathematical details are not important here (and vary between different packages).

It is possible to perform accurate photometry of crowded regions using point-spread-function fitting. However, it is clearly important that all the images should have the same profile. Thus, the presence of extended objects with their own unique profiles will invalidate the technique.

The DAOPHOT (see SUN/42[23] and Stetson[68]) and STARMAN (see SUN/141[62]) packages are available for point-spread-function fitting. However, their use is beyond the scope of this cookbook and they are not considered further here.

In the case of aperture photometry the instrumental magnitude, m_{inst}, is defined as:

$$m_{\mathrm{inst}} = A - 2.5 \log_{10} \left[\frac{(\sum_{i=1}^{n} C_i) - nC_{\mathrm{sky}}}{t} \right] \tag{14}$$

where:

A is an arbitrary constant which is often added to the instrumental magnitudes,

C_i is the count in the ith pixel inside the aperture,

C_{sky} is the average count in a background sky pixel,

[7] The name of the technique comes from an earlier generation of astronomical instrumentation when photometry was carried out with a single-element photoelectric photometer. A circular aperture was placed in front of the photometer to limit its view of the sky. Using software to define a circular region in a CCD frame mimics the effect of a physical aperture limiting the field of view of a single-element photometer.

n is the number of pixels in the aperture,

t is the integration time of the frame.

That is, the instrumental magnitude is computed from the sum of the pixels inside the aperture with the average sky background subtracted. For simplicity the number of pixels inside the aperture, n, has been presented as an integer number here. However, if necessary pixels which partly overlap the aperture can be properly accounted for. There are various ways of measuring the average[8] sky background value. One is to use an aperture positioned on a neighbouring region of blank sky, another is to use an annulus surrounding the original aperture; this latter technique is perhaps preferable. Though the details of the point-spread-function fitting technique are very different the definition of the instrumental magnitude is the same.

It is often a good idea to set the arbitrary constant, A, to a silly value (say 30) so that the instrumental magnitudes have very different values from the corresponding calibrated magnitudes and hence the two are unlikely to be inadvertently confused.

You will need to determine instrumental magnitudes for all your programme objects and standard stars and in all the colours in which you made observations. Section 14 gives a recipe for measuring instrumental magnitudes using PHOTOM and Section 15 one using GAIA.

11 Calibrating Instrumental Magnitudes

The purpose of calibrating instrumental magnitudes is to convert them into magnitudes in the target standard photometric system. To fix ideas, think of the target system as being the Johnson-Morgan UBV system. You can think of the calibrated magnitudes as the magnitudes which would be recorded by a detector which perfectly matched the standard UBV system and was operating above the terrestrial atmosphere. The magnitudes and colours recorded by such a detector still do not correspond to the intrinsic colours of the object observed because of the effects of interstellar material in-between the object and the detector. Interstellar material reddens and dims light which passes through it. However, correcting the effects of interstellar reddening and extinction is normally considered to be part of the astrophysical interpretation and analysis of the observations rather than routine data reduction. Interstellar extinction and reddening are briefly described in Appendix A, but not otherwise considered in this cookbook.

Thus, calibrating instrumental magnitudes consists of correcting two effects:

- discrepancies between the instrumental and target standard systems,
- atmospheric extinction.

Any given instrumental magnitude is, of course, simultaneously affected by both these effects. Two distinct cases can be considered for performing the calibration:

[8] Though it is simplest to think of determining the average sky background level, in practice a straightforward mean is often not a good measure of the sky background, because of contamination of the chosen region by faint stars. Instead techniques are often used which minimise the effects of outlying values in the sky background histogram, such as computing the median instead of the mean.

1. the instrumental system is well-matched to the target standard photometric system,
2. the instrumental system is less well or poorly matched to the standard system.

In the first case the detectors and filters used have been chosen carefully to match the responses of the target standard system as closely as possible. Thus, for example, the transmission profiles of an instrumental *UBVRI* system would be similar to those for the standard system shown in Figure 2. Often the instrumental system will closely match the corresponding standard one (and considerable effort and attention will have been expended at the observatory providing the instrumentation to ensure that this is the case). Staff at the observatory should be able to advise on how well matched the systems are. Other useful sources of information are handbooks, World Wide Web pages, newsletters and instrument manuals issued by the observatory. SG/10: *Preparing to Observe*[63] includes a list of URLs for the Web pages of the observatories usually used by British astronomers.

The two cases of whether the instrumental and target standard system are well or less well matched really correspond to whether it is necessary to make a colour correction when calibrating the instrumental magnitudes. The judgement of whether or not the target and instrumental systems are well matched is not absolute, but rather will depend on the precision which you wish to achieve in your photometry, which in turn will depend on the astronomical aims of your programme. Sets of observations made with the same instrumentation for different programmes may well be reduced with or without colour corrections, depending on the accuracy required and the aims of the programmes. In particular, if observations are only made in a single band then clearly colour corrections cannot be made. The following section discusses the simpler case of calibration without a colour correction and the subsequent one calibration with colour corrections.

Finally, there are types of programmes where it is not necessary to calibrate instrumental magnitudes into standard magnitudes. For example, if you are only interested in determining the periods of a variable star then these periodicities can be extracted from a time series of instrumental magnitudes as easily as from one of calibrated, standard magnitudes. (However, in this particular case it is still, of course, necessary to correct for atmospheric extinction).

11.1 Calibration without a colour correction

Calibration without a colour correction is appropriate when the instrumental system is well matched to the target standard system. The calibrated magnitude is computed solely from the corresponding instrumental magnitude. Because magnitudes are logarithmic quantities and the standard and instrumental systems are being assumed to be well matched the principal difference between them is a zero-point correction. In this case the relation between instrumental and calibrated magnitudes is of the form:

$$m_{\mathrm{calib}} = m_{\mathrm{inst}} - A + Z + \kappa X \tag{15}$$

where:

m_{calib} is the calibrated magnitude,

m_{inst} is the instrumental magnitude,

A is an arbitrary constant which is often added to the instrumental constants,

Z is a photometric zero point between the standard and instrumental systems,

κ is the atmospheric-extinction coefficient,

X is the air mass.

For programme objects A is arbitrarily chosen by you, m_{inst} is measured and X is known (remember that the air mass depends solely on the zenith distance which, in turn, can be calculated from the celestial coordinates of the object, the location of the observatory and the time of observation; see Section 8 and Appendix B). Z and κ are constants which are initially unknown. Once they have been determined Equation 15 can be used to calculate the calibrated magnitudes.

There are various methods of determining Z and κ. For example, if a single standard star[9] is repeatedly observed throughout the night then the instrumental magnitude can be plotted against the air mass. Such a plot should be a straight line with a slope of κ. Figure 4 shows a schematic example of such a plot.

However, the most common method of determining the constants is to intersperse observations of your programme objects with observations of standard stars. Suitable standard stars will typically have been selected from one of the catalogues of standard stars (see Sections 7.3 and 9). For each of the observations of standard stars m_{calib} is known in addition to m_{inst}, A and X and it is possible to simply solve for Z and κ using least squares or some similar technique.

Once Z and κ have been determined Equation 15 can be used to simply calculate the calibrated magnitudes for the programme objects.

Thus, in essence, photometric calibration consists of making a least squares (or similar) fit to a series of observations of standard stars to determine the photometric zero point and the atmospheric extinction coefficient. However, such a fit should not be made blindly. (At least) the following caveats should be borne in mind.

1. Z depends on the details of the instrumentation (CCD detector, filter, telescope *etc.*) and should remain fairly constant throughout an observing run. However, atmospheric extinction definitely varies from night to night[10]. Hence:

   observations of standard stars should only be used to calibrate observations of programme objects made on the same night.

   That is, observations made on different nights should be calibrated separately.

2. When a fit is made to the standard-star observations, the individual residuals should be examined, any observations with large residuals discarded and the remaining observations re-fitted. Passing clouds and other transient phenomena can cause temporary variations leading to aberrant and invalid observations.

[9] Strictly speaking it is not necessary to use a standard star; any star can be used as long as it is not variable on the time-scale of a night's observing.

[10] Obviously the atmospheric extinction depends on the prevailing atmospheric conditions. An unusual example of variation caused by atmospheric conditions is the disruption following the eruption of Mount Pinatubo, as described by Forbes *et al.*[27].

3. The residuals and/or the coefficients themselves should be plotted as a function of time of observation throughout the night. Systematic variations can occur during a single night and it may be necessary to discard the observations for a portion of the night or make separate fits for different parts of the night.

Section 16 gives a simple recipe for calibrating photometric observations without a colour correction.

11.2 Calibration with colour corrections

Calibration with colour corrections is usually appropriate in two cases:

- where the instrumental system is not well matched to the target standard system,
- where very high precision photometry is being carried out and even small discrepancies between the instrumental and target standard systems must be corrected for.

Calibration with colour corrections is similar to calibration without a colour correction. The calibrated magnitude is still computed from the instrumental magnitude in the corresponding band in a manner similar to Equation 15. However, an additional term is added corresponding to a colour index determined from an adjacent band. This term compensates for the mismatch between the instrumental and standard systems. For example, for the Johnson-Morgan UBV system the calibration formulæ are:

$$\begin{aligned}
U &= U_{\rm inst} - A_u + Z_u + C_u(U - B) + \kappa_u X \\
B &= B_{\rm inst} - A_b + Z_b + C_b(B - V) + \kappa_b X \\
V &= V_{\rm inst} - A_v + Z_v + C_v(B - V) + \kappa_v X
\end{aligned} \tag{16}$$

where:

U, B and V are the calibrated magnitudes in the three bands,

$U_{\rm inst}$, $B_{\rm inst}$ and $V_{\rm inst}$ are the instrumental magnitudes in the three bands,

A_x is an arbitrary constant which is often added to the instrumental constants,

C_x is the colour-correction term,

Z_x is the photometric zero point between the standard and instrumental systems,

κ_x is the atmospheric extinction coefficient,

X is the air mass, and

subscripts $x = u, b, v$ refer to the individual bands.

The operational procedure is similar to that for calibration without a colour correction. For a set of observations of standard stars Z_x, C_x and κ_x (where $x = u, b, v$) are unknowns which can be solved for by least squares fitting of Equations 16. Once the coefficients have been determined, they can be used to compute the calibrated magnitudes of the programme objects. For really accurate work more-complex equations including higher-order terms may be introduced. For example:

$$V = V_{\mathrm{inst}} - A_v + Z_v + C_1(B-V) + \kappa_v X + C_2 X(B-V) + \cdots \tag{17}$$

Sometimes the atmospheric-extinction coefficient is not constant, but includes a colour term. That is:

$$\kappa = \kappa' + \kappa''(\text{colour index}) \tag{18}$$

where κ' and κ'' are constants. Often κ'' is sufficiently small that κ can be assumed to be constant. If the colour term is significant then the lines in Figure 4 will appear curved.

The three cautionary caveats given in the preceding section for calibrating without colour corrections are equally, if not more, applicable when colour corrections are included. Briefly: programme objects should only be calibrated with observations of standards made on the same night, when standards are fitted the residuals should be examined individually and aberrant observations discarded and the residuals should be checked for systematic trends.

Often bespoke software is used for reducing photometric observations with colour corrections, partly because the colour correction terms used will depend on the bands that were observed. There is no recipe for calibration with colour corrections in this cookbook. Further discussions are given by Massey *et al.*[55], Da Costa[15], Harris *et al.*[36] and Stetson and Harris[69].

Part II

The Recipes

12 Introduction

This part of the cookbook provides a set of simple recipes for performing various parts of the photometric calibration process. The recipes are widely applicable and straightforward to follow. However, they are not appropriate if very-high-precision results are required. The recipes are:

- selecting standard stars (Section 13),
- measuring instrumental magnitudes using PHOTOM (Section 14),
- measuring instrumental magnitudes using GAIA (Section 15),
- calibrating instrumental magnitudes (Section 16).

The recipes are independent of each other; you can simply choose the ones which are appropriate for your purposes. Many different packages for performing photometry are available and they have different strengths and weaknesses. The recipes in this cookbook use the following packages:

PHOTOM for aperture photometry (see SUN/45[22]),

GAIA an interactive image display tool with facilities for aperture photometry (see SC/17[17] and SUN/214[20]),

KAPPA a set of general image-display and manipulation utilities (see SUN/95[11]),

CURSA for manipulating catalogues and tables (see SUN/190[16]).

These items should all be available at all Starlink sites. If you have any difficulty in running them then see your site manager in the first instance. To run the recipes you should use a display capable of receiving X-output (typically an X-terminal or a workstation console). Strictly speaking the software will run on a black-and-white device, but realistically you need a colour display. Before starting you should ensure that your display is configured to receive X-output.

The recipes simply show you how to use the packages for a set of specific purposes. In all cases the packages have additional features which are not described here. You should see the appropriate user manuals for full details.

13 Selecting Standard Stars

This recipe shows you how to select standard stars for inclusion in your programme of photometric observations. Obviously you would use the recipe as part of the preparations for your observing run. Section 9.1 outlined the procedure for selecting standard stars. Briefly, you usually want to choose between fifteen and twenty standard stars with a similar, or slightly larger, range of air masses, magnitudes and colours than your programme objects.

Traditionally suitable standards are identified by manual inspection of the paper copies of catalogues and this technique must still be used if a computer-readable version of the catalogue is not available. However, this recipe uses the catalogue and table manipulation package CURSA (see SUN/190[16]) to search the Landolt (1992)[53] catalogue of *UBV* standards. Numerous catalogues of standards are available and Section 7.3 gives some of the details.

> **Irrespective of whether you are using the paper or computer readable version of a catalogue it is always advisable to read the paper or other notes which accompany the it. This documentation will typically contain important information about the limitations, applicability and use of the catalogue which you should be aware of in order to use it effectively.**

1. The first step is to obtain a copy of the catalogue of standards. A collection of catalogues of photometric standards which are in a format accessible to CURSA is available via anonymous ftp. The details are as follows.

Anonymous ftp to:	`ftp.roe.ac.uk`
Directory:	`/pub/acd/catalogues`
File:	`photostandards.tar.Z`

   The file is a compressed tar archive; remember to use ftp in binary mode. Brief details of retrieving, decompressing and extracting the catalogues follow.

   (a) To start ftp type:

   ```
   % ftp ftp.roe.ac.uk
   ```

   Reply '`anonymous`' to the `Name` prompt and give your electronic mail address as the password. Then type:

   ```
   ftp> cd /pub/acd/catalogues
   ftp> binary
   ftp> get photostandards.tar.Z
   ```

   (Note that messages from the ftp commands have been omitted and '`ftp>`' is the ftp prompt rather than something that you type in.) Once the file has been retrieved type '`quit`' to leave ftp. The file `photostandards.tar.Z` should have been created in your current directory. Note the use of the `binary` command to set ftp to the appropriate mode for retrieving non-text files. If you encounter problems with ftp then seek assistance from your site manager in the first instance. There is now a veritable plethora of books about using computer communications networks. However, one which gives a good description of the ftp utility is *The Whole Internet User's Guide and Catalog* by Krol[48].

(b) File photostandards.tar.Z is a compressed tar archive. It must be decompressed before it can be used. Type:

```
% uncompress photostandards.tar.Z
```

(c) To extract all the files in the archive type:

```
% tar xvf photostandards.tar
```

Subdirectory photostandards should be created in your current directory. File photostandards/0CATALOGUES.LIS gives details of the catalogues available. The Landolt (1992) catalogue is file:

```
photostandards/ii183/ii183.TXT
```

The name of the subdirectory refers to the numbering of the catalogue by the CDS. The catalogue is in the CURSA Small Text List (STL) format for which the file type is .TXT (or .txt).

(d) Finally, move a copy of the catalogue to a convenient directory and make this directory your current directory.

2. Start CURSA. Simply type:

```
% cursa
```

A message similar to the following should appear.

```
CURSA commands are now available -- (Version 6.3)
```

3. The CURSA applications include xcatview a GUI-based catalogue browser which can be used to select standard stars that match your criteria. To start it, ensure that your terminal is configured to receive X-output, then type:

```
% xcatview &
```

(The '&' merely makes xcatview run as a detached process so you can, if you so desire, continue to issue Unix commands from the command line.) A window similar to Figure 6 should appear. Use the Select Catalogue window to open catalogue ii183.TXT. The Open Catalogue window is similar to the file-selectors often found in GUI-based applications and if you have used similar ones you should not have any difficulty using it. However, in case of difficulty, click on the Help button for assistance. The catalogue should open and the appearance of xcatview should be similar to Figure 7.

You can, if you wish, use the various functions in xcatview to browse the catalogue. Note that all the windows in xcatview contain a Help button which can be clicked for assistance.

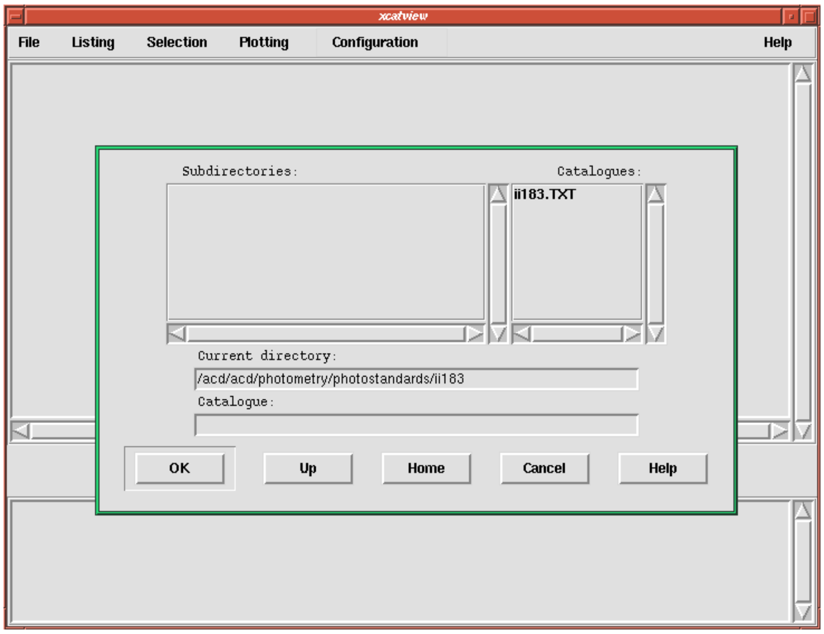

Figure 6: Starting up the CURSA catalogue browser `xcatview`

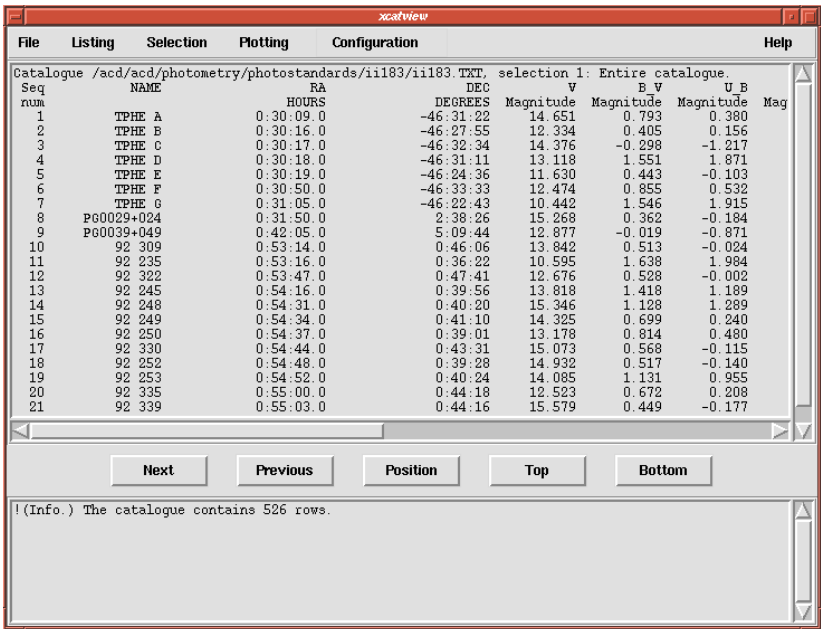

Figure 7: `xcatview` displaying a catalogue

4. In CURSA (and similar systems) each column in the catalogue has a name which is unique within the catalogue and you use this name to refer to the column. The names of the columns are shown at the top of the `xcatview` main display area (see Figure 7). Alternatively, you can list all the column names by clicking on the Listing menu in the bar at the top of the `xcatview` window and choosing the Show summary of columns option.

   In CURSA you can calculate new columns 'on the fly' by specifying algebraic expressions involving existing columns. Thus, if you had columns called `X` and `Y` you could specify `X + Y`. The actual details are not germane here. However, an important consequence which you should be aware of is that column names themselves cannot contain arithmetic operators (because such names would be ambiguous). Thus, the obvious names for colours such as $B - V$ and $U - B$ are invalid. The usual convention is to replace the minus sign with an underscore ('`_`'), so the column names become `B_V` and `U_B`. The columns in catalogue `ii183.TXT` follow this convention.

5. The next step is to select the stars which match the required criteria. Suppose that standard stars were required which met the following conditions:

   V magnitude in the range 12 to 15,
   $B - V$ colour in the range 0.5 to 1.5,
   Right Ascension in the range 15^{h} to 20^{h},
   the star was observed more than 7 times.

   The range of Right Ascension would, of course, be constrained by the place and date of your observing run as well as the coordinates of your programme objects. Note that most of the stars in the chosen catalogue are relatively close to the celestial equator, so there is little point in selecting on Declination. The final criterion (that the star was observed more than 7 times) follows a suggestion in Landolt's discussion of the catalogue[53] that stars with multiple observations make better standards.

   To generate a selection click on the Selection button in the bar at the top of the `xcatview` window and choose the Create a new selection option. A new window will appear allowing you to specify the required selection. Enter:

   ```
   V > 12.0 AND V < 15.0
   ```

   and click on the OK button. This operation selects stars in the magnitude range $12 < V < 15$. Repeat the procedure to further refine the selection by limiting the range of colours, Right Ascension and number of observations. The selections to enter are:

   ```
   B_V > 0.5 AND B_V < 1.5
   RA > 15:00:00 AND RA < 20:00:00
   OBS >= 7
   ```

   Note that in order to indicate that the Right Ascension is being specified as sexagesimal hours the value is entered unsigned and with a colon ('`:`') to separate the minutes and seconds. CURSA interprets an unsigned sexagesimal value in this format as hours. A signed sexagesimal value is similarly interpreted as degrees. Thus positive angles in sexagesimal degrees must be preceded by a plus sign. See SUN/190[16] for further details.

Alternatively, if you prefer, you can generate the required selection in one go by entering all the criteria in a single selection, with the individual elements separated by '`AND`'. However, it is probably easier to make typing mistakes this way. Whichever way the selections are specified you should finally select 24 standard stars.

6. You will probably not need to keep all the columns in the catalogue. For example, if you were just planning to observe in the U, B and V bands you might only want to keep the corresponding columns plus the star name and coordinates. The names of the required columns are:

```
NAME
RA
DEC
V
B_V
U_B
```

   Click on the Listing button in the bar at the top of the `xcatview` window and choose the Choose the columns to be listed option. A new window appears which allows you to choose the required columns. Use it to select the above set of columns. Click on the Help button in case of difficulties and on OK when you have selected the required columns. Subsequently, only the chosen columns will be listed on the screen, written to output catalogues *etc.*

7. The next step is to save the selection as a new catalogue, so that you can refer to it again (you will need the catalogue magnitudes when you come to calibrate your own photometry; the recipe in Section 16 is an example of this process). Click on the File button in the bar at the top of the `xcatview` window and choose the Save as catalogue option. A new window will appear. Enter the required file name, perhaps:

```
mystandards.TXT
```

   Note that CURSA uses the file type to recognise the format in which the catalogue is to be written. The most appropriate format for these small lists is the Small Text List (STL) format, for which the corresponding file type is '`.TXT`' or '`.txt`'. Also set the Columns button to current list (otherwise all the columns in the catalogue will be written). Then click on the OK button. A catalogue called `mystandards.TXT` containing the selected standard stars should be written in your current directory.

8. It is probably useful to also save the selected stars as a text file. Click on the File button in the bar at the top of the `xcatview` window and choose the Save as text file option. Enter the required file name, perhaps:

```
mystandards.lis
```

   set the other options as required and click on the OK button. File `mystandards.lis` will be written in your current directory. It is suitable for printing out, editing *etc.*

9. You now have a preliminary list of standard stars. The final step is to check the visibility of each star at the location and date of your observing run. A number of utilities are available to assist with this process. The document SG/10: *Preparing to Observe*[63] summarises what is available. One alternative is OBSERVE (see SUN/146[61]). To run it simply type:

```
% observe
```

and enter the required details. A series of plots and graphs are generated. You can use this output to arrive at a final list of fifteen to twenty standards. You would, of course, probably also use OBSERVE to check the visibility of your programme objects.

14 Measuring Instrumental Magnitudes with PHOTOM

This recipe shows how to use PHOTOM (see SUN/45[22]) to measure instrumental magnitudes for objects in a CCD frame. The objects may be either standard stars or programme objects. The techniques for measuring instrumental magnitudes are discussed in Section 10.

The starting point is a CCD frame which has been processed to remove instrumental effects. This process typically includes: removing cosmic-ray events and other blemishes, de-biasing and flat-fielding. It is described in SC/5: *The 2-D CCD Data Reduction Cookbook*[18] and in SUN/139[19], the manual for the CCDPACK package, and is not considered further here. SC/5 is a good introduction. PHOTOM can be used interactively, or can be supplied with a list of coordinates of stars on which it will perform aperture photometry. It is used interactively in this recipe.

The example CCD frame used in this recipe is available as file:

```
/star/examples/sc6/ccdframe.sdf
```

If you intend to work through the recipe using this file you should make a copy of it in your current directory. Alternatively, you may prefer to use a CCD frame of your own.

1. First the image containing the stars must be displayed using software which PHOTOM can interact with. Application `display` in KAPPA (see SUN/95[11]) is ideal[11]. It is best to create the display window using the `xmake` utility because in this way you can define the display to have an overlay plane, thus allowing the graphics output by PHOTOM to be cleared without destroying the displayed image. So, start the display with a command like:

   ```
   % xmake xwindows -overlay -ovcolour blue
   ```

2. Now display the data with KAPPA `display` using `xwindows` as the display device. Briefly, type:

   ```
   % kappa
   ```

   to load the KAPPA package. Then issue the following commands:

   ```
   % lutneg
   DEVICE - Name of display device > xwindows
   % display
   IN - NDF to be displayed > ccdframe
   DEVICE - Name of display device > xwindows
   MODE - Method to define the scaling limits /'SCALE'/ > FAINT
   Data will be scaled from 200 to 2666.
   ```

[11] Strictly speaking you must use display software which accesses the Starlink graphics database (see SUN/48[21]). However, you will not normally be aware of the graphics database and certainly do not need to know anything about it. It is simply a mechanism which allows different applications to co-operate in using the same plot.

lutneg sets up a negative grey-scale colour table[12]. display displays the image, which should appear as a grey-scale plot. Note that the input file name is (and must be) specified without the '.sdf' file type.

3. Next, start up PHOTOM by typing **photomstart** to enable its commands and **photom** to start. You will be asked for the name of a data frame. Again the file name must be specified without the file type. The default name for the output file written by PHOTOM is photom.dat. If this file exists, an error message will appear and you will be prompted for an alternate name. The sequence of commands and responses should be something like the following:

```
% photomstart

   PHOTOM applications are now available -- (Version 1.5-0)

% photom
IN - NDF containing input image > ccdframe
Commands are - Annulus, Centroid, End, File, Help, Ishape, Measure,
               Nshape, Options, Photons, Sky, Values
COMMAND - PHOTOM /'Values'/ >
```

4. If you hit <RETURN> here you will get a list of the default values that are set for PHOTOM at present. The result will be like:

```
COMMAND - PHOTOM /'Values'/ >

 Semim          =   5.0
 Eccen          =   0.00
 Angle          =   0.0

 Centroiding of star in aperture

 Concentric sky aperture
 Inner radius    =   1.3
 Outer radius    =   2.1    times object aperture radius

 Sky estimator   =  Mode
 Sky magnitude   =  50.0

 Photons per ADU =   1.00
 Exposure time   =   1.00
 Saturation level ( data units ) = 0.17000E+39

 Errors from sky variance

COMMAND - PHOTOM /'Values'/ >
```

You can use Help to find out what the options are:

[12] An image displayed with the lutneg colour table mimics the appearance of a conventional astronomical photographic plate: stars appear as dark spots on a light background. Various other colour tables are available in KAPPA. For example, lutgrey sets up a positive grey-scale (light stars against a dark background) and lutheat sets up a pseudo-heat sequence.

```
COMMAND - PHOTOM /'Values'/ > help
Commands are - Annulus, Centroid, End, File, Help, Ishape, Measure,
               Nshape, Options, Photons, Sky, Values
Annulus  - Toggle between sky measured in concentric annulus or in selected area
Centroid - Toggle between measuring around centroid of image or given position
End      - Exit program
File     - Supply a file of object positions
Help     - This help message
Ishape   - Select aperture shape interactively
Measure  - Make measurements interactively
Nshape   - Select aperture shape non-interactively
Options  - Change values of some parameters
Photons  - Select error estimate - photon statistics, sky or data variance
Sky      - Select sky estimator - mean, mean within 2 sigma, mode or user given
Values   - Output current parameter values
COMMAND - PHOTOM /'Values'/ >
```

Some of these choices toggle between values. The way these options work is that when the appropriate command is issued the chosen option is switched from whatever its current state happens to be to its other state. A message is issued indicating the new state. Centroiding, for instance, can be switched on or off. Generally for interactive work it is best to leave centroiding switched on.

5. The next step is to set some parameters which define the apertures which will be used and various related items. Initially a circular aperture will be used, with the sky background measured in an annulus around it. You should toggle the `Annulus` command until a concentric aperture is selected.

   Now you will need to choose some suitable values for the measuring aperture radii. The background annulus measuring region should be set so that its inner radius is a little outside the central circle, so that it is not unduly contaminated with stray light and its outer radius should not be so big that it includes too many surrounding objects.

   How big does the radius of the measuring aperture need to be, and how much bigger should the background annulus around it be? There is no hard and fast answer: it depends on the plate scale of the image, how crowded the field is and whether the programme objects are stars or extended objects. If the aperture is too small then a fraction of the light from the object being measured will fall outside the aperture and not be detected, thus leading to an underestimate of the brightness of the object.

   If your programme objects are stars and all your CCD frames have the same point-spread function (that is, the seeing remained the same whilst all the frames were acquired) then the choice of aperture is not too critical. All the objects measured, both programme stars and standard stars, have the same profile and hence they all lose the same fraction of their light. This systematic underestimation of the brightness is simply calibrated out when the instrumental magnitudes are converted to magnitudes in a standard system. In this case quite a small aperture can be used in order to minimise statistical errors in the background and contamination by faint stars.

The situation is rather different if the programme objects are extended objects. Here the programme objects will have a different intensity profile to the standard stars and hence for a given aperture size a different fraction of the total light will be lost. Thus it is important to determine the total magnitudes for both standard stars and programme objects and a larger aperture is appropriate.
An aperture radius of about twenty seconds of arc is often a reasonable starting point.

The background can be sampled using various algorithms. A simple mean will obviously be sensitive to any contaminating source, such as faint stars, within the annulus, but a mode will tend to be less affected by aberrant, outlying values.

6. Next set the size of the measurement aperture:

```
COMMAND - PHOTOM /'Values'/ > n
SEMIM - Semi-major axis /5/ > 8
ECCEN - Eccentricity /0/ >
ANGLE - Orientation /0/ >
COMMAND - PHOTOM /'Values'/ >
```

Notice a couple of things here:

- you only need to use the initial letter of your choice,
- an arbitrary elliptical aperture can be chosen. This option is suitable for measuring elliptical galaxies[13].

Now set the other required values:

```
COMMAND - PHOTOM /'Values'/ > o
INNER - Inner annular radius /1.4/ > 1.3
OUTER - Outer annular radius /2/ > 2.1
PADU - Photons per ADU /1/ >
SKYMAG - Magnitude of sky /50/ > 30
BIASLE - Bias level ( data units ) /0/ >
SATURE - Saturation level ( data units ) /1.7E38/ >
COMMAND - PHOTOM /'Values'/ >
```

A few more things to note:

- the annulus measurements are entered as *multiples* of the measurement aperture,
- `SKYMAG` is essentially the arbitrary constant A which appears in equations 14, 15 and 16. It is usually sensible to set it to an improbable value, such as 30 (as used here) so that the instrumental magnitudes measured by PHOTOM are not inadvertently confused with calibrated magnitudes. Conversely, if the absolute value of the sky background is known and used then the instrumental magnitudes will *approximate* to calibrated magnitudes, albeit without atmospheric extinction and colour corrections,

[13] The intensity profiles of the images of extended objects usually fall off more slowly with increasing radius than those of stars and hence when working with extended objects it is necessary to be careful to choose an aperture sufficiently large to include the required fraction of the total light from the object.

- other values, such as PADU and BIASLE will be specific to the data.

7. PHOTOM is now set up ready to measure stars and sky background. Type m and when prompted for the display device use xoverlay. The text boxes that appear towards the bottom of the display refer to the corresponding mouse buttons. Proceed as follows.

   (a) Position the cursor over the object to be measured and click the left mouse button or enter 1 from the keyboard.
   (b) Repeat the procedure for all the objects which you wish to measure.
   (c) To finish, click on the right mouse button or enter 0 from the keyboard and you will return to the PHOTOM 'COMMAND' prompt.

   The resulting display will look something like Figure 8. As each star is measured the terminal or workstation will output the results (and echo them to the output file specified when starting PHOTOM):

```
COMMAND - PHOTOM /'Values'/ > m
DEVICE - Display device /@xwindows/ > xoverlay
Select operation according to screen menu
Left hand box  - Press left hand mouse button
Centre box     - Press centre mouse button
Right hand box - Press right hand mouse button
===================================================================
        nx       ny        a        e       theta
       384      256       8.00     0.000      0.0

          x         y      mag     magerr      sky       signal code
    1    57.70   157.74   19.322    0.011    489.965  18675.065
    2    58.90   232.74   18.571    0.007    493.119  37287.484
    3    66.94   250.43   20.447    0.025    493.768   6622.757 E
    4    81.58    65.64   17.059    0.003    489.962 150087.483
    5   362.25    66.61   18.209    0.005    491.481  52030.981
COMMAND - PHOTOM /'Values'/ >
```

   If you are working through the recipe the actual values you obtain will probably be slightly different because you will have positioned the apertures differently. The meaning of each of the columns is described in SUN/45. Notice the following:

   - measurements of both sky and object are given,
   - magnitude values are relative to an artificial sky value of 30,
   - object 3 is the star that has been measured at the top of the image. It can be seen that the inner aperture has crossed the edge of the frame. Therefore some proportion of the flux here will have been lost. This problem has been recognized by flagging the result with an 'E' in the code column, the 'E' standing for 'edge'.

8. It is also possible to use an interactive aperture to sample the background. Here representative areas of sky are sampled independently of the measured object. The procedure is as follows.

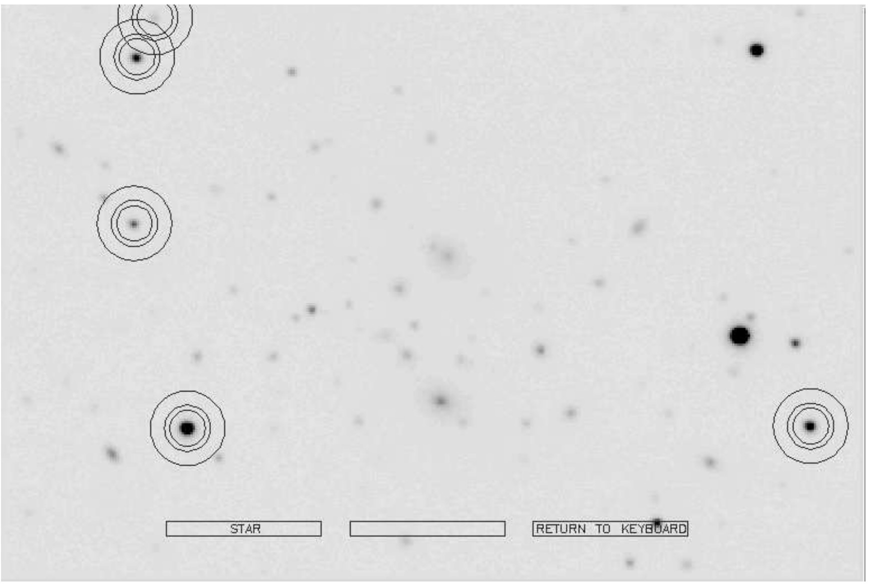

Figure 8: Display during measurement using a concentric annulus

(a) Type `a` to toggle the `Annulus` choice. The message '`Interactive aperture in use`' should be displayed.

(b) Type `m`

(c) Move the cursor to a blank patch of sky. Usually the patch chosen will be close to the object to be measured. Click on the middle mouse button. An aperture corresponding to the patch of sky measured will be shown. You can repeat this procedure for several patches of sky if you wish. Note that the sky must be measured before measuring any objects.

(d) Move the cursor over the object to be measured and click on the left mouse button (or enter 1 from the keyboard).

(e) You can make further measurements of the objects and the sky background as you wish.

(f) To finish click on the right mouse button (or enter 0 from the keyboard).

The resulting display will look something like Figure 9.

9. You should measure all the stars which you are interested in in the current frame. Their instrumental magnitudes will be included in the output file written by PHOTOM. Alternatively, if you prefer, you can make a note of the instrumental magnitudes as they are displayed (though this approach is more prone to mistakes).

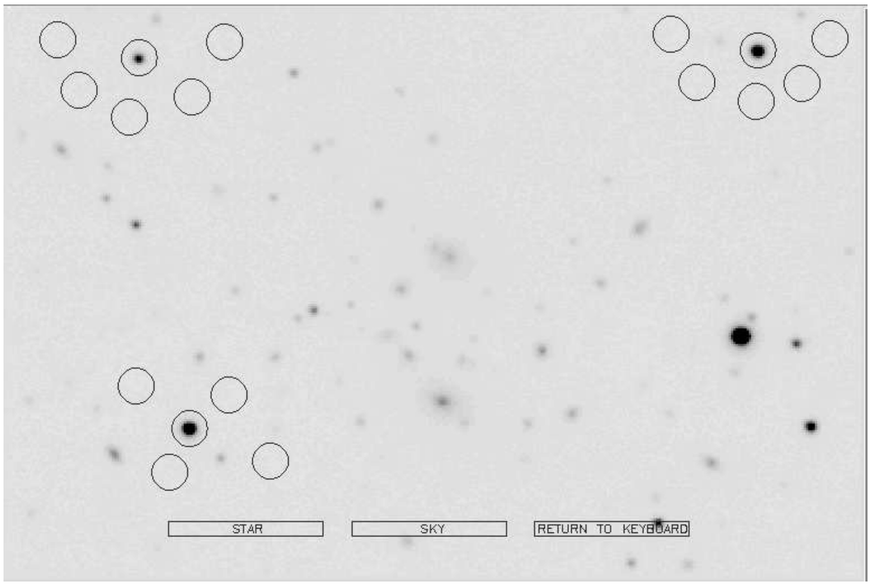

Figure 9: Display during measurement using an independent aperture

10. This recipe has shown the interactive use of PHOTOM. PHOTOM also contains an application called **autophotom** which allows PHOTOM to be used non-interactively (see SUN/45[22] for details).

15 Measuring Instrumental Magnitudes with GAIA

This recipe shows how to use GAIA (see SC/17[17] and SUN/214[20]) to measure instrumental magnitudes for objects in a CCD frame. The objects may be either standard stars or programme objects. The techniques for measuring instrumental magnitudes are discussed in Section 10.

The starting point is a CCD frame which has been processed to remove instrumental effects. This process typically includes: removing cosmic-ray events and other blemishes, de-biasing and flat-fielding. It is described in SC/5: *The 2-D CCD Data Reduction Cookbook*[18] and in SUN/139[19], the manual for the CCDPACK package, and is not considered further here. SC/5 is a good introduction.

GAIA is a powerful and flexible windows-based application for displaying and measuring two-dimensional images. In principle the current recipe is very similar to the previous one which used PHOTOM (see Section 14)[14]. However, unlike the PHOTOM recipe, in GAIA the image display and photometry are integrated into a single easy-to-use application.

The example CCD frame used in this recipe is available as file:

```
/star/examples/sc6/ccdframe.sdf
```

If you intend to work through the recipe using this file you should make a copy of it in your current directory. Alternatively, you may prefer to use a CCD frame of your own.

1. To start GAIA type:

   ```
   % gaia
   ```

   Load the appropriate image by clicking the File menu, selecting Open... and using the file-picker panel displayed.

2. Now set the display colours. For example, click on the View menu and select the Colors... option. A dialogue box will appear. Set:

   - the colour scale algorithm to Linear,
   - the colormap to ramp,
   - the intensity to neg.

   Then click on the Close button.

   Set the limits of the colour table by specifying the Low and High values in the Object panel at the top centre of the main window. If you are using the example frame suitable values are 200 and 2700 respectively.

   Finally, you might want to set the magnification. Click on the View menu and select Magnification. For the example frame the value 2x is suitable. The display should now look something like Figure 10.

[14]Indeed, technically GAIA is acting as a 'front-end' to the PHOTOM application `autophotom`. However, as a user you will not normally be concerned with these details.

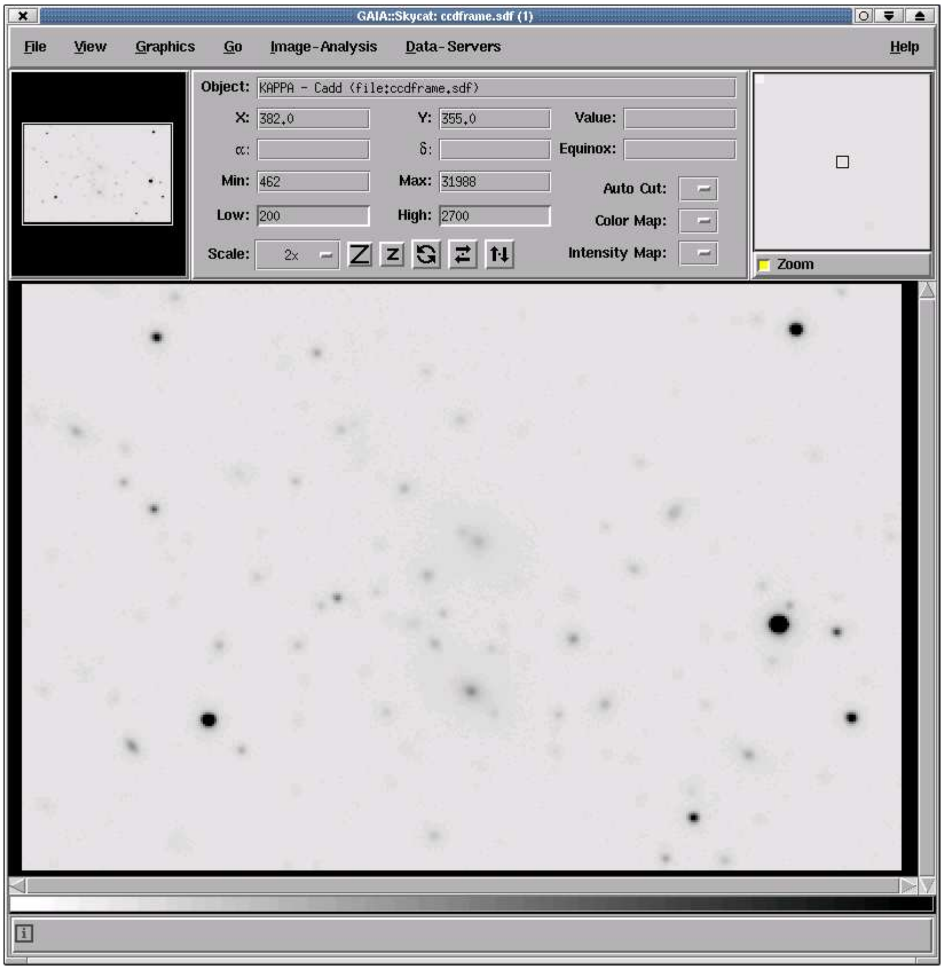

Figure 10: GAIA display of a CCD frame

3. You can now proceed to measure instrumental magnitudes. Click on the Image Analysis menu on the menu-bar along the top of the main window. Choose the Aperture photometry item. Two further items will be presented: Results in magnitudes... and Results in data counts.... Choose the former, Results in magnitudes.... (Both these options allow you to perform aperture photometry. The former displays the results in magnitudes, the second in counts.) An Aperture photometry – magnitudes dialogue box (see Figure 11) will be displayed. You can drag this dialogue box off the display panel if necessary.

   As in the previous recipe for PHOTOM, you should set the Frame zero point (mags) to an improbable value, typically 30, so that the instrumental magnitudes are not inadvertently confused with calibrated ones.

   > **This is a good time to mention on-line help. Clicking the** Help **menu in the bar at the top of the photometry dialogue box, followed by** On Window... **will bring up a window with a pretty comprehensive description of how to use the aperture-photometry facilities.**

   The process is now straightforward. Following the instructions in the on-line help, proceed as follows.

   (a) Click the Define object aperture button.
   (b) Place your cursor on the image over the star that you wish to measure.
   (c) Press down and hold down mouse button 1.
   (d) Move the mouse sideways until the circle contains all the star.
   (e) Release the mouse button.
   (f) Click the Calculate results button.
   (g) Inspect the Current object details (displayed in the upper-middle portion of the dialogue box) and view the instrumental magnitude of the star.

   You can change things like the inner and outer radii of the annulus for measuring the sky background by moving the sliders in the Aperture Photometry – magnitudes dialogue box. Apertures are drawn around stars as they are measured.

4. Clicking on the Options menu in the bar at the top of the Aperture photometry – magnitudes dialogue box will allow you to alter settings by using 'push buttons' that are labelled:

   - Use annular sky regions
   - Use circular apertures
   - Keep apertures same size

   By de-selecting the first button here (Use annular sky regions), you can use interactive apertures to measure the sky background, and by de-selecting the second you can use ellipses instead of circles. Because GAIA is acting as a 'front-end' to PHOTOM most of the parameters which can be set in PHOTOM can also be set in GAIA.

   > **There is a nice feature in GAIA that is of use when deciding how big to make the aperture radius. By Clicking on the** View **menu in the main window and selecting the** Slice... **option it is possible to obtain**

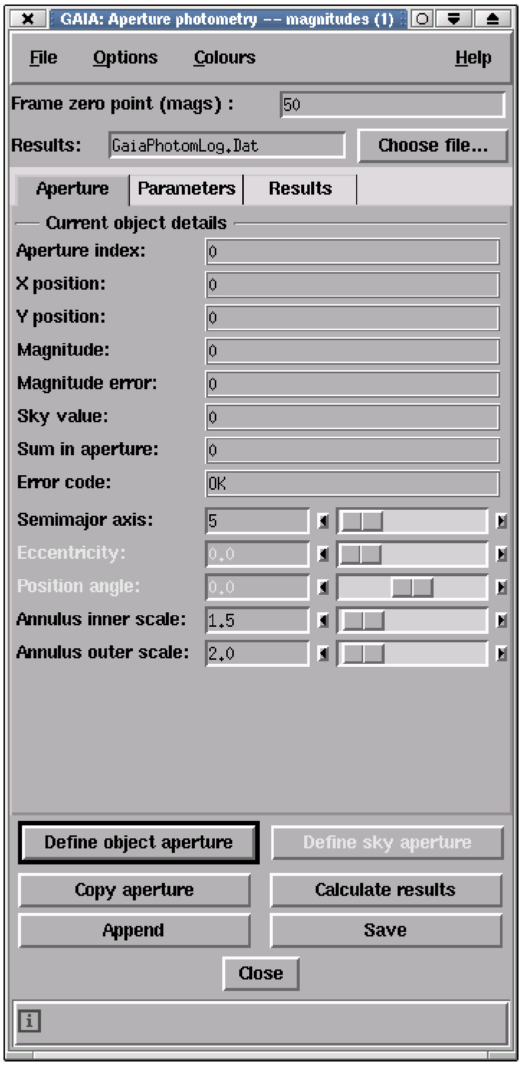

Figure 11: The GAIA Aperture photometry – magnitudes dialogue box

a 'cut' or 'slice' across any star image on-the-fly (see Figure 12). This option can usefully be used to estimate how far out from the star useful signal exists.

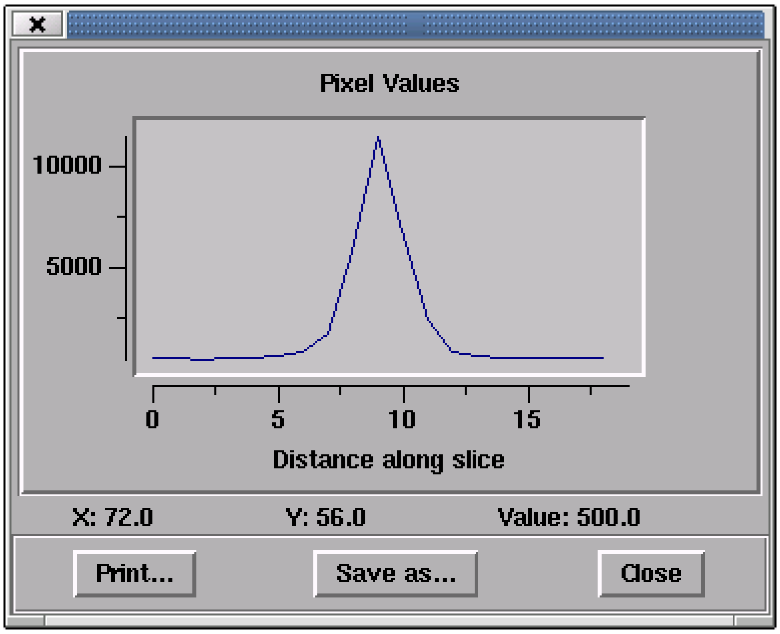

Figure 12: A GAIA 'Slice' display panel showing a slice through an object

5. If you click on the Parameters button in the Aperture photometry – magnitudes dialogue box the appearance of the box changes to resemble Figure 13. You can now set various parameters, such as the Photon data per unit, image bias level, default sky level *etc.*

   By default the statistic used to estimate the sky background is the mean. Usually it is preferable to use the mode because it is less affected by contamination due to faint stars. To select the mode click on the Sky estimator: **button and select the mode (see Figure 13).**

6. You should measure all the stars that you are interested in the current frame. (Click on the Aperture button prior to resuming measuring, if necessary.) When the job is done, click on the File menu in the menu-bar along the top of the Aperture photometry – magnitudes dialogue box (*not* the one in the main GAIA window) and select Save measurements... to save the results in a file of your choice. The instrumental magnitudes are listed in this file.

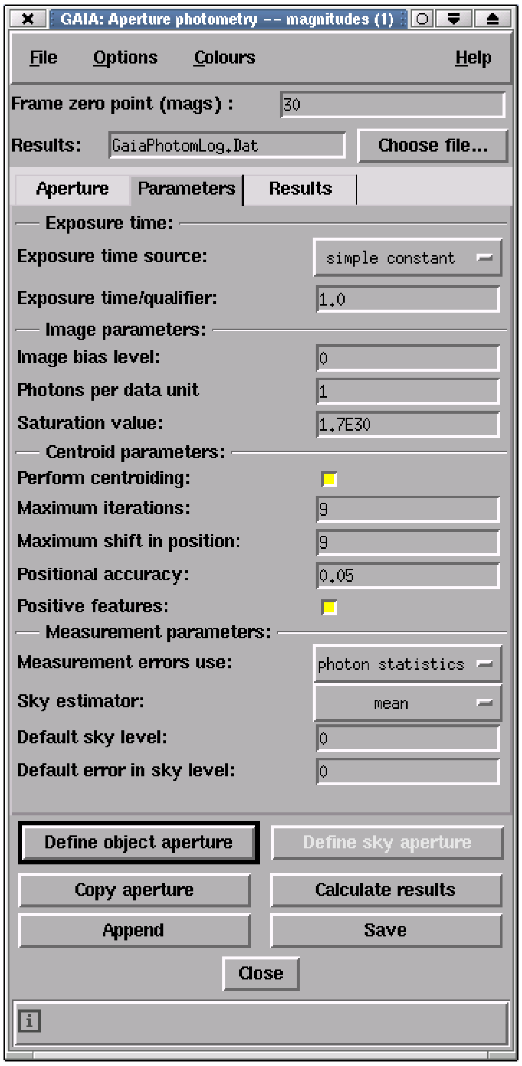

Figure 13: The GAIA Aperture photometry – magnitudes dialogue box with the options to set parameters selected

16 Calibrating Instrumental Magnitudes

This recipe describes how to calibrate a set of instrumental magnitudes into standard magnitudes. It assumes that you are going to calibrate instrumental magnitudes for a set of programme objects by the usual technique of observing a set of standard stars. Thus, the starting point is a list of standard stars with both instrumental and standard (or catalogue) magnitudes and a list of programme objects with instrumental magnitudes. The techniques for calibrating instrumental magnitudes are discussed in Section 11.

The recipe uses the photometric calibration functions in the CURSA package for manipulating catalogues and tables (see SUN/190[16]) which do not include colour corrections. Thus, the recipe is only appropriate if your instrumental system is well-matched to the target standard system and where very high precision is not required. Nonetheless, with modern instrumentation and good observing conditions it is possible to achieve results accurate to within 0.01 magnitude.

1. The first, and certainly the messiest and most time consuming, stage is to assemble the required input data. You need to assemble two tables (or catalogues[15]): one containing the data for the standard stars and the other the data for the programme objects. Strictly speaking two sets of tables are required, with each corresponding to the observations from a different night; observations from different nights should not normally be combined prior to calibration. However, for the purpose of this recipe it is assumed that you have only observations from a single night and hence only two input tables are required.

   The contents of the two tables are as follows.

   The table of standard stars should contain: the catalogue magnitude, instrumental magnitude and air mass for each standard star.

   The table of programme objects should contain: the instrumental magnitude and air mass for each object.

   In both cases, if you do not have the air mass then the zenith distance can be substituted instead. Note that it is the *observed* zenith distance, that is, as affected by atmospheric refraction, which is required. You obtain these various items of information as follows.

   - The instrumental magnitudes will be assembled from the output of other programs, such as PHOTOM or GAIA (see the recipes in Sections 14 and 15).
   - The standard or catalogue magnitudes will ultimately come from the catalogues of standards which you used when selecting the standard stars to observe.
   - The air mass or zenith distance will often be included in either your observing logs or the header information of your CCD frames. If neither the air mass nor the zenith distance is available then you will have to calculate the zenith distance. Appendix B gives some hints on inspecting CCD frames to find the required information and calculating the zenith distance.

   These various data must be edited into two tables which CURSA can read. The simplest way to format these tables is to use the CURSA Small Text List (STL) format. STL

[15] In this recipe, and more generally in CURSA, the terms 'catalogue' and 'table' are usually used interchangeably.

tables are simple text files which can be created with a text editor. If you originally used CURSA to select the standard stars to observe, as described in the recipe in Section 13, you could use the catalogue of standard stars which the recipe produces as a starting point. This approach has the advantage of avoiding have to re-type the catalogue magnitudes. Alternatively, example catalogues are available as starting points and these are used in this recipe. The catalogues of standard stars and programme objects are discussed separately below. You should copy these example catalogues into a convenient directory and make this directory your current directory.

Standard Star	Catalogue Colours R	$(B-V)$	Time (UT)	Air Mass	Instrumental Magnitudes
113Z475	09.737	1.057	19:58	1.16	16.37
110Z450	11.033	0.950	20:06	2.20	17.74
114Z531	11.672	0.732	20:12	1.13	18.29
113Z475	09.737	1.057	21:33	1.41	16.39
114Z548	10.868	1.362	21:43	1.23	17.50
94Z251	10.547	1.218	00:19	1.14	17.17
93Z424	11.067	1.084	00:25	1.18	17.69
95Z74	10.931	1.127	00:32	1.17	17.55
96Z737	10.982	1.331	00:38	1.26	17.62
97Z249	11.369	0.651	03:11	1.14	17.99
94Z251	10.547	1.218	03:16	1.57	17.21
95Z301	10.527	1.285	03:20	1.32	17.16
99Z367	10.618	1.005	05:36	1.15	17.23
96Z737	10.982	1.331	05:42	1.81	17.67

Table 4: Table of standard star observations. These data were observed with the Jacobus Kapteyn Telescope (JKT) on La Palma on 16/11/1993. They are provided courtesy of John Lucey

Standard star catalogue Table 4 shows a list of observations of standard stars kindly provided by John Lucey. Figure 14 shows an example catalogue compiled from this list. This example is available as file:

```
/star/examples/cursa/photostandards.TXT
```

Note that the example catalogue does not contain all the columns in Table 4. The catalogue is in the CURSA STL format. This format is probably more-or-less self-explanatory. In case of difficulty there is a short introductory tutorial in the CURSA manual, SUN/190[16]. The most relevant points are:

- lines beginning with an exclamation mark (`!`) are comments,
- blank lines are ignored,
- in CURSA each column in a table has a unique name within the table and you use this name to refer to the column. The lines beginning with `C` define the columns in the table. The word immediately following the `C` is the name of the column, the next item is its data type and the following one its sequence number

in the table of values. Thus in Figure 14 the first column is a character string called `NAME`, the second column a double-precision number called `MCAT` *etc*,

- the table of values itself occurs immediately following the '`BEGINTABLE`' line.

The catalogue must contain columns containing the instrumental magnitude, the catalogue magnitude and the air mass (or alternatively the observed zenith distance). It may optionally contain a column containing a name for each of the standard stars and a column of 'include in the fit' flags. All five columns are included in the example. If supplied, the star name is listed in the table of residuals produced when the fit is made. Often being able to identify each standard star will be useful to you. The 'include in the fit' flag column is of data type `LOGICAL` and determines whether each star is included in the fit or not. To include or exclude a given star in the fit you simply edit the STL format catalogue and toggle the value of the flag for the star to '`T`' (or '`TRUE`') or '`F`' (or '`FALSE`') to include or exclude it as appropriate. This procedure is much less troublesome and error-prone than deleting and reinserting stars from the catalogue. Initially set the flags for all the stars to '`T`' (or '`TRUE`') so that they are all included in the fit. In the example all the stars are included in the fit except 99Z367 (the penultimate one in the list). This star is excluded as an illustration. When preparing your own catalogues you will usually initially include all the stars.

The zenith distance is an angle and if it is used it must ultimately be presented to the CURSA applications in radians. If you wish you can simply type the values into the STL catalogue in radians. Alternatively, if it is more convenient, you can define the zenith distance column as containing a sexagesimal angle, usually in degrees, and type in the values as sexagesimal degrees. The example catalogue of programme objects in Figure 15 includes a column of zenith distances in this form.

Though both the columns of star names and 'include in the fit' flags are optional their use is strongly recommended.

The columns do not have to have the names shown in the example. However, if you use these names you will be able to accept the defaults from the prompts in the CURSA applications.

A useful trick is to enter the observations in the table in chronological order of observation. Then, when the residuals are computed they also will be listed in order of observation, making it easy to spot any systematic trends during the night.

Obviously the catalogue can contain additional columns, though these are not used. For example, if you are calibrating multi-colour photometry you could prepare a single catalogue containing the instrumental and catalogue magnitudes in all the colours observed. Obviously the columns for magnitudes in different colours would have to have different names. If you did not observe all the stars in all the colours simply use the STL mechanism for indicating missing (or 'null') values: enter the string '`<null>`' instead of the missing value (see SUN/190 for further details).

Programme object catalogue Figure 15 shows an example catalogue of programme objects. This example is available as file:

`/star/examples/cursa/photoprog.TXT`

As an illustration this catalogue contains columns of both the air mass and the observed zenith distance. It does not need to contain both, but must contain one

```
!+
! Example catalogue of photometric standards.
!
! These data were observed with the Jacobus Kapteyn Telescope
! (JKT) on La Palma on 16/11/1993.  The catalogue magnitudes are in
! the R band and the instrumental magnitudes approximate to this
! system.  The data are provided courtesy of John Lucey (Durham).
!
! A C Davenhall (Edinburgh) 12/10/97.
!-

C NAME    CHAR*7  1  EXFMT=A7    ! Star name.
C MCAT    DOUBLE  2  EXFMT=F7.3  ! Catalogue magnitude.
C MINST   DOUBLE  3  EXFMT=F7.3  ! Instrumental magnitude.
C AIRMASS DOUBLE  4  EXFMT=F7.3  ! Air mass.
C INCL    LOGICAL 5  EXFMT=L5    ! 'Include in the fit' flags.

BEGINTABLE
113Z475  09.737  16.37  1.16  T
110Z450  11.033  17.74  2.20  T
114Z531  11.672  18.29  1.13  T
113Z475  09.737  16.39  1.41  T
114Z548  10.868  17.50  1.23  T
 94Z251  10.547  17.17  1.14  T
 93Z424  11.067  17.69  1.18  T
 95Z74   10.931  17.55  1.17  T
 96Z737  10.982  17.62  1.26  T
 97Z249  11.369  17.99  1.14  T
 94Z251  10.547  17.21  1.57  T
 95Z301  10.527  17.16  1.32  T
 99Z367  10.618  17.23  1.15  F
 96Z737  10.982  17.67  1.81  T
```

Figure 14: Example of a catalogue of photometric standard stars

or the other. Here the zenith distance has been entered as sexagesimal degrees and minutes.

```
!+
! Example catalogue of photometric programme objects.
!
! Note that this table contains both the air mass and the observed
! zenith distance.  The zenith distance is given in sexagesimal
! degrees and minutes.
!
! A C Davenhall (Edinburgh) 12/10/97.
!-

C MINST   DOUBLE  1 EXFMT=F7.3    ! Instrumental magnitude.
C AIRMASS DOUBLE  2 EXFMT=F7.3    ! Air mass.
C ZENDIST DOUBLE  3 UNITS='RADIANS{DM}' TBLFMT=DEGREES ! Zenith distance.

BEGINTABLE
 17.38  1.00   1:43
 17.03  1.24  36:06
 17.49  1.11  25:47
 17.87  1.04  15:28
 17.42  1.05  18:20
 17.26  1.91  58:27
```

Figure 15: Example of a catalogue of photometric programme objects

The columns do not have to have the names shown in the example. However, if you use these names you will be able to accept the defaults from the prompts in the CURSA applications.

The catalogue can contain additional columns; indeed a programme catalogue will often contain celestial coordinates and/or object names. Also, if you are calibrating multi-colour photometry you could prepare a single catalogue containing the instrumental magnitudes in all the colours observed. Obviously the columns for magnitudes in different colours would have to have different names. If you did not observe all the objects in all the colours simply use the STL mechanism for indicating missing (or 'null') values: enter the string '`<null>`' instead of the missing value (see SUN/190 for further details).

2. Once you have prepared the input catalogues you are ready to start CURSA. Simply type:

```
% cursa
```

A message similar to the following should appear.

```
CURSA commands are now available -- (Version 6.3)
```

3. The next stage is to use the standard stars to define the transformation between instrumental and catalogue magnitudes. If your table of standard stars contains air masses (as in the example) then simply type:

   ```
   %  catphotomfit
   ```

   Conversely, if the catalogue of standard stars contains observed zenith distances then type:

   ```
   %  catphotomfit  zenithdist=true
   ```

   In both cases you will be prompted for various column names. If you have used the same column names as the example in Figure 14 you will be able to hit return in response to the prompts. `catphotomfit` then displays some details of the fit, writes a file of transformation coefficients and terminates.

```
Coefficients determined successfully from fitting 13 stars:

 zero point = 23.474252
 atmospheric extinction = 0.085569

 (minimum residual vector length = 0.018932)

Seq.  Star         Fit Air      Cat.       Instrumental Mag.
no.                    mass     Mag.     calc.  observe residual
  1  113Z475         Y  1.16    9.737    9.745  16.370  -0.008 :**********
  2  110Z450         Y  2.20   11.033   11.026  17.740   0.007 :********
  3  114Z531         Y  1.13   11.672   11.668  18.290   0.004 :*****
  4  113Z475         Y  1.41    9.737    9.744  16.390  -0.007 :********
  5  114Z548         Y  1.23   10.868   10.869  17.500  -0.001 :*
  6  94Z251          Y  1.14   10.547   10.547  17.170   0.000 :
  7  93Z424          Y  1.18   11.067   11.063  17.690   0.004 :****
  8  95Z74           Y  1.17   10.931   10.924  17.550   0.007 :********
  9  96Z737          Y  1.26   10.982   10.986  17.620  -0.004 :*****
 10  97Z249          Y  1.14   11.369   11.367  17.990   0.002 :**
 11  94Z251          Y  1.57   10.547   10.550  17.210  -0.003 :***
 12  95Z301          Y  1.32   10.527   10.521  17.160   0.006 :*******
 13  99Z367             1.15   10.618   10.606  17.230   0.012 :---------->
 14  96Z737          Y  1.81   10.982   10.989  17.670  -0.007 :*********

Standard deviation of the residuals:
   Fitted stars:  0.005       (13 points).
   All stars:     0.006       (14 points).
```

Figure 16: Example output from `catphotomfit`

Figure 16 shows the output displayed by `catphotomfit`. The transformation coefficients are self-explanatory. The minimum residual vector length is a measure of the goodness of the fit. The table of residuals is also mostly self-explanatory. The column of star names will be absent if parameter `NAME` was specified as '`NONE`'. A '`Y`' in the 'Fit' column indicates that the star was included in the fit. The residuals are defined in the sense:

$$m_{\mathrm{catalogue}} - m_{\mathrm{calculated}} \tag{19}$$

The transformation coefficients are shown to six places of decimals and the calculated magnitudes and residuals to three places of decimals. These formats do not imply that the results are this accurate; the actual accuracy will depend on the data used. It is noteworthy, however, that in the example data the largest residual is only slightly larger than 0.01 magnitude, despite the method ignoring colour corrections.

The bar to the right of the residuals is a simple graphic representation of the absolute size of the residual; the length of the bar is scaled according to the absolute size of the residual for the star. The scaling is such that the largest absolute residual amongst the stars included in the fit is ten asterisks long. Stars which are included in the fit are shown as a row of asterisks ('`*`'). Stars which are excluded from the fit are shown as a row of dashes ('`-`'). Because excluded stars will often have larger residuals than the included stars, for excluded stars with residuals larger than the largest included residual a right chevron ('`>`') is shown beyond the last dash (thus forming an arrow).

4. The first fit will usually reveal some unsatisfactorily large residuals which you will want to exclude from the fit. (Aberrant results for individual stars can be caused by various effects, including passing clouds.) Edit the table of standard stars and toggle the 'include in the fit' flag for the star to be excluded to '`F`' (or '`FALSE`'). Then re-run `catphotomfit`. Repeat this process until you get a satisfactory fit. Note that as you exclude new stars you may well wish to experiment with re-instating ones excluded previously.

   In the example data no additional stars really need excluding. However, you might like to experiment with re-instating the penultimate star, 99Z367 (edit the table of standards and toggle the 'include in the fit' flag for 99Z367 to '`T`', or '`TRUE`').

5. The final stage is to use the file of transformation coefficients written by your final, satisfactory, run of `catphotomfit` to calibrate the instrumental magnitudes for the programme objects. If your table of programme objects contains air masses (the example contains both air masses and zenith distances) then simply type:

   ```
   %  catphotomtrn
   ```

   Conversely, if the catalogue of standard stars contains observed zenith distances then type:

   ```
   %  catphotomtrn  zenithdist=true
   ```

   In both cases `catphotomtrn` will prompt you for various items. When prompted for the name of the output catalogue it is probably best to give a name ending in the file type '`.TXT`' or '`.txt`' so that the table is written in the STL format. If you have used the same column names as the example in Figure 15 the you will be able to hit return in response to the prompts.

   A new table containing the calibrated magnitudes in the standard system, as well as all the columns in the original table of programme objects, will be written. If you specified the STL format for this table it will be a simple text file and you will be able to examine it with a text editor or Unix commands such as `more` or `cat`. It can also be examined with the CURSA catalogue browser `xcatview` (see Section 13 for an example using `xcatview`), though this is probably overkill for a small table of programme objects. Figure 17 shows an output catalogue written in the STL format by `catphotomtrn`. In this catalogue the calibrated magnitudes are column `MCAT`. Column `MCAT`, and the other columns, are defined in the lines beginning with a '`C`' or '`:`' in the upper half of the figure. The values for `MCAT` are the rightmost column in the table beneath the '`BEGINTABLE`' line.

```
!+
!  Catalogue: photocalib
!
!  This catalogue is formatted as a CURSA small text list (STL).
!  For a description of this format see Starlink User Note 190 or URL
!  http://www.roe.ac.uk/acdwww/cursa/home.html.
!-

C  MINST    DOUBLE    1     EXFMT=F7.3
C  AIRMASS  DOUBLE    2     EXFMT=F7.3
C  ZENDIST  DOUBLE    3     EXFMT=D19.10
:    UNITS='RADIANS{DM}'
C  MCAT     REAL      4     EXFMT=F7.3
:    UNITS='Magnitudes'
:    COMMENTS='Calibrated magnitude.'

T
T Column MCAT was calculated using the following coefficients:
T    Arbitrary constant:       30.0000
T    Zero point:               23.4743
T    Atmospheric extinction:    0.0856
T


BEGINTABLE
 17.380    1.000     0.2996148549D-01   10.769
 17.030    1.240     0.6300638600D+00   10.398
 17.490    1.110     0.4500040588D+00   10.869
 17.870    1.040     0.2699442576D+00   11.255
 17.420    1.050     0.3199770295D+00   10.804
 17.260    1.910     0.1020144948D+01   10.571
```

Figure 17: Example catalogue of calibrated magnitudes written by `catphotomtrn`

A Interstellar Extinction and Reddening

Interstellar space is not empty but is permeated by the Interstellar Medium (ISM). The ISM affects starlight which passes through it and the effects of the ISM on the observed magnitudes and colours of stars must be allowed for if their intrinsic properties are to be recovered. However, correction for interstellar effects is usually considered part of the astrophysical analysis of observations rather than part of their data reduction. Hence it is only mentioned here briefly in an appendix.

The main components of the ISM are gas and dust. Interstellar gas will tend to absorb (and re-radiate in a different wave-band) and dust will scatter the stellar radiation. These effective losses are known collectively as **extinction**. Unfortunately, generally extinction is not uniform across the whole spectrum. The observed magnitude ($m_{obs}(\lambda)$) at some wavelength, λ, of a star will be the sum of its intrinsic magnitude ($m_{int}(\lambda)$) and some extinction factor ($A(\lambda, position)$) known as the **total absorption**[16] which is dependent on both the wavelength of observation and the position of the star (which determines how much ISM is traversed by the observed light). Now A can be written as the product of an **absorption coefficient**, $\kappa_a(\lambda)$, which is a function only of wavelength and a factor which is dependent only on the quantity of the ISM along the line of sight. We can define a function:

$$\zeta(\lambda) = \frac{\kappa_a(\lambda)}{\kappa_a(\lambda = 5500\text{Å})} \tag{20}$$

This equation is the **interstellar absorption law** and is normalized at 5500Å (that is, in the centre of the 'visible'). Shorter wavelength light is affected more than longer wavelengths, so it is often also referred to as the **reddening curve**. Now we can write an extinction correction:

$$A(\lambda, position) = \zeta(\lambda) A_1(position), \tag{21}$$

were $A_1(position)$ is a function only of the location of the observed star. So finally we have:

$$m_{obs} = m_{int}(\lambda) + \zeta(\lambda) A_1(position). \tag{22}$$

Simple models[40] have been derived to model the distribution of the absorbing medium in the Galaxy, and maps[59, 60] showing the amount of absorption as a function of Galactic longitude and latitude (l, b) and distance are available. The reddening curve $\zeta(\lambda)$ when plotted against $(1/\lambda)$ is pretty linear across the *UBVRI* bands[64]. It is therefore relatively easy to correct any observed magnitude for the effects of interstellar extinction.

There is little interstellar extinction at infrared wavelengths. Hence objects which are heavily obscured at optical wavelengths, because they are deeply embedded in dense interstellar clouds, can often be observed at infrared wavelengths.

[16] Total absorption in, say, the V-band would usually be written as A_V and known as the *visual extinction*.

B Finding the Air Mass and Zenith Distance

This appendix gives some advice on how you can find out the air mass and zenith distance of your individual observations. It is impossible to give simple instructions which will work in all cases because the procedures adopted by different observatories are different. Ideally, at the conclusion of your observing run you would be given a summary list of all your observations which would include the air mass for each. However, it is much more likely that the air mass or zenith distance will be included in the auxiliary information stored in the data file for each observation. Again, different observatories use different data formats and different keywords[17].

B.1 Information required

Ideally you need to know the average air mass, X, of each observation. Alternatively, the zenith distance, z, is just as good. The CURSA applications for calibrating instrumental magnitudes (see the recipe in Section 16) can automatically calculate the air mass from the zenith distance. Conversely, if you need to calculate the air mass from the zenith distance yourself then Section 8 gives the requisite formulæ.

If the auxiliary information for your observations contain neither the air mass nor the zenith distance then you will have to calculate the zenith distance from whatever information is available about the celestial coordinates and times of your observations. The zenith distance, z, can be calculated from:

$$\sec z = \frac{1}{(\sin\psi\sin\delta + \cos\psi\cos\delta\cos h)} \tag{23}$$

where:

ψ is the latitude of observation,

δ is the Declination of the object observed,

h is the Hour Angle of the object observed.

The Hour Angle is simply:

$$h = s - \alpha \tag{24}$$

where α is the Right Ascension of the object observed and s is the local sidereal time. Again, the local sidereal time may not be recorded in your observations and it might be necessary to calculate it from whatever information is available about the time of your observations. Most standard textbooks on spherical astronomy give further details of calculating the zenith distance and converting between time systems (see, for example, *Spherical Astronomy* by Green[31]). Another useful source of information is the explanation and notes for the SLALIB positional-astronomy subroutine library (see SUN/67[75]).

[17] In this context, a keyword is simply the name of each datum or item of information. For example, the keyword for the air mass might be '`AIRMASS`'.

The keywords used to represent these various items of information differ between different observatories. Table 5 gives some examples. It is based on CCD frames observed with the Jacobus Kapteyn Telescope (JKT) on La Palma. In this case both the air mass and the zenith distance are included and hence there is no need to calculate them. The keywords used at the Anglo-Australian Observatory are available via the World Wide Web (at URL `http://www.aao.gov.au/local/www/tjf/fits.html`). The appropriate instrument and observatory manuals should document the keywords used in a given dataset. In case of difficulty staff at the observatory where the dataset was acquired should be able to advise.

Keyword	Description
`AIRMASS`	air mass
`ZENDIST`	zenith distance (degrees)
`TIMSTART`	start time of exposure
`TIMEND`	end time of exposure
`RA`	Right Ascension of the object
`DEC`	Declination of the object
`EQUINOX`	equinox of coordinate system
`DATE-OBS`	date of the observation

Table 5: Example of some keywords present in a CCD frame acquired with the Jacobus Kapteyn Telescope (JKT) on La Palma

B.2 Examining files

Files containing observations come in a number of different formats. The procedures for inspecting them to determine the values of the keywords that they contain differ for different formats. The following notes cover some of the more common formats, though they are not comprehensive. Note that you can convert a data file between any of the formats mentioned below (and others) using the CONVERT package (see SUN/55[12]).

Starlink NDF and HDS files If you are using Starlink applications such as PHOTOM (see Section 14) or GAIA (see Section 15) to measure instrumental magnitudes in CCD frames then you will probably have converted them to the n-dimensional Data Format (NDF; see SUN/33[77]) which itself is a special case of Starlink's Hierarchical Data System (HDS; see SUN/92[78]). HDS files, including NDF ones, usually have file type '`.sdf`'. In this case, the file name specified to applications, such as those in KAPPA, *must* omit the '`.sdf`' file type.

If the observations were originally formatted as FITS files (see below) prior to being converted to the NDF format then all the FITS keywords are preserved in an extension to the NDF file and usually this extension will contain any information about the air mass *etc.* Application `fitslist` in KAPPA (see SUN/95[11]) will list the FITS extension of an NDF. Briefly, if you have not previously started KAPPA type `kappa`. Then type `fitslist` *filename* (remembering to omit the file type).

If you know the name of the required keyword then you can use the Unix command `grep` to extract just the required line from the output produced by `fitslist`. For example, if the required keyword was '`AIRMASS`' you would type:

```
%  fitslist filename | grep -i AIRMASS
```

If you cannot find the required datum in the FITS keywords then it is worth reading the FITS comments to see if they give any useful information.

You can examine the entire contents of an HDS file using `hdstrace` (see SUN/102[10]). This option will be useful if the file is not an NDF which was created from a FITS file. Simply type `hdstrace` *filename* (again remembering to omit the file type). `hdstrace` is a flexible utility and you should refer to SUN/102 for a full description.

FITS files The FITS[18] (Flexible Image Transport System) format is in widespread use in astronomy. The original observations which you brought away from the observatory after your observing run are perhaps most likely to be in this format.

Application `fitshead` in KAPPA (see SUN/95[11]) will list all the header information, including the keywords, in a FITS file. Briefly, if you have not previously started KAPPA type `kappa`. Then type `fitshead` *filename*. Alternatively, and perhaps even more simply, the header information can be displayed using 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 description of the FITS format is beyond the scope of this note. However, briefly, a FITS file comprises a primary dataset and optionally one or more extensions. `fitshead` allows you to access the header information for the primary dataset and all the extensions. Conversely, often only the primary header information can be conveniently accessed with `more`.

Figaro DST files Figaro DST files are another special case of the Starlink HDS format and can be examined with `hdstrace`. See above for details. The air mass, zenith distance and similar information are most likely to be found in the `.FITS` or `.OBS` structures.

IRAF files A given IRAF (Image Reduction Analysis Facility) dataset is comprised of two files. One file has type '`.pix`', the other '`.imh`'. The `.pix` file contains the 'bulk data' for the dataset; the array comprising the two-dimensional image in the case of CCD photometry. The `.imh` file contains all the header information. It is a simple text file and the keywords have a similar format to FITS keywords. It can be listed using standard Unix commands such as `more` or `cat`.

[18] The original FITS format was proposed by Wells *et al.*[79] 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[47].

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Any mistakes are, of course, our own.

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