

PROJECT

1

CCD IMAGE ANALYSIS

Objective: Before any sort of meaningful information can be extracted from a CCD image taken at the observatory, it has to be corrected for instrumental effects (vignetting, inhomogeneous illumination of the chip, artificially induced signal or bias, etc). In this project the students will learn how to remove these unwanted effects, assess the quality of a CCD image, and become familiar with the calibration techniques of astronomical images.

Observations:

- bias frames before and after the observations
- flat fields for each filter
- CCD images of a low-populated field at various exposures

Theory topics: The characteristics of a CCD, seeing, signal-to-noise, point spread function, calibration techniques. The meaning of these concepts is explained in simple terms. Especially emphasis is put on the understanding of the calibration process.

Analysis: Image processing (bias & flat field correction), seeing estimation, background determination, uncertainty of the measurements (signal to noise ratio).

Contents: CCD Image Analysis

1. The CCD cameras
2. Calibration: bias, dark current & flat fields
3. Astronomical Seeing
4. Study of the signal to noise
5. Aperture Photometry. Instrumental magnitudes

In the following we assume that the user has loaded the IRAF and SAO image DS9 software tools.

1. The CCD cameras

A CCD (Charge Coupled Device) is best described as a semiconductor chip, one face of which is sensitive to light. The light sensitive face is rectangular in shape and subdivided into a grid of discrete rectangular areas (picture elements or **pixels**) each about 10-30 micron across. The CCD is placed in the focal plane of a telescope so the light-sensitive surface is illuminated and an image of the field of sky being viewed forms on it. The arrival of a photon on a pixel generates a small electrical charge which is stored for later read-out. The size of the charge increases cumulatively as more photons strike the surface: the brighter the illumination the greater the charge. It is possible to estimate the amount of light that has fallen onto each pixel by examining the amount of charge it has stored up. Thus, the charge which has accumulated in each pixel is converted into a number. This number is in arbitrary 'units', so-called '**analogue data units**' (ADUs). The **ADC factor** is the constant of proportionality to convert ADUs into the amount of charge (expressed as a number of electrons) stored in each pixel.

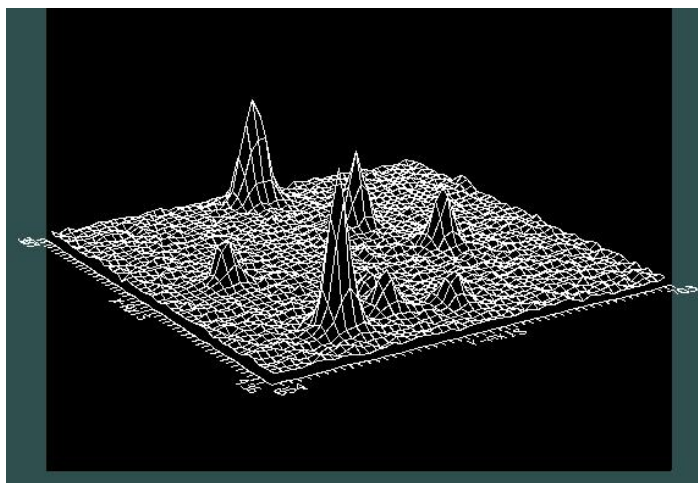


Fig. 1. Surface plot of a portion of a CCD chip. Stars are clearly seen as peaks over the more or less flat background.

The first thing you need to start processing an image is a program to view it. A good freeware program called Iris is available for download on the Internet. You can download it from the [IRIS Home Page](http://www.astrosurf.com/buil/us/iris/iris.htm) (<http://www.astrosurf.com/buil/us/iris/iris.htm>). Another one is ds9 (<http://he-www.harvard.edu/RD/ds9/>).

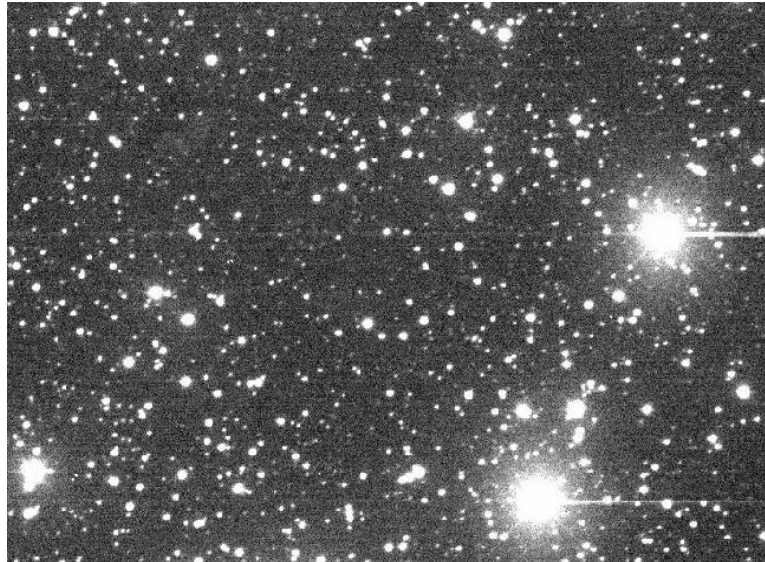


Fig. 2. CCD image

- **Unsigned integer:** Most modern computers store memory in units of 8 bits, called a "byte" (also called an "octet"). Arithmetic in such computers can be done in bytes, but it is more often done in larger units called "**(short) integers**" (16 bits), "**long integers**" (32 bits) or "**double integers**" (64 bits). Short integers can be used to store numbers between 0 and $2^{16} - 1$, or 65,535. Long integers can be used to store numbers between 0 and $2^{32} - 1$, or 4,294,967,295, and double integers can be used to store numbers between 0 and $2^{64} - 1$, or 18,446,744,073,709,551,615.

The CCD that you will be using for your observations stores the information of the number of counts as signed integers. However, some of the programs and tools that you will be using to solve the exercises suggested in this project, work with unsigned integers. It is possible that you will get an error message if the program tries to read a negative value (that is, a value greater than 32767). Data truncation may occur if an inappropriate data type is specified.

Exercise 1: Transform your image so that the number of counts is stored as unsigned integers.

Check whether if any of your pixels have a negative value. If this is the case then you must first convert your *signed* data into *unsigned* integers.

The conversion from signed to unsigned integer can be done easily with the IRAF tool `rfits` and the option `datatype`

```
iraf> rfits input.fit output.fit datatype=u
```

where `input.fit` is the raw image and `output.fit` is the transformed image.

2. Calibration: bias, dark current & flat fields

Preparation (or PRE-PROCESSING) of an astronomical CCD image consists of removing the bias and thermal contribution (DARK FRAME) and dividing the resultant image by the FLAT-FIELD in order to standardize the response of each image pixel.

The **dark current** is charge that accumulates in the CCD pixels due to thermal noise. The effect of dark current is to produce an additive quantity to the electron count in each pixel. This effect is negligible if the CCD has been cooled down with liquid nitrogen. Cooling the CCD from room temperature to -25 °C will reduce dark current by more than 100 times.

The **bias level** is an artificially induced electronic offset, which ensures that the conversion from the accumulated charge to a digital value is positive. The examination of a bias frame tells you if your camera is working properly: if you see wavy lines or patterns, your camera may not be functioning well or its electronics may interfere with other electronic equipment (power supply or CCD controller cables, etc).

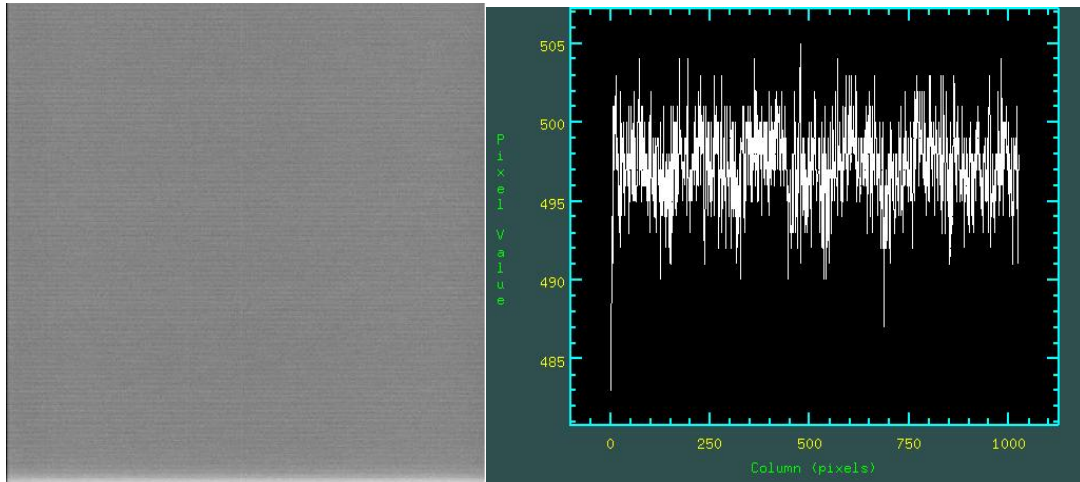


Fig. 3. A bias frame (left) and a cut along a line (right). The bias level is around 497 counts

Exercise 2: Subtract the BIAS level from your images.

BIAS frames are zero second exposures obtained with the shutter closed. You should have at least 10 of such frames at the beginning and at the end of the observation. If the bias level does not change through the night one average BIAS frame can be produced. From this average frame we extract the average level and subtract that level from all other images (target star, standard star and flat fields).

1. Check that the bias level does not change much throughout the night. The IRAF command `imstat` computes and prints image pixel statistics. Check that the mean is roughly the same in all bias frames, as in the example bellow

```
iraf> imstat bias*.fit
```

| # | IMAGE | NPIX | MEAN | STDDEV | MIN | MAX |
|---|--------------|---------|-------|--------|------|------|
| | bias-001.fit | 1048576 | 491.7 | 2.984 | 470. | 761. |
| | bias-002.fit | 1048576 | 491.3 | 3.075 | 469. | 505. |
| | bias-003.fit | 1048576 | 491.3 | 3.12 | 469. | 821. |
| | bias-004.fit | 1048576 | 491.5 | 3.074 | 470. | 849. |
| | bias-005.fit | 1048576 | 492. | 2.939 | 470. | 507. |
| | bias-006.fit | 1048576 | 491.9 | 2.916 | 470. | 505. |
| | bias-007.fit | 1048576 | 492.1 | 2.959 | 470. | 504. |
| | bias-008.fit | 1048576 | 492.2 | 2.938 | 470. | 505. |

2. Obtain a mean bias frame

```
iraf> imcombine input=@bias.lis output=bias_av.fit combine=average
```

bias.lis is an ASCII file that contains the name of the bias filenames, one filename in each row. Like this

```
bias-001.fit  
bias-002.fit  
bias-003.fit  
bias-004.fit  
bias-005.fit  
bias-006.fit  
bias-007.fit  
bias-008.fit
```

bias_av.fit is the name of the output file

3. Subtract the mean bias level from the flats, target and standards
`iraf> imarith operand1=@data.lis op=- operand2=bias_av.fit result=@data.lis`

data.lis is a file that contains the name of the filenames of the objects that you want to subtract the bias from, one filename in each row.

Flat-field calibration frames are images taken of a flat source using the same set-up as that used to take the object frames. It accounts for the non uniformity of the sensitivity of the CCD across its surface. Unlike BIAS correction which is an additive effect, FLAT-FIELDING is a multiplicative effect. So, we have to divide the data by the flat field. Another important difference with respect to the correction for the bias level is that the pixel sensitivity depends on wavelength. Thus, in the case that you are using different filters, flat-field frames have to be obtained for each filter separately. Chip sensitivity, vignetting and dust all appear as variations in the sensitivity of the CCD itself: division by FLAT-FIELD will remove these defects.

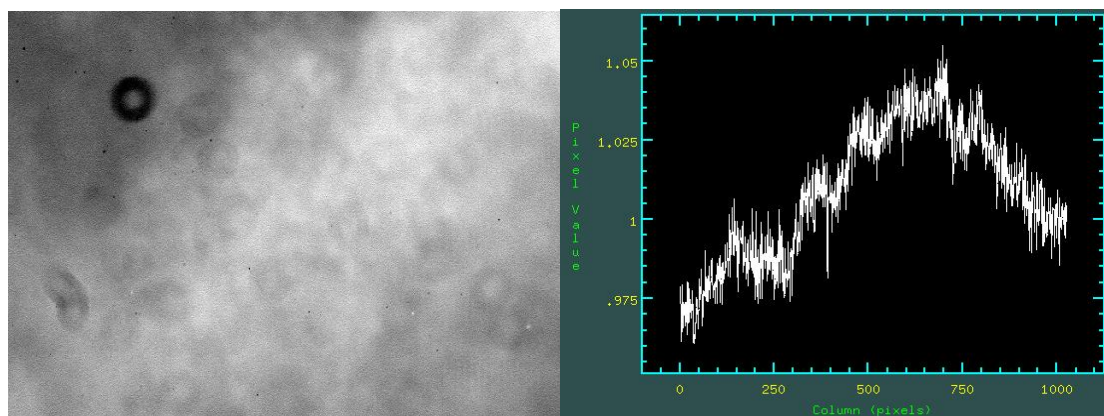


Fig. 4. A flat field (left) and a cut along a line (right). Note the different response along the chip

Exercise 3: Correct your images for Flat-field.

You should have at least 3-5 FLAT FIELDS for each filter. The procedure is as follows:
subtract the bias level from the flat-field images, normalize the flat-field exposures to some average value, obtain a MEAN flat-field by averaging all flat fields of the same filter and divide the data by this averaged frame.

1. Normalize each flat field to unity. First, determine the mean intensity level of each flat field by using imstat. Then divide each flat field by its mean

```
iraf> imarith operand1=flat-field op=/ operand2=mean result=flat-field_norm
```

You can check that the normalization process was successfully done by running once again the imstat task on the output image

```
iraf> imstat flat-field_norm
```

The mean should be 1. Check it by running the imstat command

```
cl> imstat flat*
```

| # | IMAGE | NPIX | MEAN | STDDEV | MIN | MAX |
|---|--------------|---------|------|---------|--------|-------|
| | flat001B.fit | 1048576 | 1. | 0.03429 | 0.2098 | 1.062 |
| | flat001V.fit | 1048576 | 1. | 0.03272 | 0.2214 | 1.086 |
| | flat002B.fit | 1048576 | 1. | 0.03428 | 0.2089 | 1.061 |
| | flat002V.fit | 1048576 | 1. | 0.03275 | 0.2231 | 1.092 |
| | flat003B.fit | 1048576 | 1. | 0.03423 | 0.2087 | 1.064 |
| | flat003V.fit | 1048576 | 1. | 0.03268 | 0.221 | 1.084 |
| | flat004B.fit | 1048576 | 1. | 0.03409 | 0.2106 | 1.081 |

2. Obtain an average flat field for each filter

```
iraf> imcombine input=@flatb.lis output=flatb_av.fit combine=average
```

Repeat for each filter

3. Divide the target and standard images by the average flat field

```
iraf> imarith operand1=@data.lis op=/ operand2=flatb_av.fit result=@data.lis
```

3. Astronomical seeing

In astronomy, seeing refers to the clarity with which stars and other celestial objects can be observed. It is primarily determined by the atmosphere of the Earth. The most obvious phenomenon is twinkling, when the brightness of a star seems to fluctuate. Known to astronomers as scintillation, twinkling is caused by thermal motion of the air, which swirls air layers of different temperature and density. This motion causes minute alterations in the path of light from a star because different densities of air will bend light by different amounts.

The most common seeing measurement is the diameter (technically Full Width Half Maximum) of the **seeing disc**. The seeing disc diameter or "*seeing*" is a reference to the best possible angular resolution which can be achieved by an optical telescope in a long photographic exposure, and corresponds to the diameter of the fuzzy blob seen when observing a point-like star through the atmosphere.

Exercise 4: Obtain radial profiles. Estimate the seeing of your images by measuring the FWHM in the radial profile.

In this exercise we will make use of the IRAF tool `imexamine`.

1. Start IRAF and ds9
2. display the image (e.g `input.fit`)
`iraf> display image=input.fit frame=1`
3. Run `imexamine`
`iraf> imexamine input.fit`
4. Move the cursor on the image display and press
 - m for statistics of a rectangular region (`ncstat`, `nlstat`)
 - j,k fit gaussian curve along lines and columns. Print out info
 - s surface plot. More parameters in `simexam`
 - r radial profile fit. More parameters in `rimexam`
 - e contour plot
 - c plot column/s
 - l plot line/s

Estimate the following image characteristics:

1. the full width at half maximum (FWHM) of the point-spread function("r").
The last three numbers inside the yellow strip at the bottom of Fig. 5 are the FWHM, derived through different methods (see IRAF manual for more details)
2. the radius at which the light from the brightest star of interest disappears into the noise ("r").

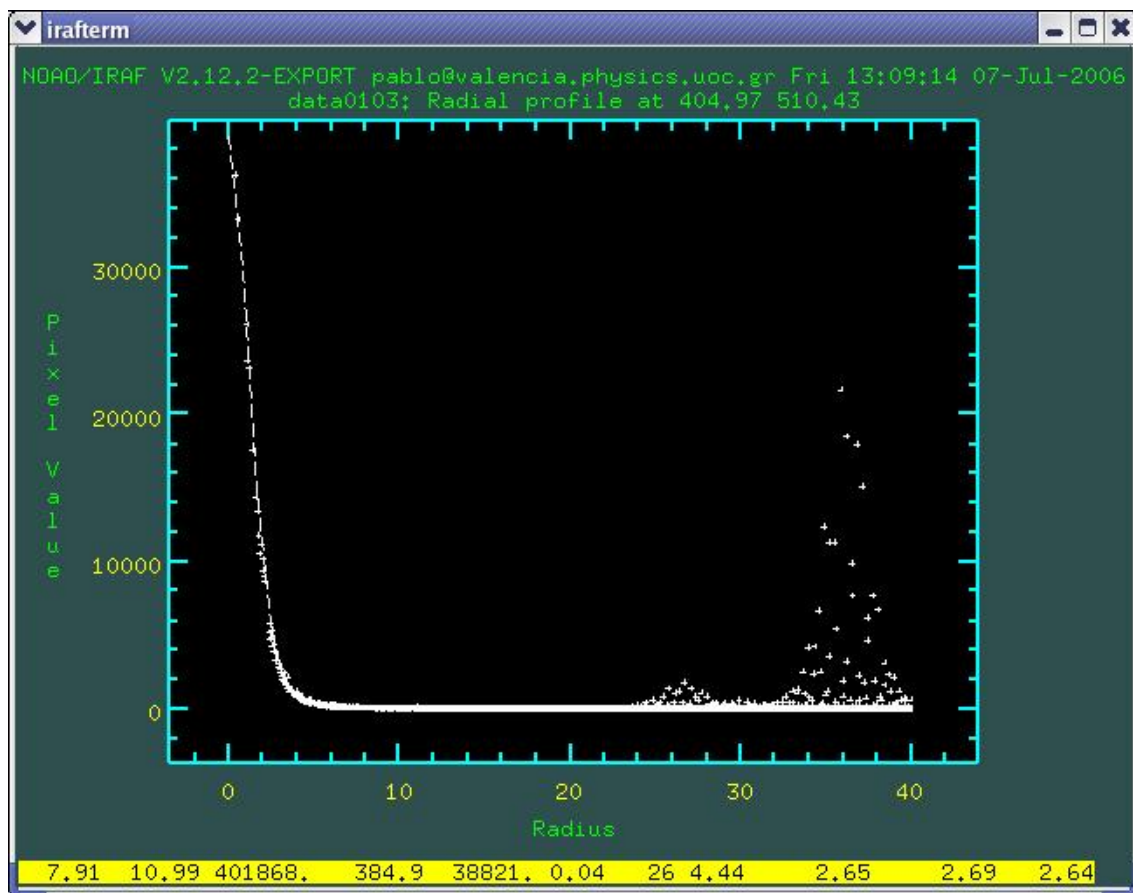


Fig. 5. Radial profile of a star. It represents the variation of light as the radius increases. 0 indicates the center of the star. The clouds of points at radius 26 and 36 represent nearby stars. The radius units in this figure are pixels.

This graph represents the radial photometric profile of the star. The vertical axis is graduated in relative intensity and the horizontal axis represents the distance in pixels relative to the geometrical center of the star. You can check on this graph that the FWHM is about 2.6 pixels.

4. Study of the signal to noise

The signal-to-noise ratio (S/N) is a technical term used to characterize the quality of the signal detection of a measuring system (e.g. a CCD camera). If the measuring system is a CCD camera, then the S/N is given by the ratio of the light signal to the sum of the noise signals. The noise signals are:

Photon noise refers to the inherent natural variation of the incident photon flux.

Read noise refers to the uncertainty introduced during the process of quantifying the electronic signal on the CCD.

Dark noise arises from the statistical variation of thermally generated electrons within the silicon layers comprising the CCD.

Sky noise refers to the level of background light in the image per pixel.

Assume that I_s is the star intensity, within an aperture, in ADU (i.e. counts as measured in the CCD image). g is the gain in electrons/ADU, N_{pix} is the number of pixels within this aperture. I_{sky} is the sky flux in ADU/pixel in an off-star aperture containing p pixels and σ_{sky}^2 is the rms value in the off-star aperture. The background measurement should be made in a region of the image devoid of stars. The value of σ_{sky}^2 in that background region will take account of all processes that contribute noise to the measurement of the signal except for noise due to the star's incident photons (e.g., it will take account of noise due to dark current, noise due to "readout noise," even noise due to numerous, but individually undetected stars in the background, and uncertainties introduced by dark-corrections or flat-field corrections).

It is known that the photons emitted from a star follow the Poisson distribution (the standard deviation is the square root of the mean). The same distribution is followed by the electrons generated within the CCD camera. However, the recorded signal is given in arbitrary units known as ADU and does not follow this distribution. Fortunately, the ADU can be converted back to electrons by multiplying by the gain factor.

The signal-to noise ratio is as measured from the image pixel values (ADU) is then

$$\frac{S}{N} = \frac{I_s - N_{pix} I_{sky}}{\sqrt{\frac{I_s - N_{pix} I_{sky}}{g} + N_{pix} \sigma_{sky}^2 + N_{pix} \frac{\sigma_{sky}^2}{p}}}$$

Exercise 5: Derive the S/N equation in the case of a very bright star. Using your observations calculate the S/N of several stars in the field.

If the star is very bright, then $I_s \gg N_{\text{pix}} I_{\text{sky}}$ and $I_s \gg \sigma_{\text{sky}}^2$

So,

$$\frac{S}{N} = \frac{I_s}{\sqrt{\frac{I_s}{g}}} = \frac{gI_s}{\sqrt{gI_s}} = \sqrt{gI_s}$$

1. Start IRAF and ds9
2. display the image (e.g input.fit)
iraf> display image=input.fit frame=1
3. Run imexamine
iraf> imexamine input.fit ncstat=20 nlstat=20
4. Move the cursor on the image display and place it on a star, then press “m”

For example, for star 1 in Fig. 6, the total number of counts in a circular region with 197 pixels is $I_s \approx 261627$ counts. If the gain of the CCD is $g=10$

$$\frac{S}{N} = \sqrt{10 \times 261627} \approx 1600$$

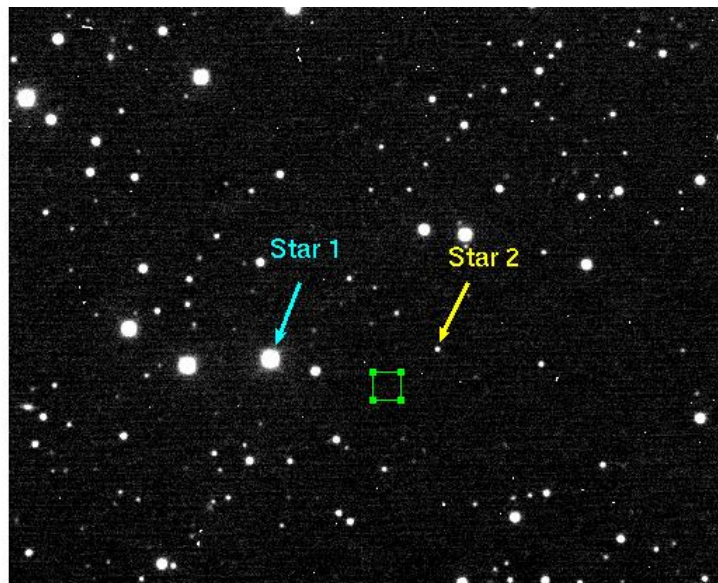


Fig. 6. CCD image showing a bright and a faint star used in the example of the S/N calculation. Also shown is the size of the box used to add up counts.

Star 2 is too faint. The simplified equation cannot be used. Using the correct equation

$$I_s \approx 23160 \text{ counts}$$

Go to an empty region of the image, close to the star and do again “m”

$$P=400 \text{ pixels}$$

$$I_{\text{sky}}=52.31 \times 400= 20924 \text{ counts}$$

$$\sigma_{\text{sky}}= 4.038 \text{ counts}$$

$$\frac{S}{N} = \frac{23160 - 400 \times 52.31}{\sqrt{\frac{23160 - 400 \times 52.31}{10} + 400 \times 4.038^2 + 400 \frac{4.038^2}{400}}} = \frac{2236}{82.23} = 27$$

Exercise 6: Derive the uncertainty in the star’s magnitude as a function of the S/N. Calculate the magnitude uncertainty for a S/N=100, S/N=10 and S/N=5.

The magnitude of a star is proportional to the intensity

$$m = -2.5 \log (I) + C$$

where C is a constant that depends on the wavelength of the radiation that is been measured. The error on the magnitude can be found by taking the derivative

$$\sigma_m = \left(\frac{2.5}{\ln 10} \right) \left(\frac{\sigma_I}{I} \right) = 1.086 \sqrt{\frac{g I_s}{g I_s}} = \frac{1.086}{\sqrt{g I_s}}$$

This relation assumes that the selected star is bright enough to ignore the errors introduced by the readout noise and by the sky subtraction process.

The correct relation would read

$$\sigma_m = 1.086 \frac{\sqrt{\frac{I_s - N_{\text{pix}} I_{\text{sky}}}{g} + N_{\text{pix}} I_{\text{sky}} + N_{\text{pix}} \frac{\sigma_{\text{sky}}^2}{p}}}{I_s - N_{\text{pix}} I_{\text{sky}}}$$

In either case

$$\sigma_m = 1.086 \frac{1}{S/N}$$

The noise is basically the error on the flux measured, that is, $S \pm N$. Therefore the relative error on the measurement is $1/(S/N)$.

- $S/N = 100$: measurement at 1%, error on magnitude = $-2.5 \log(1.01) = 0.0108 \sim 0.01$ mag
- $S/N = 10$: at 10%, error on mag = $-2.5 \log(1.1) = 0.103 \sim 0.1$ mag
- $S/N = 5$: at 20% error on mag = $-2.5 \log(1.2) = 0.198 \sim 0.2$ mag

Exercise 7: Using your observations, select a bright star at different exposure times

- 1. Obtain the S/N for each exposure**
- 2. Plot I_s vs. exposure time. What do you observe?**
- 3. Plot the $\log(\sigma_m)$ vs. $\log(I_s)$. The resulting curve should be approximately a straight line. What is the slope of this line? What is its y intercept? What do these values represent? If it deviates significantly from a straight line, try to explain why.**

One of the advantages of using CCD with respect to photographic plates is **linearity**, that is, the linear character of the CCD response. This means that If a CCD pixel receives twice the number of photons than another pixel, then it will have double the amount of charge than the first pixel. The number of electrons in a pixel therefore is proportional to the number of incident photons to within about 0.1%, typically. Obviously, the longer the exposure time the larger the amount of photons. Linearity is lost if the amount of photons is very large. Each CCD has a different response, hence the linearity range, the range in exposure times for which the response is linear, varies for different CCDs. The objective of this exercise is to find the point where the linearity is lost.

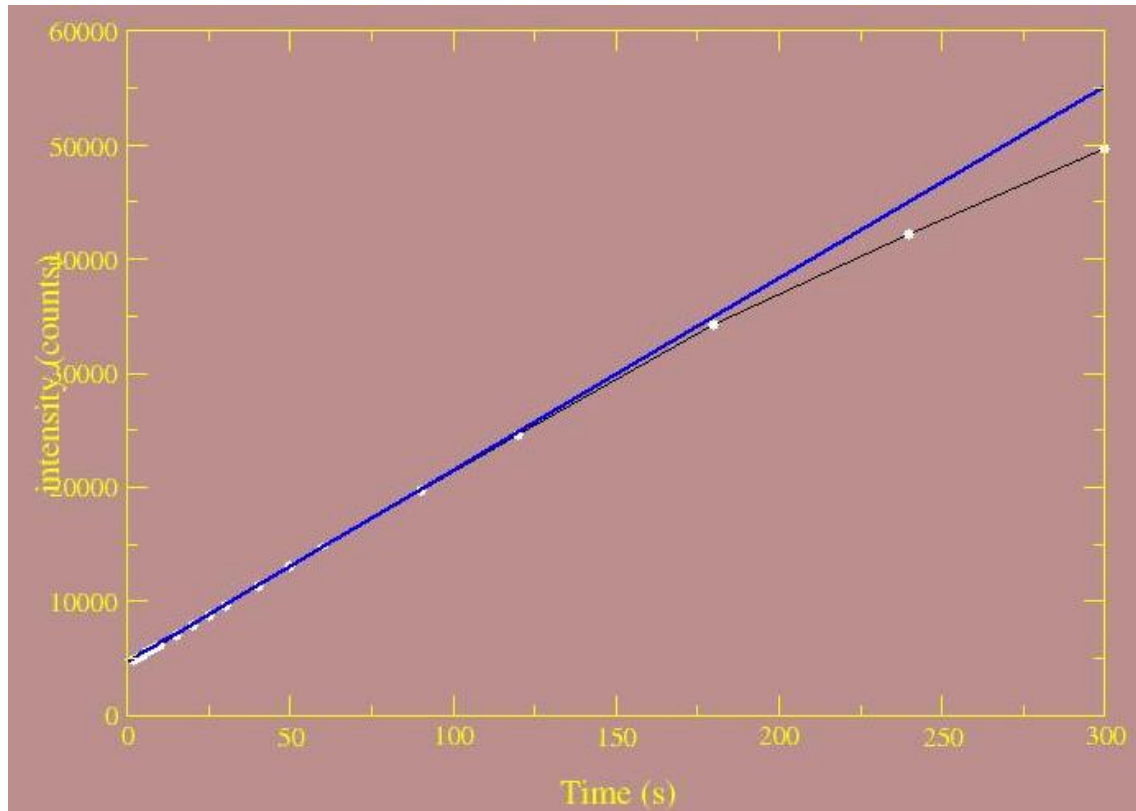


Fig. 7. Intensity as a function of exposure time. Note that for this particular CCD linearity is lost at around 150 s or $I \sim 30000$ counts/pixel.

5. Aperture photometry. Instrumental magnitudes

The basic principle of aperture photometry is to sum up the observed flux within a given radius from the center of an object, then subtract the total contribution of the sky background within the same region, leaving only the flux from the object to calculate an instrumental magnitude. It is called instrumental magnitude because the resulting value depends on the characteristics of the instrumental set-up (telescope reflectivity, filters, CCD, etc).

The aperture size is important since seeing, tracking, and focus errors affect the amount of flux within the stellar profile. The noise grows linearly with radius as the stellar flux trails off in the wings of the profile. Increasing the size of the aperture will increase the Poisson shot noise of the background sky and any flat-field errors that may be nearby.

Before you can start measuring magnitudes, you need to pick a good size for the aperture. If you pick an aperture which is too big, you'll include light from neighboring stars. If you pick a too small aperture, light from the star will be missed.

The goal is to pick an aperture which will include

- most of the light from the star but
- little extra light (and noise) from the background sky

A good compromise is an aperture which is a little bigger than the visible extent of faint stars. In practice, a good choice for the radius of an aperture is about 3 times the FWHM.

You also need to set the radii of the annulus used to measure local background sky values for each star. Reasonable values for the sky annuli are around 4-5 times the aperture radius for inner boundary, and around 6-7 times the aperture radius for outer boundary. Having one or two stars within the annulus is not a problem as long as the great majority of its pixels are purely background sky.

Exercise 8: Using your observations, determine the best aperture and obtain the instrumental magnitudes of a number of stars.

The starting point is a CCD frame which has been processed to remove instrumental effects, that is, you must have subtracted the bias and divided by the flat-field.

If you use the IRAF task `phot` then you must select a number of parameters

cbox: The centering box width in pixels

annulus: The inner radius of sky annulus in pixels

dannulus: The width of the sky annulus in pixels

datamin: use $I_{\text{sky}} - 8 \cdot \sigma_{\text{sky}}$ (σ_{sky} can be obtained using `imstat`)

aperture: The list of photometry apertures

exposure: the exposure time

annulus and *dannulus* define the region where the background is calculated. In the simplest case, we just go away from the star and take the mean level, I_{sky} and standard deviation σ_{sky} . This is what we did in the previous exercise using the option “m” of `imexamine`. In order to minimize effects of any non uniform background (e.g. presence of weak stars nearby), we consider an annulus (i.e. a ring) around the star. *annulus* is then the inner radius of the ring in pixels and *dannulus* the width of this ring. *aperture* is the size of the aperture radius in pixels. All the light inside the aperture area will be measured. *annulus* should be a few pixels larger than the aperture radius. `phot` computes accurate centers for each object using a centering algorithm, pixels inside *cbox*. A value of 5 is fine for *cbox*.

PROCEDURE

1. Start IRAF and ds9
2. display the image (e.g input.fit)
`iraf> display image=input.fit frame=1`
3. Obtain instrumental magnitudes for various apertures (different radii).
`iraf> phot image=input.fit cbox=5 annulus=14 dannulus=6 datamin=100
apertures=8,10,12 itime=10`
4. Calculate the difference between magnitude obtained with the largest aperture and all the others
5. Plot this difference as a function of radius.

Which aperture would you use to determine the magnitude of the star?

The best aperture will be the one at which the instrumental magnitudes start to level off.

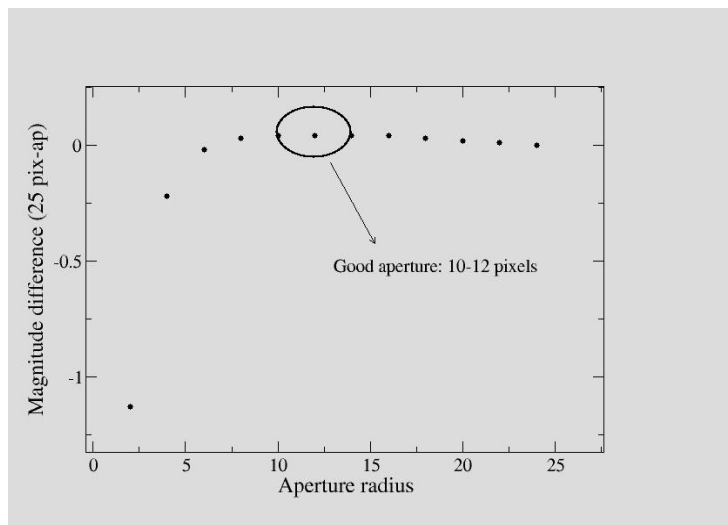


Fig. 8: Magnitude difference as a function of aperture size.