**Fall-Term Project - Part 1/3 Comments: Processing and Analyzing CCD Data**

Part 1 of the Fall-Term Project was not well done in general. As a result, I have decided to let you review the written comments I embedded in the PDF you originally submitted, as well as the general remarks I am providing in this document/video, before you submit the final version of your M34 project due 10 pm, Monday 18 January 2021.

Intro and General Remarks:

This is a scientific report. This means that while it may / should be divided into appropriate sections, it should not be treated as it were a recipe, a series of enumerated text. It should consist of introductory and connecting sentences for each section. Each (representative) calculation should be supported by some explanatory / concluding text.

I did not require an introduction as such, but it only makes sense to begin with some brief text that provides a rationale for the report. It should also explicitly link “your filter” with your student number.

* An astronomical filter is always given in *italics*. SDSS filters are *r’* (or *g’* or *I’*) and not r or r’.
* A report should not be single-spaced. True, in the online era, this is not a major issue, but a number of you single-spaced your report… this makes it more difficult for the reader to follow your work/arguments.
* Units are never in italics. Units have standard short forms. There is no need to make up your own; e.g., “as” for “arcseconds.”
* This is a scientific report. *Anything that distracts from the science should be avoided in the report.* There is absolutely no reason to mention in a report how difficult you found transferring your data to cosmos, or that cosmos was down for part of Nov 1, or that you had trouble saving “mag files”, etc. There are no sympathy marks for this project. And next time, some of you might consider starting the project earlier rather than later. I was/am always available to answer questions (though there is a limit to my expertise when it comes to data handling).

Calibration:

Most of you did well here, likely because things were reasonably straightforward.

* Avoid using “discrepant” as in, there did not appear to be any discrepant bias frames and so were all used in creating the average bias. It’s fine to use “discrepant” when lecturing or talking to a colleague. But in a report, you need to explain what this means. Many of you were clear: the means and standard deviations were reasonably similar and so there was no reason to reject any of the bias frames.

It is helpful, even necessary, in a report at this level (as opposed to a scientific paper) to show a table with the image statistics to justify using all the bias images to create the average bias. (The “lines” or “columns” that appear in the image are not necessarily “bad”, but there is a physical explanation for their existence.)

Everyone subtracted the average bias from their flat-field and science images well.

Most did not realize that the *imcombine*’ing of the flat-field data was/is “special.” Most flat-field data are taken of a lamp projected on a screen on the inside of the observatory dome. Not in our case. Our flat fields were *twilight flats*, meaning, images of the sky were taken of the sky during astronomical twilight. Usually telescope tracking is off and so any stars that appear in the image are streaked. This is not a problem, however, because clever averaging (with sigma clipping) will ensure the stars will not show up on the combined flat field.

The advantage of twilight flats is that they illuminate the focal plane exactly as the science images do. The disadvantage is that they may have trailing stars in individual images and their sky background levels are normally radically different. (The sky brightness is changing rapidly during astronomical twilight.) In order to combine twilight flats, it is necessary to perform “modal scaling” as in the instructions. It was important that this be mentioned – at least in passing – in the report. Take note of this, because this is the most difficult flat-field situation you’ll encounter as an astronomer.

Normalizing the combined flat field was not a problem for any of you. (Because the *i’* people had only three flats with which to build their combined flat, there may have been some small residuals here and there from the stars in the twilight flats.)

* Few students remarked on using ds9 to examine their individual / combined flat field(s). This is essential if one is to assess whether any image is “discrepant”.
* It is very helpful at this point to show the final science image (minus the average bias and divided by the normalized flat field). To conform to usual convention, with N up and E to the left, it is necessary to rotate the image by -90 degrees. As I’ve noted elsewhere, I should have directed your attention to the *imrot* or *imtranspose* utilities and not to *rot*. (This made no difference marks-wise, but it made for a nicer image.)
* When you show ANY astronomical image, my rules are that it must include:
  + Inverse colour map
  + Cardinal directions
  + Scale (or scale bar; e.g., what 1 arcmin corresponds to)
  + Informative title/caption

Positional Analysis:

The J2000 positions for Wolf 1346 (W) and star HD 340612 (H). In order to compute the *pixel scale* (or focal plane scale or – in the old days – the plate scale), it is necessary to calculate their separation in pixel space and angular space (arcseconds). No one had trouble with employing the Pythagorean Theorem in pixel space. But the angular scale was another matter. W and H differ by a few seconds of time which, which with the average declination, is easily transformed into arcseconds.

* Why did so many of you transform the entire RA coordinate (20h 34m …) into seconds of time and then into arcseconds. Crazy. And a similar remark may be made for the declination.
* Even worse, many rounded the number of degrees to 2 or 3 decimal places. Why? 0.01 degrees corresponds to just under 1 arcminute. If you’re going to work in degrees, you need to keep 4 decimal places (if you have coordinates accurate to 1 arcsecond).
* This led to an inaccurate pixel scale *s* (which is about *s* = 0.61”/pixel) [One should note that the astronomical slang, “pixel,” can refer to a linear quantity – the length of the side of the actual pixel, or to an areal quatity – the square of the length of the side of the actual pixel, depending on the context.
* Only one person carried uncertainties of the measured quantities through in their analysis. This is normally essential (though I didn’t take marks off for this).

The tilt of the CCD gave many of you a lot of trouble. Most realized that one can use the arctangent function to calculate the position angle of H relative to W in both the RA-Dec and Col-Row spaces, and then take the difference to get magnitude of the actual tilt which was bout 1.7 or 1.8 degrees. But only one person realized that the tilt was to the west and so was actually -1.7 degrees according to convention. (No marks were taken off for missing the sign.)

* Finding the RA, Dec position of unknown star Q gave almost everyone trouble for obvious reasons (see above). Only one remark: many of you thought you would never use the 2D rotational transformation you learned in first-year linear algebra. Wrong!

Photometry:

A significant number of students did not even get to this section, which was the heart of the assignment.

It was essential to undertake a curve of growth analysis for a reasonably bright (unsaturated), isolated star in order to establish and aperture correction (and aperture radius) that would be used later for determining the apparent magnitudes for 25 more stars. Some students chose a single faint star which was entirely inappropriate. Some students chose a bright and a faint star, mimicking what is done in my notes, though for illustrative purposes, not for doing actual photometry.

* I was unimpressed by the unimaginative way most students approached this; simply parroting my suggested command. This is a capstone science course. You’re supposed to be scientists. You should explore things by using a variety of parameters (e.g., annulus, dannulus, etc.).

The sky brightness gave almost everyone a great deal of trouble. Averaging the means of a few “blank” spots (away from the edges of the image) gave a reasonable estimate of the sky background flux in counts/s or ADU/s. But

* The sky level was the average background level and not the sum of the blank area. It is entirely incorrect to divide the brightness by 5×5 or 25!
* It is necessary to divide the average flux this by the exposure time to get the background in ADU/s/pixel
* To get the background in ADU/s/arcsecond, it is necessary to divide this by *s*2 or 0.37.
* This is the flux to compute an instrumental magnitude, which transforms into the surface brightness after the addition of the appropriate photometric constant

With the reduced Wolf 1346 r' image displayed, the centroids and parameters for four stars was measured using the "," option in IMEXAMINE

Star Xcen Ycen FWHM Comment

W 1040.43 384.17 8.92 Wolf 1346 (circled star on chart)

H 1214.29 651.27 8.83 HD 340612 (labelled “H”)

Q 1407.08 252.02 8.75 Star Q on chart (unknown)

I 735.14 616.23 9.44 Isolated star selected for curve-of-growth analysis

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| --- | --- |
|  |  |

The average FWHM of unsaturated, reasonably bright, unblended stars is about: 8.85 +/- 0.10 pixel.

[For the *g*’ images, the average FWHM is 7.75 +/- 0.05 pixel, while for the *i’* images, the average FWHM is 7.1 +/- 0.10 pixel.]

Notice that the star images appear slightly elongated E-W on the reduced image. This likely indicates that tracking was "off" during the exposure. This is not a problem, so long as the standard and target stars are each unblended. Notice also that the FWHM of the isolated star I chose for curve of growth analysis is slightly larger than the other stars. This could be because "I" is blended with a much fainter star, or because it is further from the centre of the field and therefore could be slightly out of focus. This does not detract from the subsequent analysis. (I carried out the same analysis on “W” with almost identical findings.)

Scales:

In order to measure the scale of the image, it is necessary to compare the positions of two stars, W and H in this case, in both pixel space and RA-Dec space. (The same method is followed for all filters.)

Wolf 1346 (W):

Pixel space centroid: (1040.4, 384.2) = (x,y) RA: (20h 34m 21.9s) Dec: (25d 03' 50")

HD340612 (H):

pixel space centroid: (1214.3, 651.3) RA: (20h 34m 13.7s) Dec: (25d 06' 30")

dx = x(H)-x(W) = 1214.3 - 1040.4 = 173.9 px

dy = y(H)-y(W) = 651.3 - 384.2 = 267.1 px

ds = sqrt{dx^2 + dy^2} = 318.7 px (an invariant, the hypotenuse)

dRA" = 15 dRA(s)\*cos(Dec) = 15\*(-8.2s)\*cos(25.1) = -111.4" [take care with the cosine factor!]

dDec" = 6' 30" - 3' 50" = 160"

ds" = sqrt{dRA"^2 + dDec"^2} = 195.0" (the same hypotenuse)

The pixel- or focal-plane scale is then ds"/ds = 195.0 / 318.7 = 0.61(2) arcsec/pixel

Orientation:

It is difficult to align perfectly one of the CCD axes (columns in this case) exactly N/S. The CCD axis often tilted by angle T (degrees). To compute this angle, which is essential in astrometry for accurate positions, two coordinate systems are established, centred on W. The difference between the position angle (PA) of star H with respect to the CCD columns, and the position angle of star H with respect to RA/Dec is T, the tilt of the CCD. Take time to sketch out the 2D geometry of this situation.

It turns out that sin(PA(CCD)) = dx/ds or PA(CCD) = arcsin(173.9/318.7) = 33.1 degree.

And sin(PA(RA/Dec)) = dRA"/ds" or PA(RA/Dec) = arcsin)111.4/195.0) = 34.8 degree.

Thus, the CCD columns are titled by -1.7 degrees (where the negative sign reflects a clockwise rotation) to the RA/Dec frame.

Star Q has the CCD coordinates (1407.1 252.0). Relative to W,

dx = 1407.1 - 1040.4 = 366.7 px = 224.4”

dy = 252.0 - 384.2 = -132.2 px = -80.9

The separation between stars Q and W is 0.61 \* ds = 0.61\*(dx^2 + dy^2) = 238.5".

The actual RA and Dec position, however, requires an application of linear algebra (rotation of a 2D x',y' to x,y coordinate system). (You thought you only needed to know this for quantum mechanics, eh!) Be sure to look up the rotation transformation equations. In addition, don’t forget the wrinkle that RA increases to the left (i.e., E) which can mess up signs.

RA(Q) = RA(W) - ( dx"cos(T) + dy"sin(T)) = -221.8" or RA(Q) = -221.8/(15 cos(25.1) = -16.3s

Dec(Q) = Dec(W) + (-dx" sin(T) + dy" cos(T)) = - 87.8"

So,

RA(Q) = 20h 34m 21.9s -16.3s = 20h 34m 5.6s

Dec(Q) = +25d 03' 50" -88" = 25d 2' 22"

Without the rotation, RA(Q) = RA(W) - -224.4" or RA(Q) = -16.5s and Dec(Q) = -81" which is close, but not proper astrometry.

Note that this is a kindergarten approach to astrometry. Practicing astrometrists will be able to identify a large number of stars scattered through the image whose coordinates (according to a given frame of reference) on which a 2D higher order (surface) fit is carried out to establish the RA, Dec coordinates of the stars/celestial objects for a given epoch. Such fits take into consideration aberrations introduced by the optics and the detector.

Photometry:

In order to perform the curve of growth analysis, it is best to identify one (or more) isolated, bright, unsaturated stars in the field. Star “I” was selected (though the same analysis on Wolf 1346, "W", yields the same results). DISPLAYing the reduced Wolf 1346 image, a sky annulus was selected carefully, without any apparent cosmetic defects or other celestial objects. A radius of 30 pixels with width 5 pixels was used. The result of qphot yields:

Raper Sum Area Flux IRAF\_mag Inst\_mag Err\_mag Aper\_cor\_mag

4 194680 51 183967 11.838 -10.662 0.002 1.32

6 340450 113 316448 11.249 -11.251 0.001 0.72

8 461519 201 418839 10.945 -11.555 0.001 0.42

10 555130 314 488500 10.778 -11.722 0.001 0.25

12 629981 453 534029 10.681 -11.819 0.001 0.15

14 693774 616 563231 10.623 -11.877 0.001 0.09

16 752619 805 582081 10.588 -11.912 0.001 0.06

18 810333 1018 594560 10.565 -11.935 0.001 0.04

20 869400 1257 602991 10.549 -11.951 0.001 0.02

22 930769 1521 608448 10.539 -11.961 0.001 0.01

24 995572 1810 611987 10.533 -11.967 0.001 0.00

26 1064409 2124 614223 10.529 -11.971 0.002 0.00

28 1137471 2463 615383 10.527 -11.973 0.002 0.00

30 1215390 2828 616103 10.526 -11.974 0.002 0.00

[*g*’: Aperture correction: 12 px = 0.11 mag

Sky background: 229 +/- 4 ADU. Exptime: 20s Sky: 11.5 +/- 0.2 ADU/s/px

Wolf 1346: 2,498,000 ADU/20s or 124,900 ADU/s m(*g*’)inst = -12.74 m(*g*’) = +11.40 C*g*’ = +24.14 ]

[*i*’: Aperture correction: 12 px = 0.14 mag

Sky background: 143 +/- 5 ADU. Exptime: 10s Sky: 14.3 +/- 0.5 ADU/s/px

Wolf 1346: 395,200 ADU/10s or 39,520 ADU/s m(*i*’)inst = -11.49 m(*i*’) = +12.06 C*i*’ = +23.55 ]

A few remarks. "Raper" refers to the aperture radius. "Sum" refers to the total signal, including background, in the aperture. "Area" refers to the number of pixels in the circular aperture. "Flux" refers to the total background-subtracted signal in the aperture. "IRAF\_mag" refers to IRAF's instrumental magnitude which is -2.5log(flux)+25. "Inst\_mag" is the "true" instrumental magnitude we require: -2.5log(flux/exposure time) . "Err\_mag" is the formal uncertainty in the instrumental magnitude. "Aper\_cor\_mag" is the aperture correction (in magnitudes) for each aperture. The asymptotic apparent magnitude was taken to be -11.97. (Note that the actual uncertainty is much larger than the formal uncertainty and so the third decimal place is not entirely realistic!) The (apparent) asymptotic (or total) instrumental magnitude for any star will be instrumental\_mag(r) - aperture\_correction\_mag(r).

The aperture-correction estimation normally involves a number stars, not merely a single star. This technique is used in order to improve photometric accuracy, particularly for moderately crowded fields where the probability of a foreground or background star within ~1 seeing disk is high. It is important to remember that all point sources (in a uniformly focussed image) have the same FWHM and so vary only in scale. By using an aperture of order 1 to 1.5 seeing disks where the SNR is higher (for fainter stars) improves the photometric results, especially for fainter stars. In truly crowded fields, a full 2D PSF-fitting technique is often used (e.g., DAOPHOT).

The photometric constant is determined via: apparent r' magnitude of a photometric standard = total r' instrumental magnitude + C(r') where C is the photometric constant in the r' filter. (Note that this is not a full-blown photometric analysis, but rather an exercise in differential photometry. A full-blown analysis, as you recall, involves a number of standard stars with a variety of colours, taken over a wide range in airmass.)

In this case Cr' = 11.75 - -11.97 = +23.72.

Apart from stars W, H, and Q, the total r' instrumental magnitudes (with aperture correction) for 25 more stars were to be measured and, using this photometric constant, the total r' apparent magnitudes estimated.

The r’ instrumental magnitude of Q is -12.30, which yields an apparent *r*’ magnitude of +11.42

[*g*’ instrumental mag Q: 797,600/20, m(*g*‘)inst= -11.50 m(*g*’)= +12.64

[*i*’ instrumental mag Q: 905,100/10, m(*i*‘)inst= -12.39 m(*i*’) = +11.16

Surface Brightness:

In this context, surface brightnesses are calibrated in the same way as stars. This often confuses students. Don't worry about the extended nature of the light, only its total flux (in a square arcsecond of sky).

From above, the r' flux for a 1s exposure per pixel (ADU/s/px) is 21.0 . One pixel, however, subtends (0.61 \* 0.61) = 0.37 square arcseconds. The flux per square arcsecond of the sky background is then 21.0/0.37 = 56.4 ADU/s/arcsec2.

The instrumental magnitude of an object with this flux is -2.5 log(56.4) = -4.38.

Thus the apparent magnitude of an object with this flux is -4.38 + 23.72 = +19.3.

The *r*' surface brightness of the sky background in this image is +19.3 mag/arcsec^2. This is a moderately bright sky background; better than at the AICO, but much poorer than at Maunakea.

[*g*’: 11.5/0.37 = 31.1 μinst(*g*‘)= -3.73 μinst(*g*‘) = +20.4 mag/arcsec2]

[*i*’: 14.3/0.37 = 38.6 μinst(*i*‘) = -3.97 μinst(*i*‘) = +19.6 mag/arcsec2]

[Remember, uncertainties are important. In the surface brightness measured earlier, the uncertainty was 21.0 +/- 0.30. Be careful when translating this into uncertainties in magnitudes. But you may recall that an uncertainty of 0.05 magnitudes is an uncertainty of 5%.]

Last comments:

Remember to provide images only using an inverse colour map. And don’t forget to provide titles for your plots, tables and images. Images should have some hint of the scaling of the axes.