AAVSO Citizen Sky DSLR Photometry Workshop

07 August 2009
Presented
by
Hopkins Phoenix Observatory

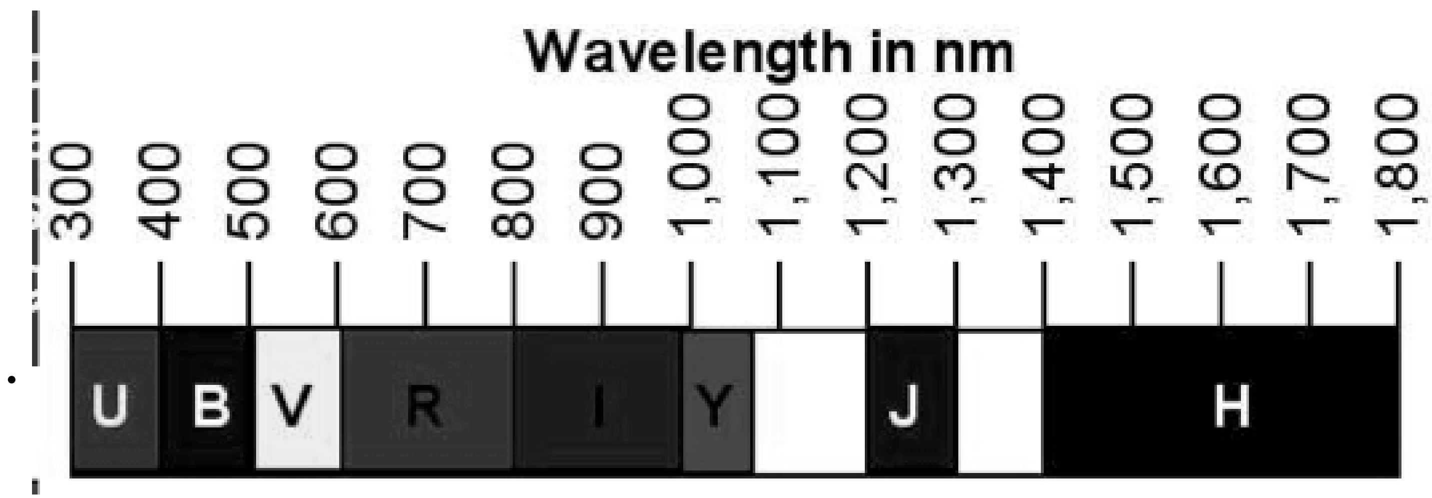
Introduction

Many people wish they could contribute something of scientific value to astronomy. The Epsilon Aurigae Project may be just the ticket.

This talk will discuss a means to use a Digital Single Lens Reflex (DSLR) camera mounted on a tripod (no telescope needed) to do excellent V band filtered photometry on the star system from a light polluted urban backyard setting.

Photometry

To be scientifically useful, photometry must be done using standard filters that measure the brightness within a narrow band of wavelengths. The following chart is for the most popular wavelengths. While research extends into the gamma ray and radio regions, the below is where most work is done.



Photometers work in the UBV, BVRI and JH bands.
300 nano meters = 3000 Å

Photometers

With proper equipment, one can do professional level photometry fairly easily.

The are basically two types of photometers

1. Single Channel Photometers.

2. CCD/DSLR Photometers

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Note: PEP stands for photoelectric photometry. All types of electronic photometry are PEP.

Single Channel Photometers

This includes Photomultiplier Tube (PMT) based photometers and PIN diode photometers, e.g., the Optec SSP-3 and SSP-4 units.

For the Epsilon Aurigae Project single channel photometers are the best choice, but these may be out of reach for many.

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HPO UBV Photon Counting

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HPO JH Near Infrared

Optec SSP-4
JH Band
Photometer
on
12” LX200GPS

CCD Photometers

These include astronomical CCD cameras (specifically for astronomy), modified web cams and popular Digital Single Lens Reflex CCD cameras.

While monochrome cameras with standard filters are the best way to do CCD photometry, some people have used color cameras and the B, G(V) and R planes of the images to do photometry.

HPO BVRI CCD Photometry

Modified DSI Pro with 3.3 focal reducer BVRI filter, filter wheel, and TEC/heat/sink/fan

Problems

Most of the advantages of CCD photometry become disadvantages for observing epsilon Aurigae.

This is because the star system is too bright and acceptable comparison stars are not in the same image. By stopping down the telescope or shortening exposures, other problems are created.

DSLR Photometry

Is it possible to use a Digital Single Lens Reflex (DSLR) color camera to do serious CCD photometry of epsilon Aurigae?

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Posibilities

John Hoot presented a paper at a SAS meeting in 2007 suggesting it might be possible to use a DSLR camera for filter CCD photometry.

The V band is close to the response of the Green plane of color CCDs. With proper calibration, good filter photometry should be possible. In fact it may be possible to use the Blue and Red planes also.

CCD chips must use RGB filters.

Problem Solved

By using a DSLR color camera with a 50 – 100 mm lens on a tripod and splitting out the G plane, most of the problems of CCD photometry of epsilon Aurigae are solved.

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CCDs

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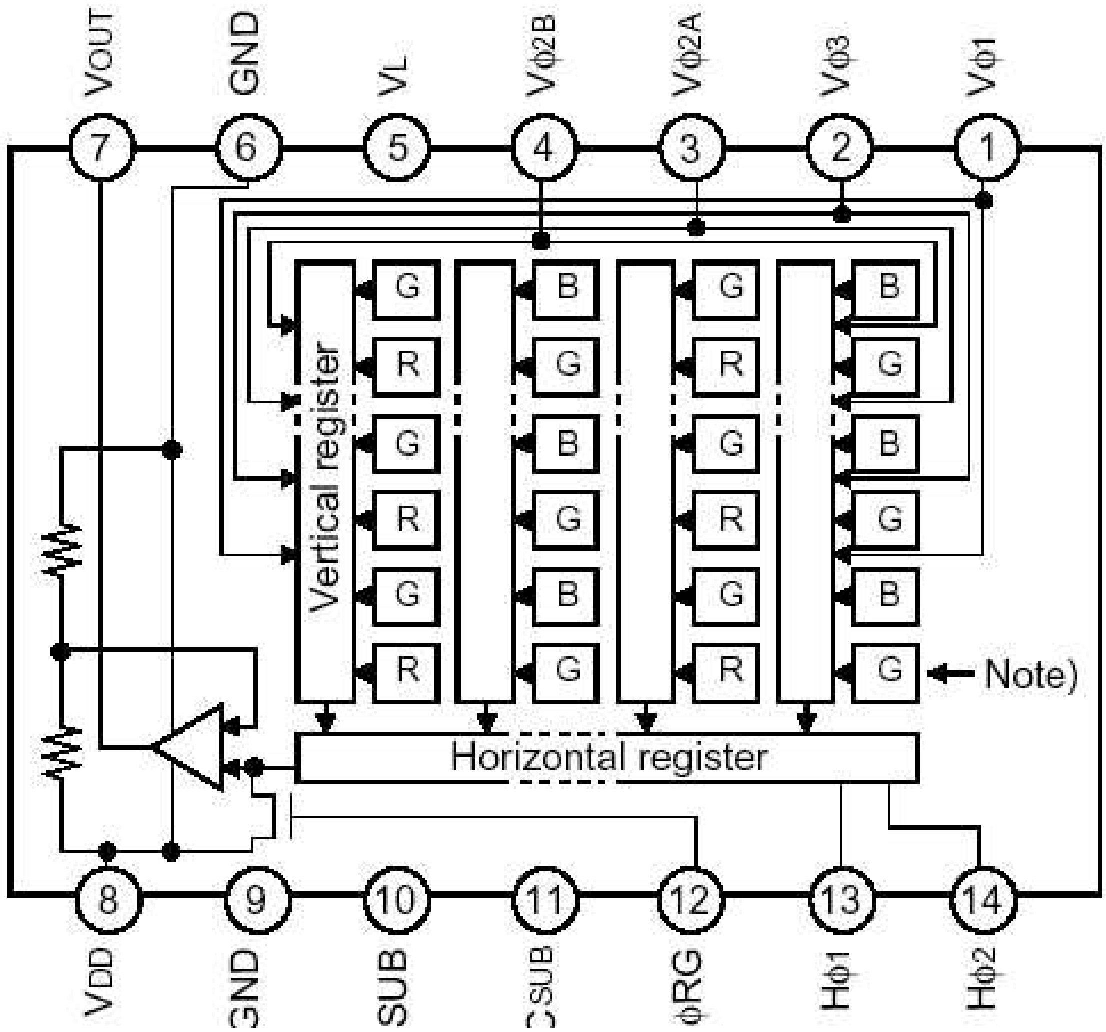
Color CCD Chip



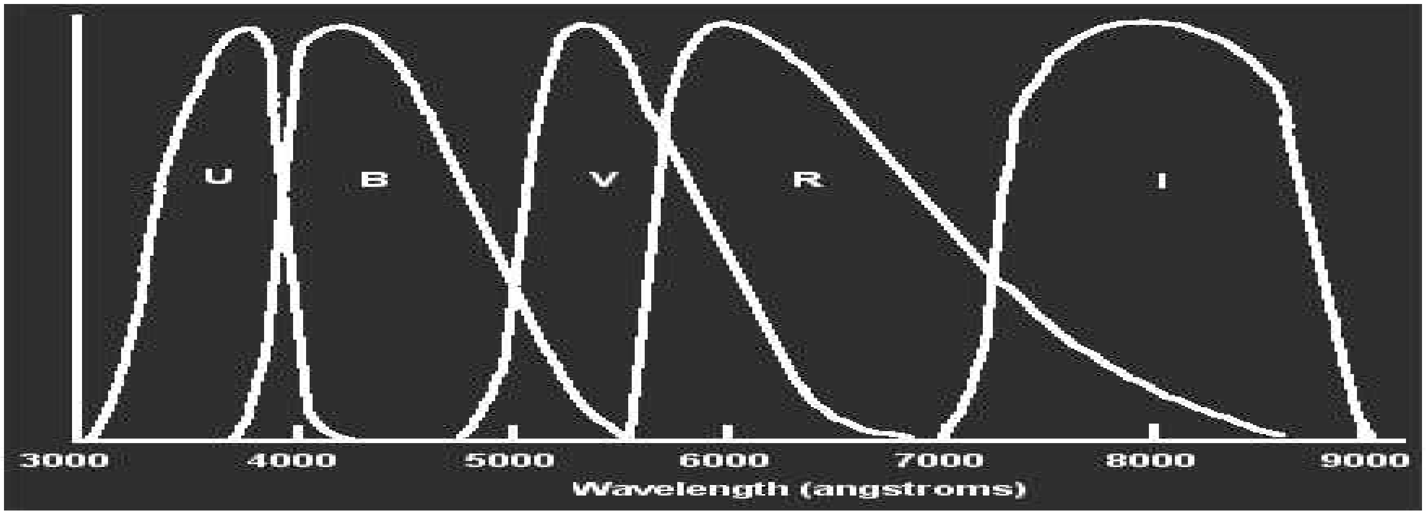
Typical color chip
Sony ICX098BQ

Note: Some chips Do not use RGB filters but Cyan, Green, Yellow and Magenta filters.

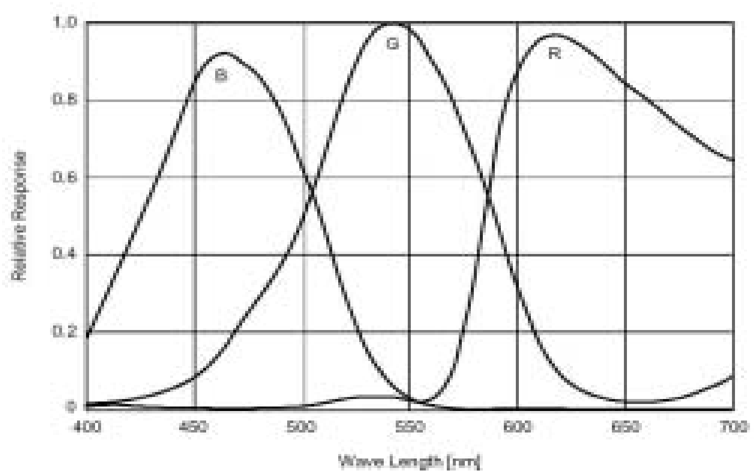
Filter
Detector

Note) ☐ : Photo sensor

Filter Bands



Standard UBVRI filter response.



Color CCD response.

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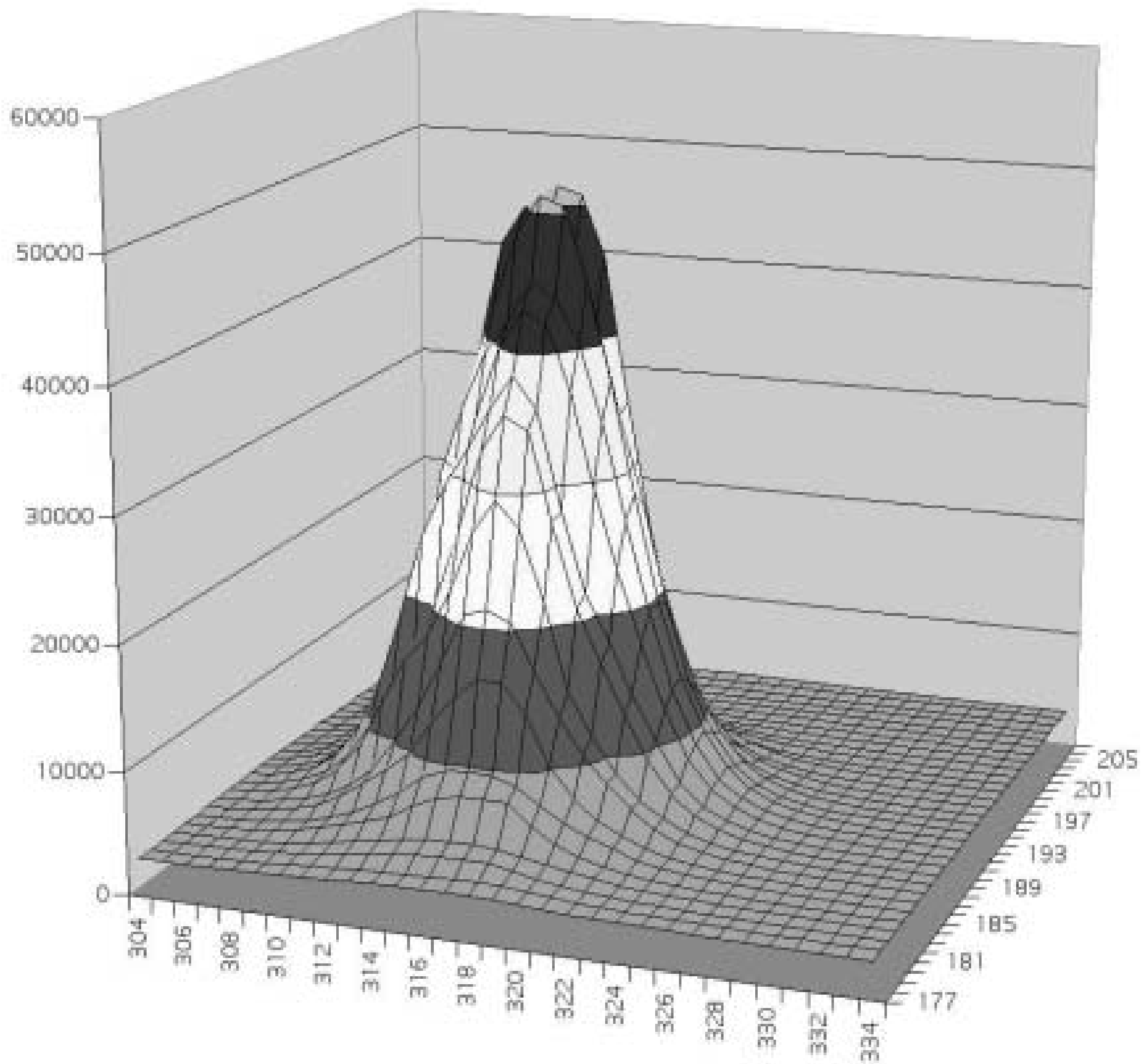
CCD Pixel Matrix

	310	311	312	313	314	315	316	317	318	319	320
180	3779.32	4097.25	4415	4726.84	5047.76	5310.82	5331.74	5423.02	5322.83	4923.12	4563.87
181	4371.3	4812.48	5384.92	6002.85	7067.51	7949.01	8340.21	8386.21	8296.38	6782.79	5526.46
182	4484.63	5208.55	6174.23	7368.01	8809.66	9510.74	9686.05	9578.16	8891.35	7630.38	6487.86
183	5600.96	6852.5	8211.4	9723.73	12384.39	14871.62	16527.66	16271.87	14141.78	10090.5	7725.49
184	5873.1	7496.8	9948.83	12929.27	16714.71	20764.27	21453.84	20580.89	16930.77	13308.81	10590.52
185	8490.06	12275.93	15827.62	18073.45	21809.18	26748.82	29521.3	27416.07	21896.31	14836.22	11479.45
186	9447.82	12878.01	16738.9	20551.26	26232.25	32706.31	35778.83	34700.03	27614.17	21014.54	16753.73
187	12393.01	18277.68	24938.69	29192.39	32156.25	35649.47	38397.21	35816.98	28007.9	21529.71	17859.19
188	12101.12	18336.28	24242.95	29578.06	34340.32	39834.37	43161.46	42225.25	36967.59	29356.52	23168.9
189	13815.1	21379.91	29124.2	34485.61	38957.76	41627.18	45086.91	43756.62	40318.64	34279.31	26546.73
190	12770.99	20648.26	28851.46	35022.19	42442.76	48087.29	51270.57	50674.71	44759.38	37148.3	28210.59
191	12258.97	19877.06	29787.71	38730.95	47046.46	49896.43	48911.69	45771.47	41543.14	33946.97	27044.58
192	11271.51	17556.08	25578.17	34716.81	41915.56	49916.32	51399.33	50860.07	46098.5	34438.14	24113.88
193	10291.23	16145.24	23743.09	32550.54	38208.16	41844.45	42846.96	39979.23	34320.7	26526.03	19571.31
194	7427.21	11203.13	16076.35	21256.2	26853.55	30308.85	31835.54	31252.75	27672.63	20526.31	15564.76
195	6741.43	9040.79	11778.59	14651.6	17119.26	19015.76	21074.66	21327.68	18957.44	14530.76	10695.23
196	4890.9	6219.2	7661.59	8941.49	10863.78	11776.14	12060.95	11251.58	10118.4	9143.89	7961.45
197	4538.09	5176.5	5822.3	6406.44	7267.25	7764.14	8218.69	8675.89	8534.32	7390.78	6032.46
198	3742.99	4058.34	4384.75	4789.05	5232.52	5432.85	5515.88	5460.36	5161.89	4890.15	4579.92
199	3508.11	3643.81	3834.37	4011.98	4265.67	4319.13	4419.47	4434.37	4344.19	4177.77	4019.18

- Readout of a portion of the pixel matrix. Vertical axis shows pixel ADU counts in rows 180 to 199. Horizontal axis shows ADU counts for pixels in columns 310 to 320.

Epsilon Aurigae in 3D



A 3D Excel plot of the ADU counts for the pixel matrix of showing a 3 D profile of epsilon Aurigae

Photometry Steps

Single Channel

1 – Acquiring Star Data
2 – Determining Magnitudes

Color CCD/DSLR

1 – Imaging Stars
2 – Split RGB Planes
3 - Acquire Star Data from the Image
4 – Determining Magnitudes

Imaging Stars

Goal: To create a computer file with the image of the star of interest and comparison star.

Here is where those who have been taking pretty CCD astronomical pictures will have a large advantage. If you fall into that category you have this step mastered.

In fact you should be confident with CCD photography before proceeding with CCD/DSLR photometry.

DSI Pro with Camera Lens

Test set up

BVRI photometry of epsilon Aurigae with DSI Pro and 50 mm camera lens

CCD/DSLR Camera Imaging Considerations

1. Star Field

1. Exposure/Stacking/Dark Frames

2. RGB Plane Splitting

1. Linearity problems

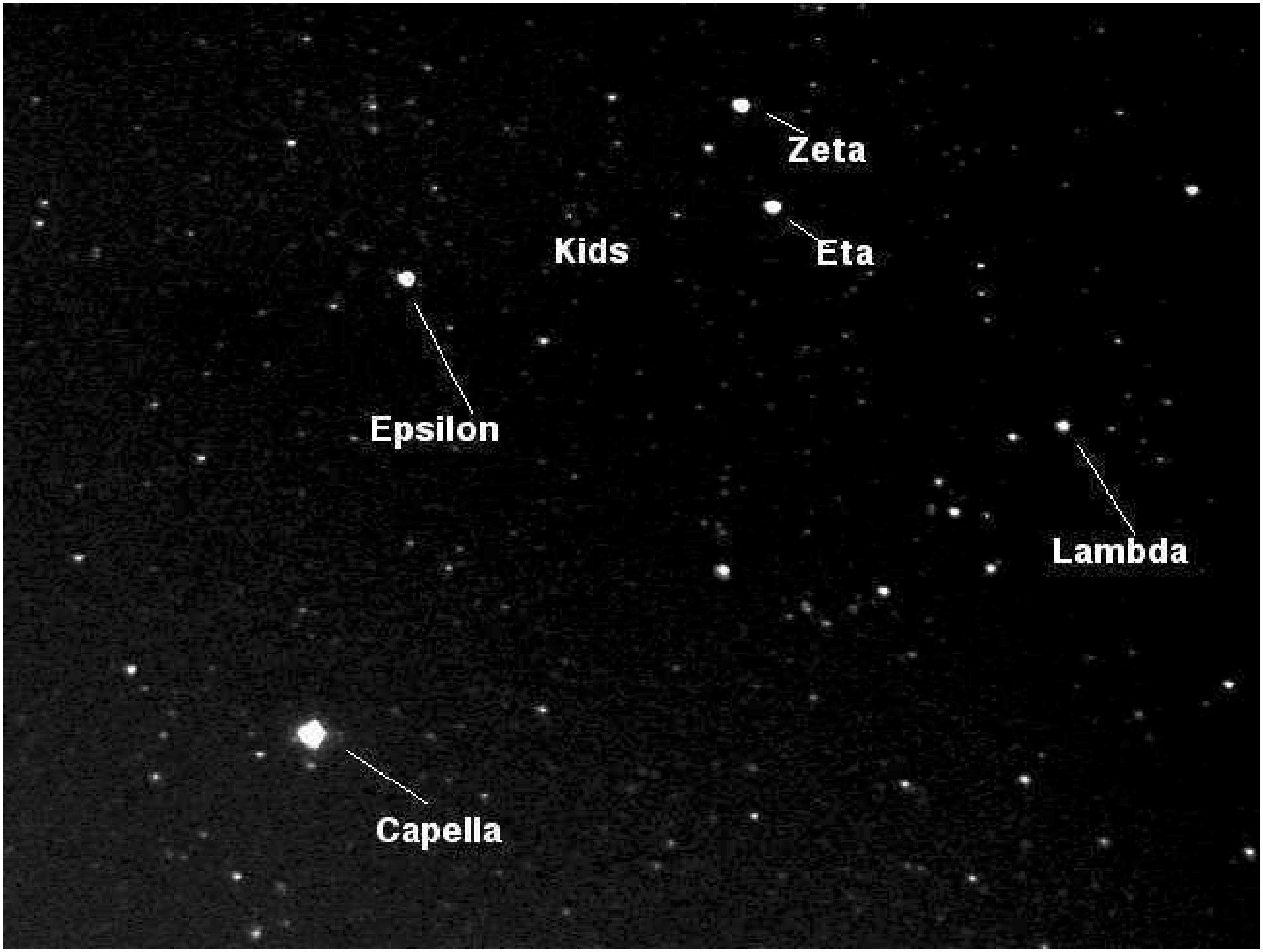
1. Under Sampling

Star Field

Make sure the program (epsilon Aurigae) and comparison (eta & zeta Aurigae) stars are all in the image.

For the V band DSLR photometry of epsilon Aurigae, eta and zeta Aurigae can be used as the comparison stars. Normally lambda Aurigae is used, but it’s 5 degrees away. The further apart the program and comparison stars are the more important extinction considerations.

Star Field



Taken with DSI Pro and 50mm camera lens

Exposure/Stacking

Ideally take at least a 10 - second exposure to minimize atmospheric scintillation effects.

A shorter exposure with stacked images works as well.

Taking 5 – 2 second exposures and stacking them is equivalent to taking 1 – 10 second exposure.

Dark Frames & Flat Fields

Because of the short exposure (less than 1 second) dark frames are not required.

While it is always a good idea to use Flat fields, for this project they are optional.

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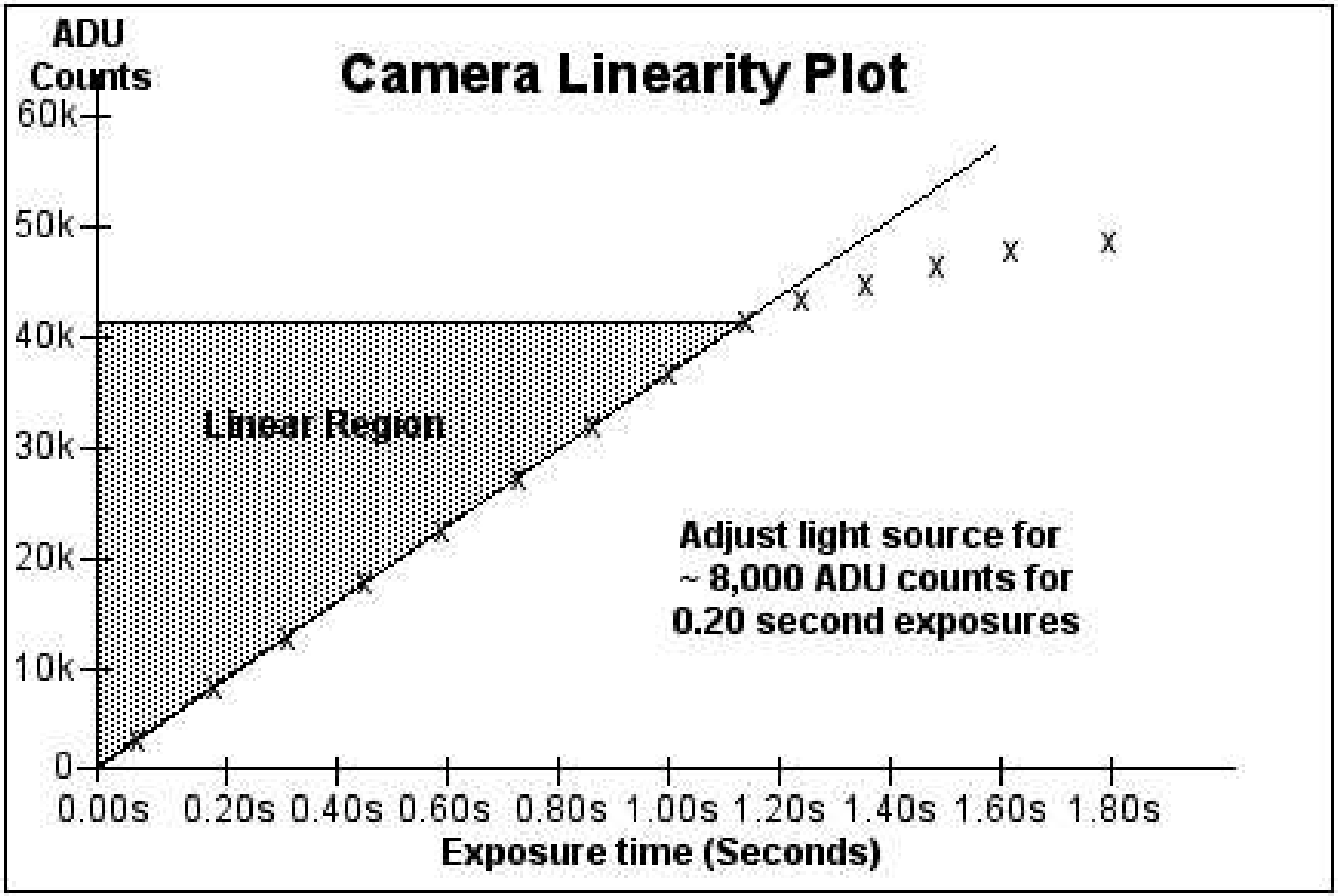
Linearity

Be aware of linearity problems. Keep peak pixel counts under 40,000 ADU. Ideally you should test your camera by using a fixed light source taking multiple images on a bench and increasing the exposure times. Then make a plot of average or peak ADU counts versus the exposure times.

- You should see a slanted straight line that starts to bend around 40,000 counts. Up to that point the camera is linear.

Linearity Plot



Histogram Counts

If possible monitor the peak or maximum Histogram counts for the image. Keep them well under 40,000 counts. Be sure Capella is not in the image as that will be very bright and foil the exposure.

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RGB Plane Splitting

AIP4WIN and most image processing software allow easy splitting of the color image into separate R, G, and B images.

More on this later.

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Under Sampling

Be aware of under sampling.

Because the individual detectors (pixels) on the CCD chip are not continuous and have gaps separating them, if light only falls on a couple of pixels, a significant amount will fall in the gaps and be lost. The more pixels covered, the less percentage of the light is lost to the cracks.

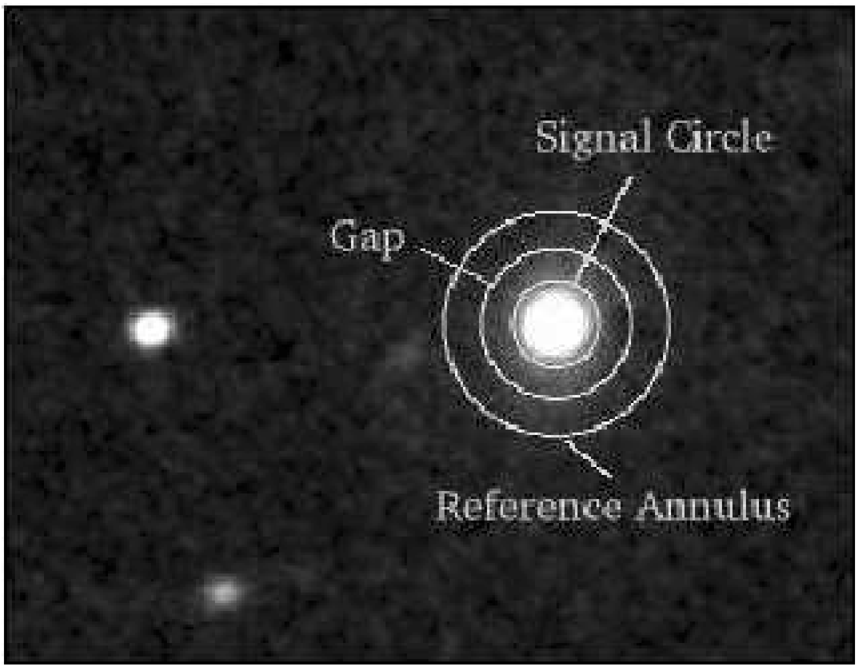
Defocusing and/or turning off tracking help spread the star image and reduce under sampling.

Acquiring Star Data

Once the image(s) has been taken (and stacked) and darks subtracted the processing starts.

The goal here is to examine an image and extract total Analog to Digital Unit (ADU) counts that represent the brightness of the star or star system. This is the sum of all the ADU counts for the pixels covered by the star minus an area around the star to subtract the sky.

Image Processing

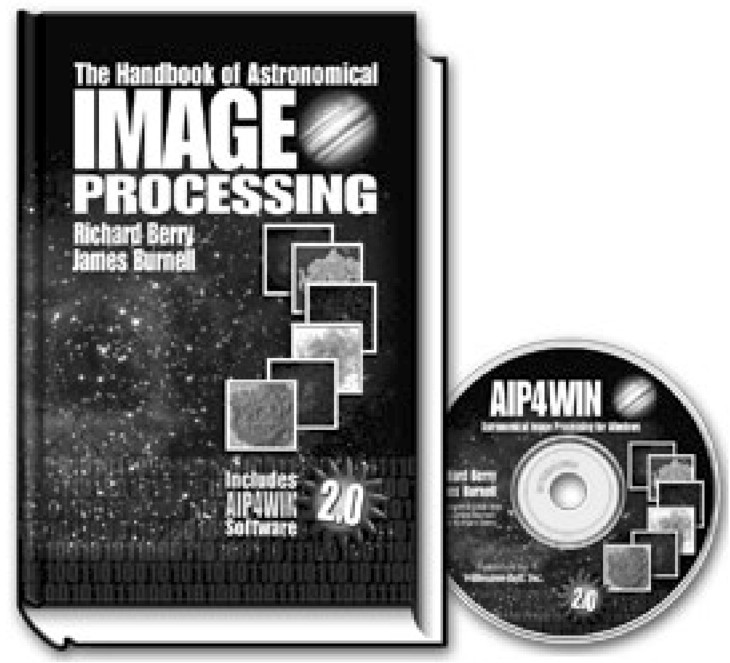


The size of the circle for the star data and a reference annulus for the sky data can be specified.

AIP4WIN

There are several software packages that allow the necessary image processing.

AIP4WIN is one of the best. For under $100 it comes with a very large book (*The Handbook of Astronomical Image Processing* by Richard Berry and James Burnell) that is excellent for explaining much of what is going on. It's a "must read."



Determining Magnitude

The goal of astronomical photometry is to determine the magnitude of a star or star system as would be seen outside the Earth’s atmosphere.

- As we see it through the atmosphere , depending on the distance from the zenith, a constant magnitude star will be observed to be vary in brightness.

A Review

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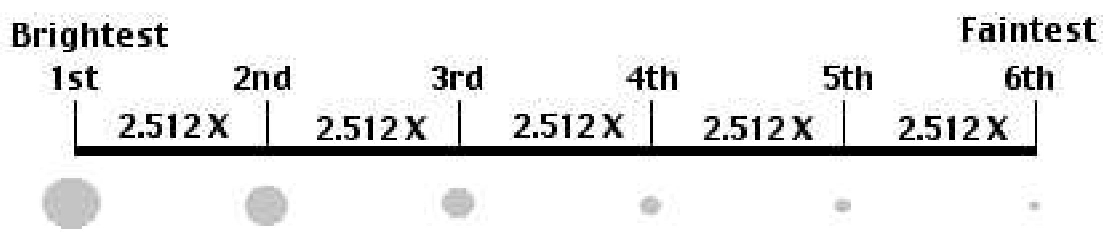
Brightness - Magnitude

The Greeks devised the original stellar magnitude system by dividing stars into 6 groups from the brightest to the faintest they could see. The brightest were determined to be magnitude 1 and the faintest magnitude 6. A 1st magnitude star is 100 times brighter than a 6th magnitude star.



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It turns out the are some stars brighter than 1st magnitude and many many stars fainter than 6th magnitude. But it was a start.

Magnitude System

$$\text{Magnitude} = -2.5 * \log_{10}(b) + C$$

b is some measure of the star brightness (star measure), counts (e.g., ADU counts or number of photons) or a voltage level.

C is a zero point constant dependent of the sensitivity of the equipment used.

Note: That's -2.5 not -2.512.

Magnitudes

Magnitudes as a ratio don't need the zero point factor.

$\Delta m = -2.5 * \log_{10}$ (Star 1 measure/Star 2 measure)

Magnitude Difference (Δm)

$m = -2.5 * \log_{10}$ (Star 1 measure/0 Mag Star measure)

m is the measured (raw or instrumental) magnitude not the final magnitude

Problem: Zero magnitude stars are rare.

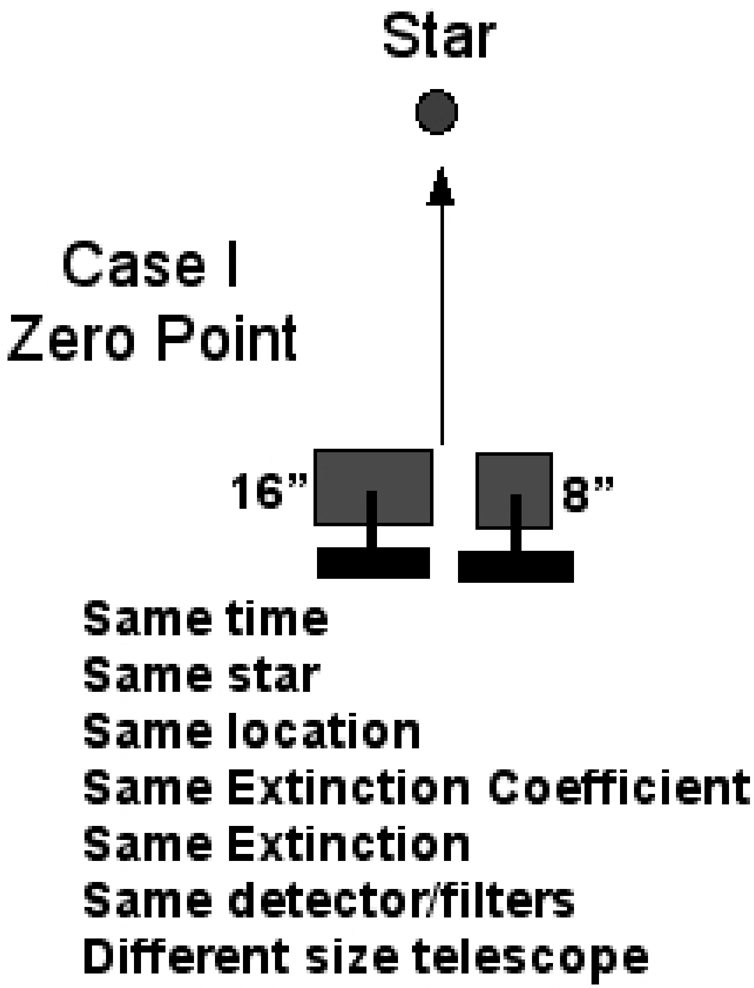
V Magnitude Equation

$$Mv = -2.5 * \log_{10} (SM) + \varepsilon * (B-V) - X * k'v + Zpv$$

The equation for calculating the magnitude can be considered in several phases.

1. Raw or instrumental magnitude calculation.
2. Zero Point factor.
3. Extinction factor.
4. Color Transformation factor.
5. Differential Magnitude.

Zero Point



Zero points calibrate the sensitivity of the equipment. A 16” telescope will have a very different zero point than an 8” scope.

Zero Point Factor

Phase 1

$m = -2.5 \log_{10} (SM) + Zp$

m = raw magnitude
SM= Star Measure (ADU counts)
Zp = Zero Point

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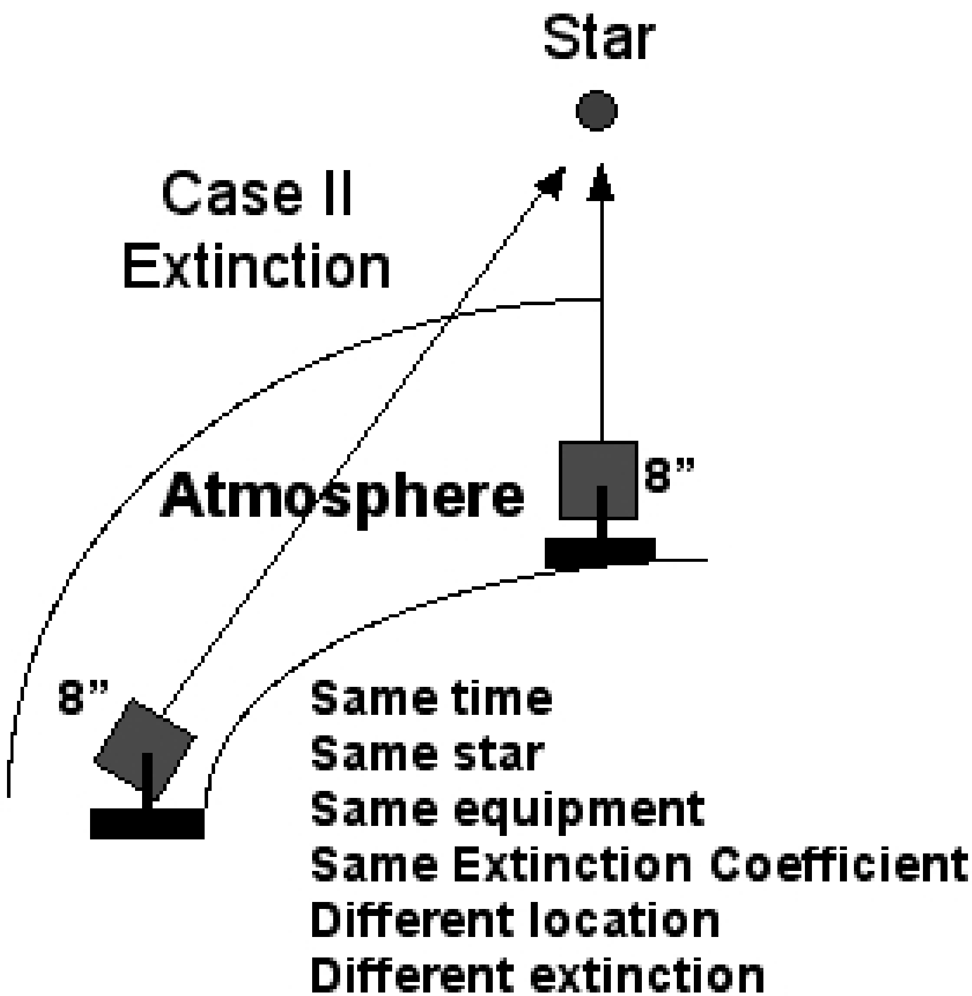
Extinction



Extinction is the attenuation of light due to the Earth's atmosphere.

Extinction Factor

Stars at zenith have an Air Mass (X) = 1 and least extinction.

Extinction goes up exponentially the closer to the horizon the star is.

- Extinction is higher at shorter wavelengths.

Extinction Coefficient
(V Band)
Phase 2

k'v is a V band extinction coefficient and varies nightly. Ideally it should be determined each observation night.

The extinction is the air mass (X) times the extinction coefficient k'v. [X * k'v]

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$$m_v = -2.5 \log_{10} (SM_v) - X * k'_v + Zp_v$$

Air Mass

Air Mass (X) is 1.00 at the zenith and increases fast closer to the horizon.

$$X = \sec Z \, (1 - 0.0012 * (\sec^2 Z - 1)$$

$$X = \sec Z - 0.0018167 * (\sec Z - 1) - 0.002875 * (\sec Z - 1)^2 - 0.0008083 * (\sec Z - 1)^3$$

$$\sec Z = (\sin Lat * \sin\delta + \cos LAT * \cos\delta * \cos HA)^{-1}$$

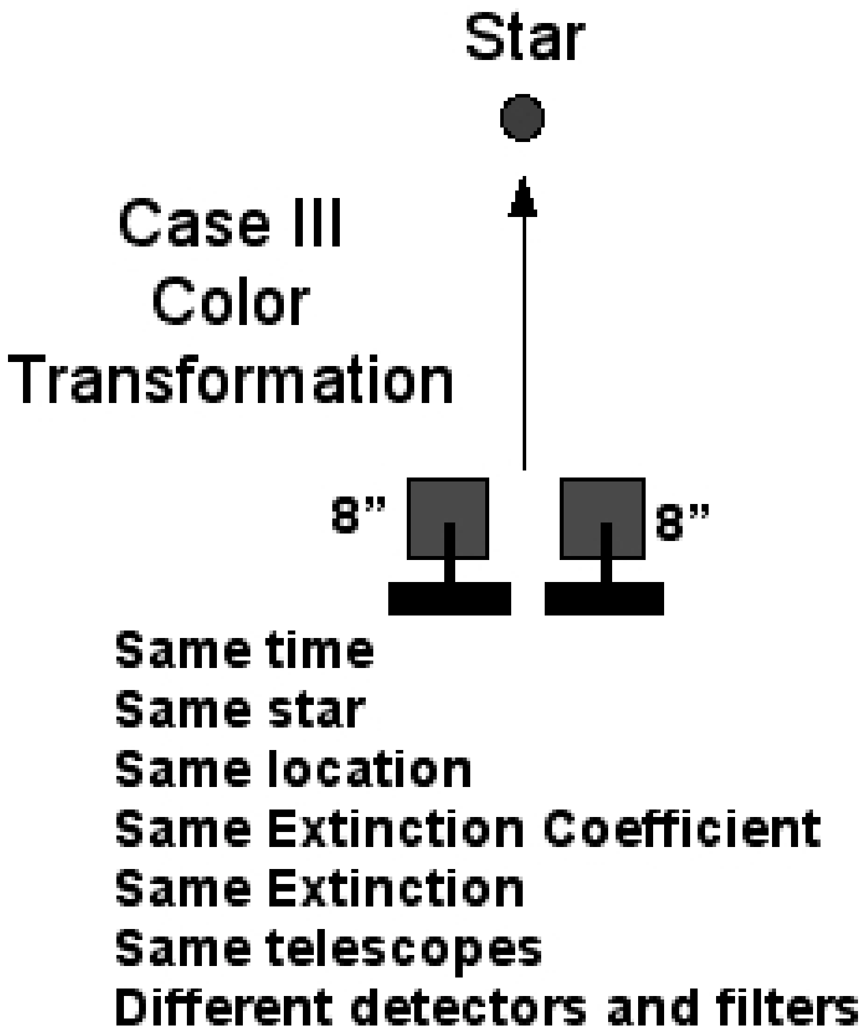
Z= angular distance of the star from zenith

Lat= observation latitude

δ= star's declination

HA= star's Hour Angle

Color Transformation



Color transformation coefficients correct for different wavelength sensitivity of the system, mainly the detector and filters.

Color Transformation
(V Band)
Phase 3

For V band data the color transformation coefficient is epsilon (ε) and is multiplied by the color index of the star (B-V). The closer to zero ε is the better. [$\varepsilon * (B-V)$]

Mv= extra-atmospheric star V band magnitude

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$$Mv = -2.5 \log_{10} (SM) + \varepsilon * (B-V) - X*k'v + Zpv$$

Differential Photometry

The most accurate photometry is differential photometry.

Here the difference between the star of interest (program star) and a comparison star of similar color (B-V) is measured. The comparison star should be a non-variable with known magnitudes and close in brightness to the program star. The results are then normalized to the comparison star.

Sample Calculation

ΔMv= Differential Magnitude = $Mv_p - Mv_c$
e.g., ΔMv= 3.011 – 3.213
ΔMv= - 0. 202

Mv_p and Mv_c are the program and comparison star reduced magnitudes respectively.

If comparison star has a listed magnitude of
Mv_c= 3.200
$Mv_p = \Delta M + Mv_c = (-0.202) + 3.200 = 2.998$
$Mv_p = 2.998$
The program star's final V magnitude.

Tricks and Shortcuts

The preceding is complex and involved, but necessary for the highest accuracy and precision. Computers simplify the process. More details of the foregoing can be found in the book *AutoStar CCD Photometry*.

With CCD (DSLR) photometry, if the program and comparison star are close (minimizing extinction effects) in the same image and if the stars are close in color (the (B-V) values), it is possible to get reasonable magnitudes without the data reduction. Most software has this capability built-in.

Experiment

Before you plan on making observations to report, you should experiment on some stars of known non-varying magnitude. Pick stars close to the zenith, make your observations and determine the magnitudes.

Once you have consistent agreement with the published magnitudes then you can proceed to work on epsilon Aurigae.

Until you produce the same magnitudes of the test stars as the published magnitudes, your efforts on epsilon Aurigae will produce poor data. Experimenting will instill confidence in your work.

Data Reduction Software

As mentioned earlier AIP4WIN is a good choice for image processing and producing the raw ADU counts.

AIP4WIN **does not** reduce the data.

For data reduction and archiving FileMaker Pro (FMP) database application is highly recommended. You need to develop a program yourself, however.

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While many use spreadsheets to do this, they are a poor choice.

FileMaker Pro

Database Advantages

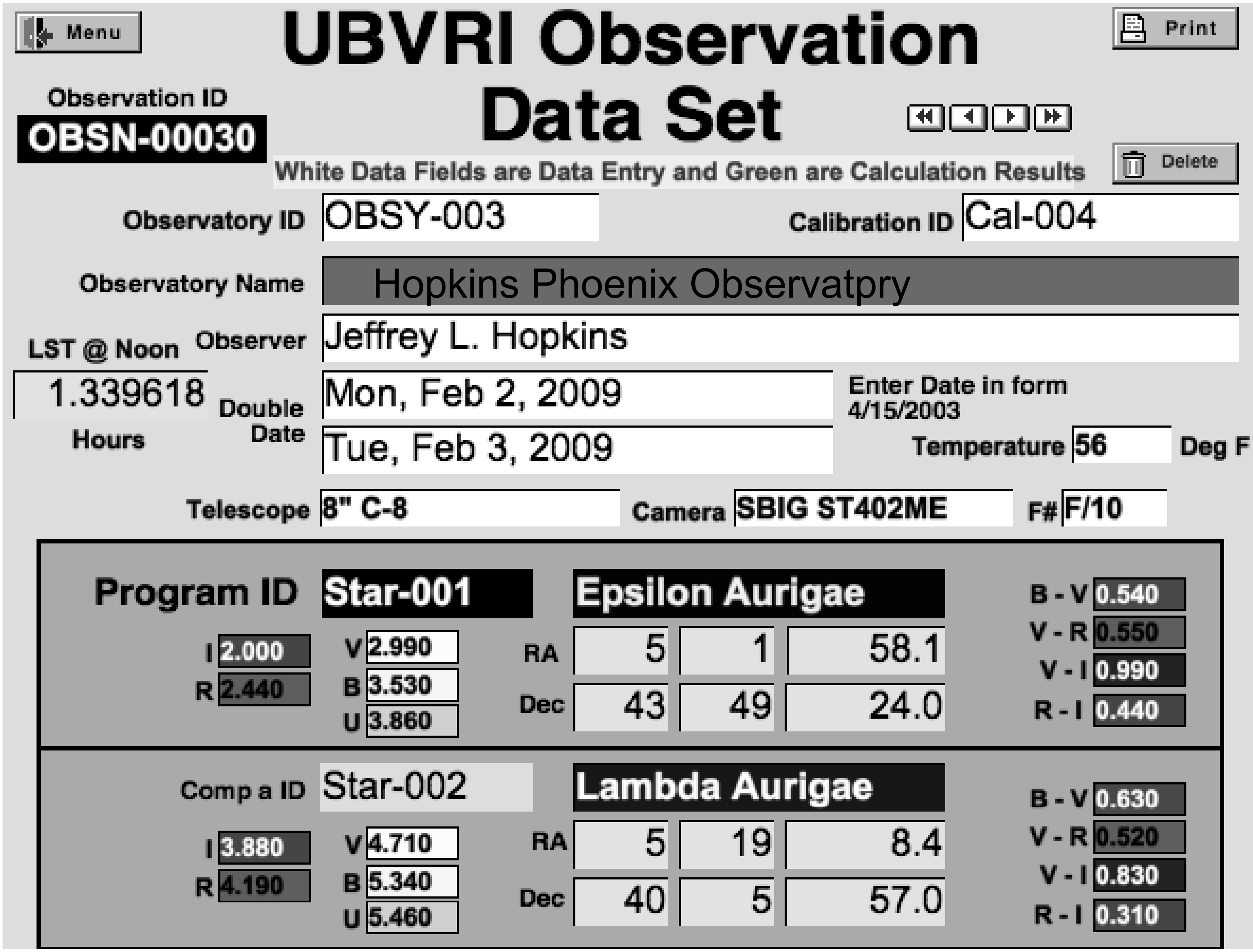
Each observation can be a record.

The database can be easily designed as desired.

Data can be found, summarized, sorted, viewed, exported and printed.

All the math functions of a spreadsheet are available in FMP plus much more capability.

Observation Start



Menu

UBVRI Observation Data Set

Print

Observation ID: **OBSN-00030**

Delete

White Data Fields are Data Entry and Green are Calculation Results

Observatory ID: OBSY-003

Calibration ID: Cal-004

Observatory Name: Hopkins Phoenix Observatpry

Observer: Jeffrey L. Hopkins

LST @ Noon: 1.339618 Hours

Double Date: Mon, Feb 2, 2009 / Tue, Feb 3, 2009

Enter Date in form 4/15/2003

Temperature: 56 Deg F

Telescope: 8" C-8

Camera: SBIG ST402ME

F#: F/10

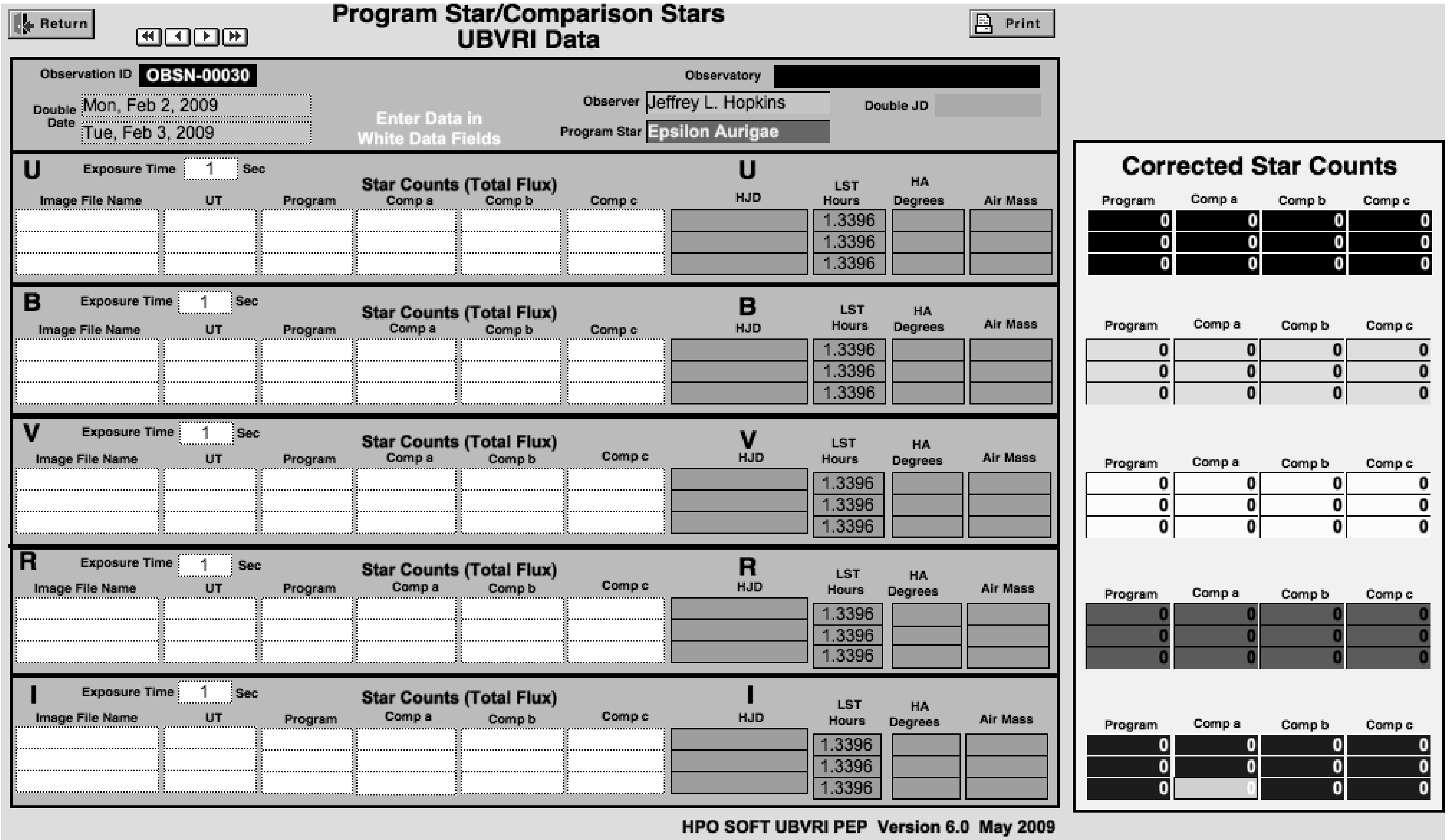
Program ID: Star-001 — Epsilon Aurigae

I	2.000	V	2.990	RA	5	1	58.1	B - V 0.540
R	2.440	B	3.530	Dec	43	49	24.0	V - R 0.550
		U	3.860					V - I 0.990
								R - I 0.440

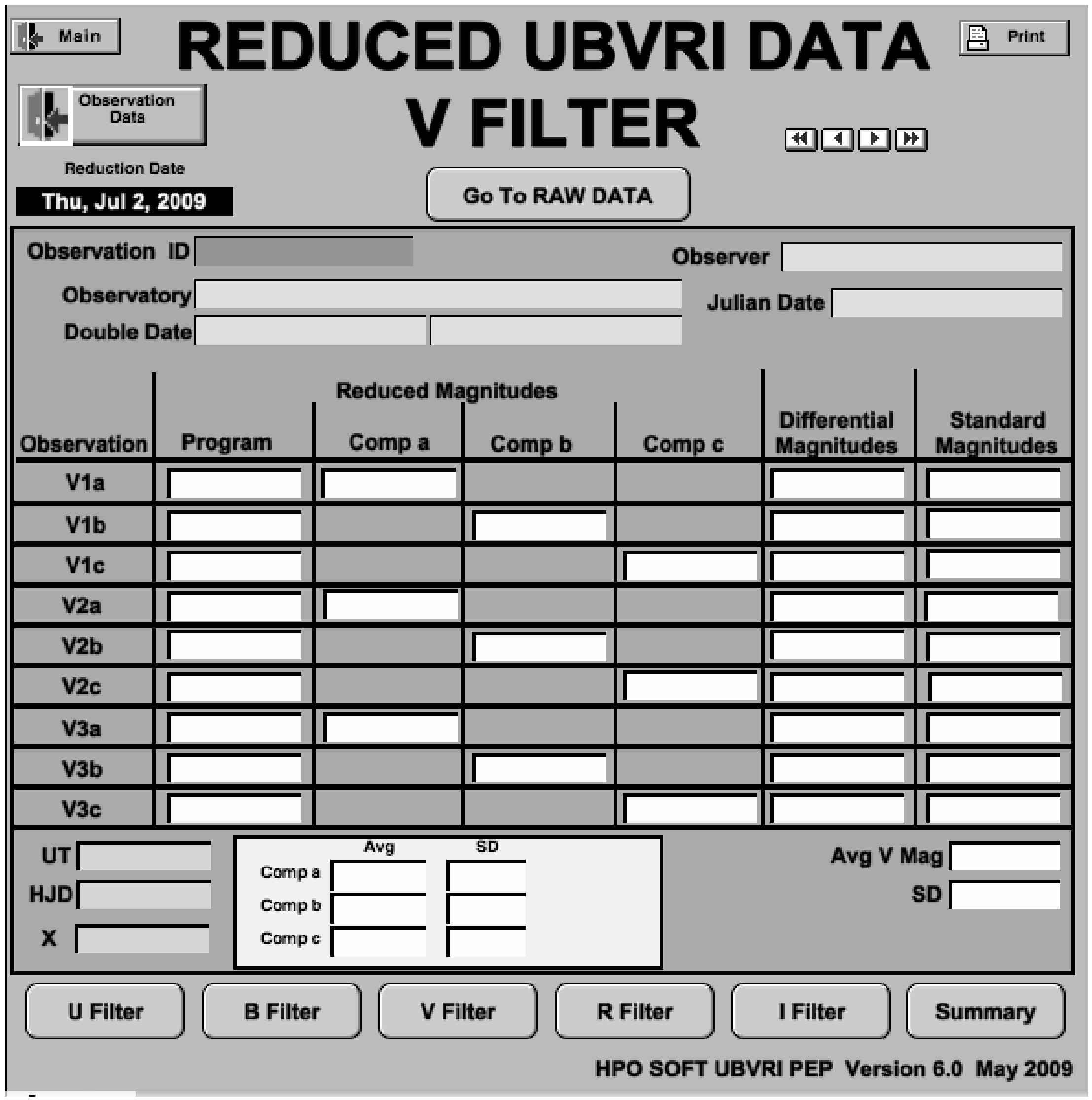
Comp a ID: Star-002 — Lambda Aurigae

I	3.880	V	4.710	RA	5	19	8.4	B - V 0.630
R	4.190	B	5.340	Dec	40	5	57.0	V - R 0.520
		U	5.460					V - I 0.830
								R - I 0.310

Data Entry


Return
Print
Program Star/Comparison Stars
UBVRI Data
Observation ID OBSN-00030
Observatory
Observer Jeffrey L. Hopkins
Double JD
Double Date Mon, Feb 2, 2009
Tue, Feb 3, 2009
Enter Data in White Data Fields
Program Star Epsilon Aurigae
U Exposure Time 1 Sec
B Exposure Time 1 Sec
V Exposure Time 1 Sec
R Exposure Time 1 Sec
I Exposure Time 1 Sec
Star Counts (Total Flux)
Image File Name
UT
Program
Comp a
Comp b
Comp c
HJD
LST Hours
HA Degrees
Air Mass
1.3396
Corrected Star Counts
0
HPO SOFT UBVRI PEP Version 6.0 May 2009

Data Reduction



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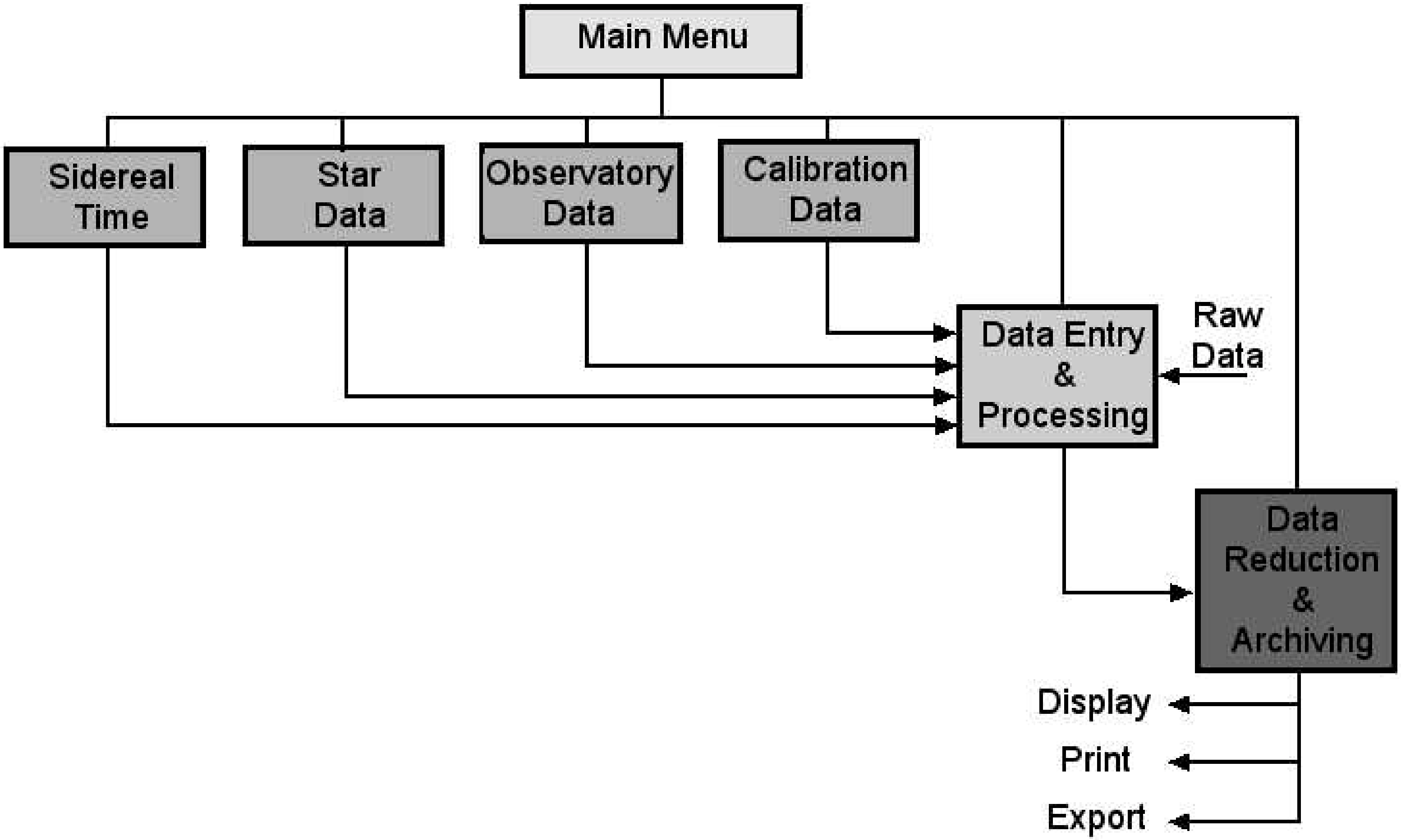
Software Design

FileMaker Pro Database
Suggested Design



Real DSLR Photometry

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Des Loughney

Edinburg, Scotland

Equipment

Des Loughney of Edinburg, Scotland has perfected a means of using an off-the-shelf digital single lens reflex camera to do quality V band photometry of epsilon Aurigae.

He uses a Canon DSLR 450D with a 85 mm lens, undriven on a tripod. Nikon and other DSLR cameras can also be used.

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No telescope needed. A remote shutter is used to reduce vibrations.

Imaging Procedure

RAW images of epsilon Aurigae and comparison star eta Aurigae (3.18V) are taken.

Note: We have determined the magnitude for eta Aurigae to be V= 3.231

Both stars are easily accommodated within the field of view of the 85 mm lens.

Ten images are taken at ISO 200, F/4 and with 5 second exposures.

On every observing night a master dark frame is created using ten images with the same settings.

Atmospheric Scintillation

Variations in the Earth’s atmosphere can cause photons to arrive in bunches rather than a smooth stream. Twinkling starlight is an example.

While measurements (exposures) should be 10 seconds to smooth out the photon stream, that may cause the peak pixel values to become too high and non-linear.

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Des uses 5 second exposures, but stacks 10 of them solving both problems.

DSLR ε Coefficient

It turns out that the standard green filter used in Canon cameras is approximately equivalent to the Johnson V filter.

The V band color transformation coefficient ε can be determined by comparing the estimates of unvarying stars taking into account the difference in (B-V). The epsilon coefficient (ε) of the 450D camera turned out to be 0.15. There are suitable unvarying stars near lambda Aurigae which can be used to work out the coefficient.

Procedure

API4WIN software is used to process each image. Dark frames are subtracted and the ‘green channel’ of each image isolated and analyzed.

Each observing session Des makes three sets of estimates of epsilon Aurigae.

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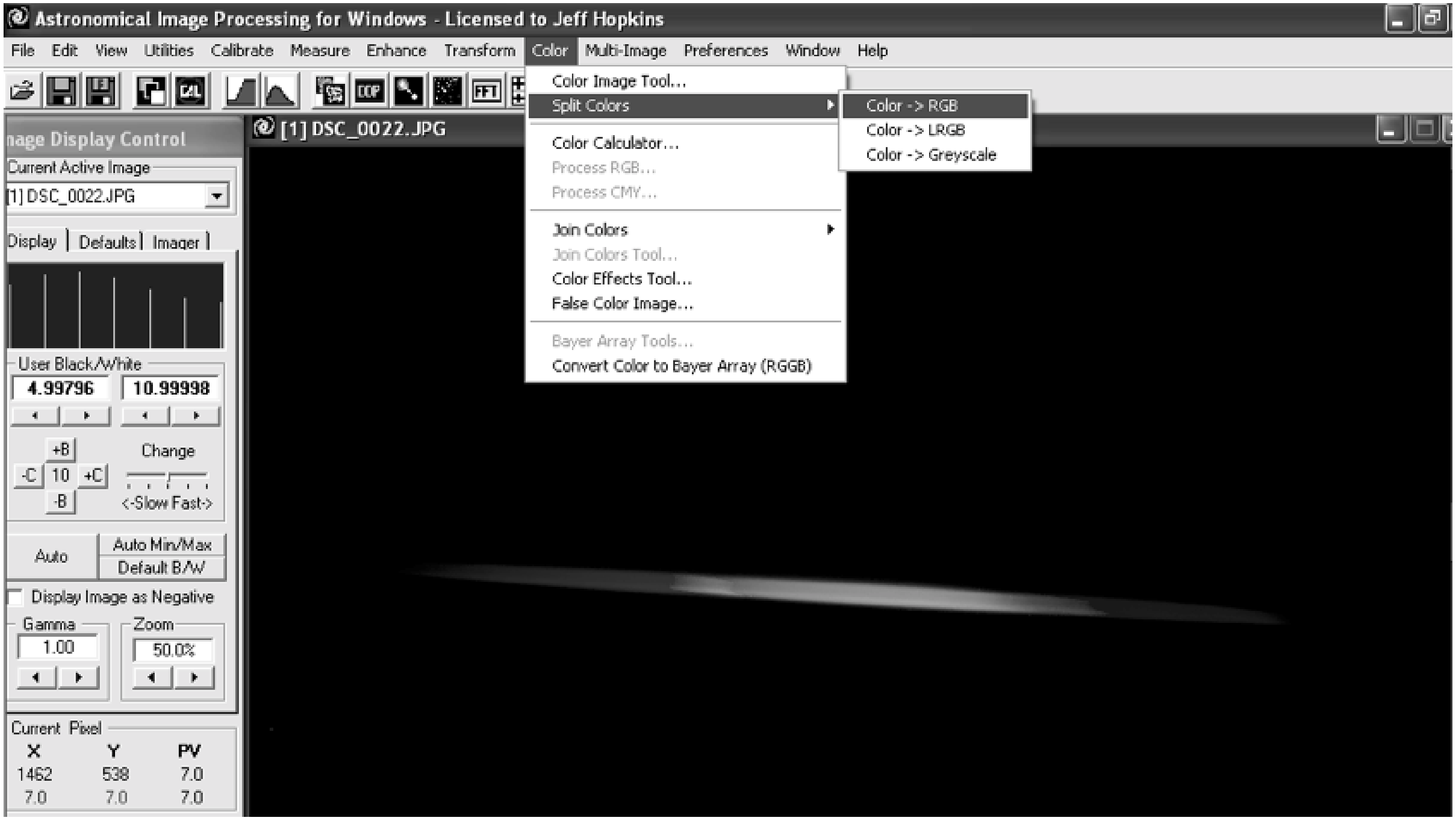
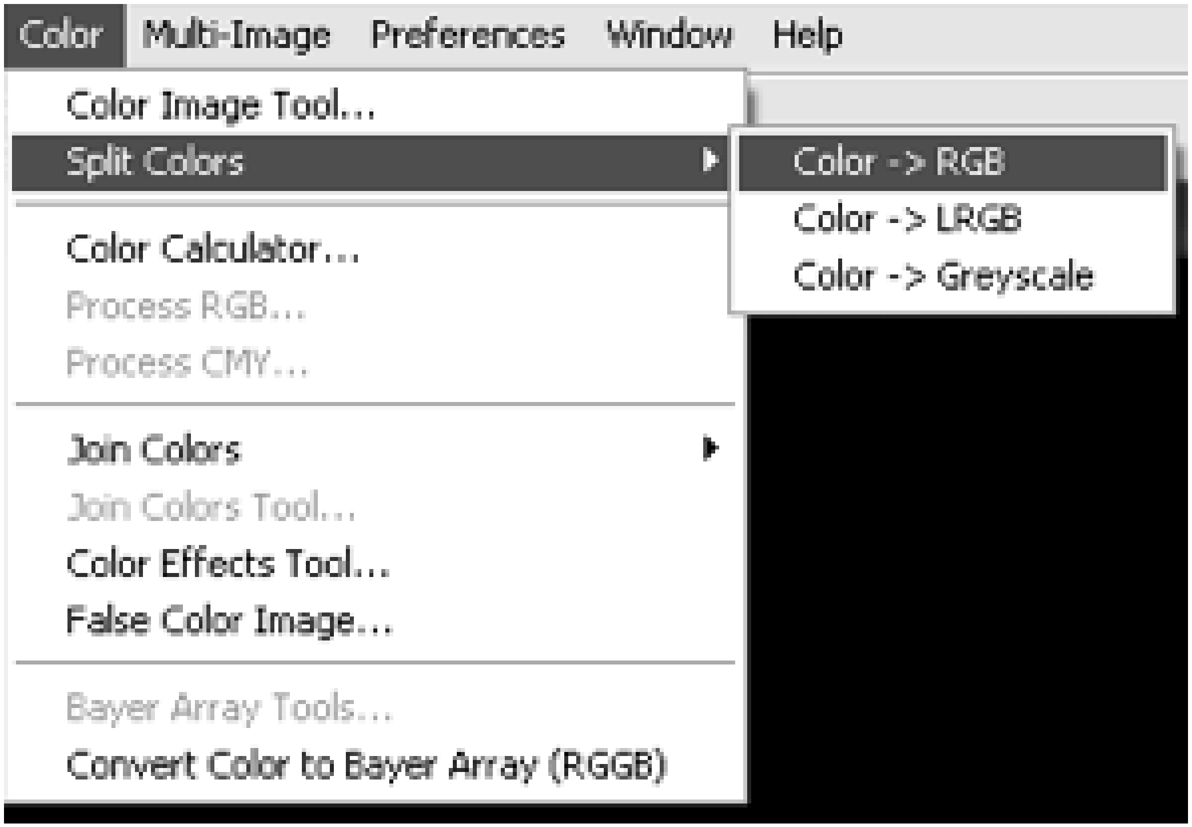
Sample RGB Image



The color image will consist of 3 planes, R, G, and B. These must be separated and just the G plane used to determine the V magnitude.

Splitting Colors



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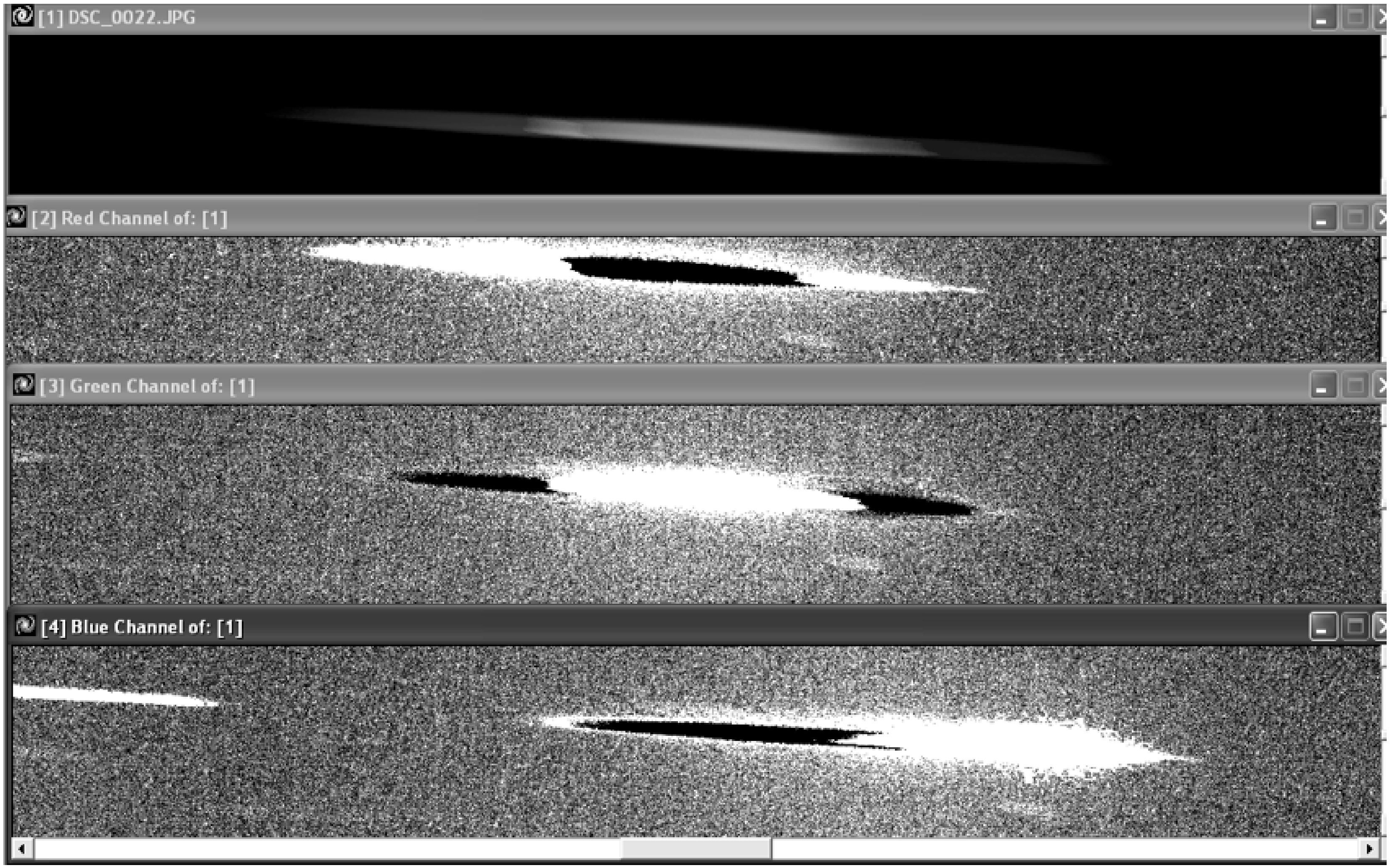
From the AIP4WIN menu bar select the **Color** pull down menu, **Split Colors** and then Color-> **RGB**

RGB Planes



Original RGB Image

Red Data Plane

Green Data Plane

Blue Data Plane

The RGB color image can be split into 3 separate images (channels), Red, Green and Blue

Master Flats

Des says in theory it is advisable to also construct master flat field frames in order to remove the effects of the edge distortions of lens. Des has found, however, that the field of view of a DSLR is so wide that a flat field is not required, if you are using high quality lenses, provided the target star and comparison are in or near the center of the field of view.

Stopping down the lens (as part of the process to get the right amount of light) also minimizes lens distortion around the edges of the image.

Finding Target Star

A drawback with a DSLR camera is its viewfinder. It was not built with astronomy in mind. Only bright stars can be seen. For epsilon Aurigae this is not a serious problem.

Once the target has been imaged several times one soon learns how, by eye, to offset the camera correctly from a bright star. Similarly one learns the right movement of the camera between image sets to compensate for the rotation of the earth.

Field of View

The field of view of the 85 mm lens is so large that little adjustment is necessary. Two or three sets of images can be taken ten or fifteen minutes apart.

The field of view of the 200 mm is significantly smaller and more care has to be taken particularly near the ecliptic.

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Experiment

Do not plan on getting good data the first few times you try.

Experiment and see what works for you.

When you get good repeatable data, then you are ready for some serious photometry.

Reporting Data

While this may sound simple, it can get complex quickly. You should submit basic information about you, your location and equipment, how the data were obtained and any other such information that may be deemed important.

Because the data will be combined with other data it is important to standardize how it is reported. For a typical night there will be one data point for each band observed and one observation date and time for the evenings obserations.

Dates

Again this may sound simple, but there are many different ways to do it. The best way is to use a double date for the date, e.g., 14/15 July 2009 for an observation occurring either during the evening of the 14^{th} or morning of the 15^{th}.

It is also desirable to use Julian Date. There are tables and equations for determining it or you can find web sites that will convert dates for you.

Julian Dates start at noon 12:00 Universal Time.

Noon 01 August 2009 is JD 2,455,044.0000. Just add the number of days from then on.

Times

To specify the time of day when using Julian Dates, use decimal days. For an observation observation on 03/04 July 2009 at 23:03 UT the JD is 2,455,016.461. Remember JD started at Noon UT.

Because epsilon Aurigae is a long period system, exact times are not critical. The middle time of the observations is good.

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Report Format

For the Epsilon Aurigae Campaign we prefer the following format, AAVSO may want it differently:

For V Data

Double Date	JD	V Mag	#	SD
03/04 July 2009	2,455,016.461	2.984	3	0.001
04/05 July 2009	2,455,017.452	3.005	3	0.012

- **Note:** # is the number of observations and SD is the standard deviation of the magnitudes for each band. The SD provides an indication of data spread.

Results

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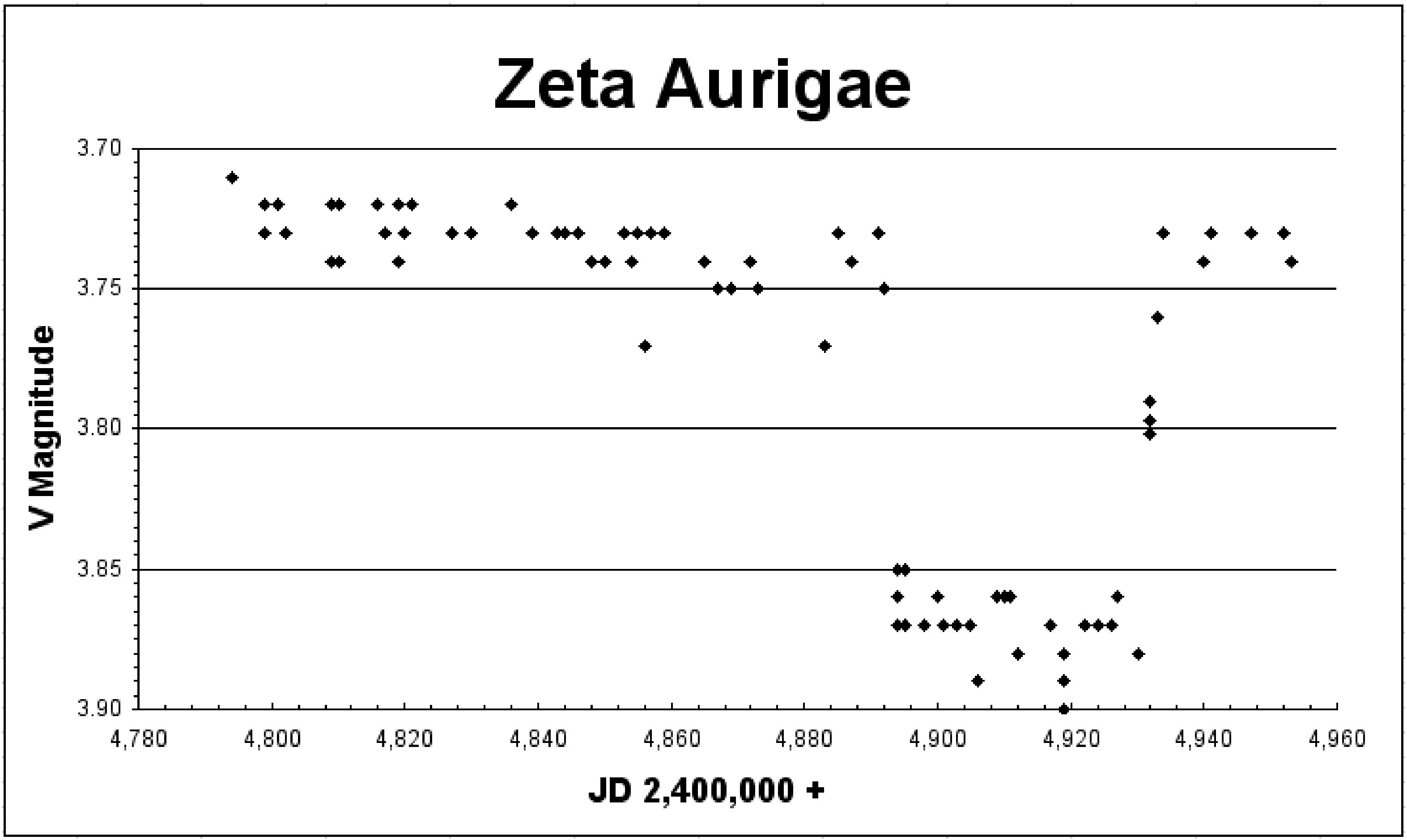
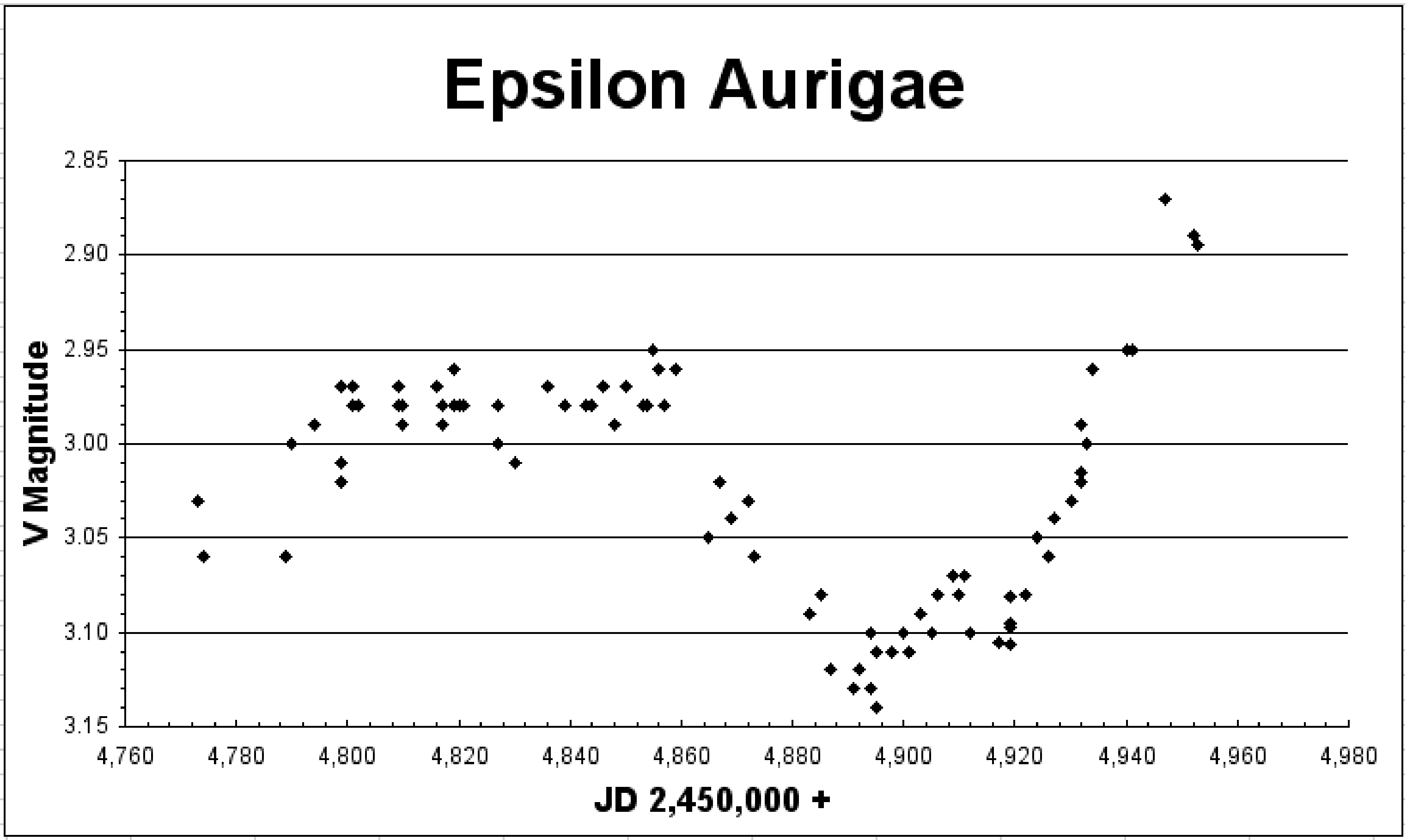
DSLR Photometry
Zeta Aurigae Data Plot



Data from 23 November 2008 to 01 May 2009

DSLR Photometry
Epsilon Aurigae Data Plot



Out-of-eclipse data from 02 November 2008 to 01 May 2009

Conclusion

Des Louhney has proven that DSLR V band photometry can result in measurements of epsilon Aurigae that are useful and significantly more accurate than visual estimates.

An amateur astronomer, without a telescope or a drive can make accurate V band observations of epsilon Aurigae, before, during and after the current eclipse using just a color DSLR camera mounted on a fixed tripod.

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