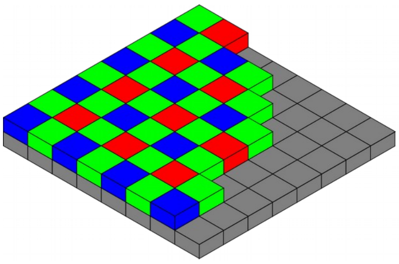
Transformation from Tri-colour DSLR observations to Johnson system

A case story by anthrophosophical astronomer Søren Toft

Photometry.

The use of colour cameras for photometry is an alternative to the classical monochrome CCD technique + a filter wheel with the traditional Johnson filters B V and the Cousin R filter. In this case study we describe the Canon EOS 550 APS-C chip with the four colours R G1 G2 B and 14 bit in every pixel, but this technique can also be used to the 16 bit cameras from Atic and many others.

Bayer pixels



The fundamental layout of the sensor is a 2 x 2 matrix: 2 green, 1 blue and 1 red pixel.
The specification of the EOS 550D the chip is described as 22.3 x 14.9 mm and 5184 x 3456 pixels. This gives a nominal pixel size of 0.0043mm, but for a photometric point of view the pixel-size is the Bayer-pixel, so the size is the double, 0.0086 mm. That is the distance from one blue pixel to the next blue pixel.
One of the main facilities of this sensor-type is the simultaneous observation of the star through four filters. It is especially interesting, that the two green layers gives two independent observations of the same star. The difference G2 – G1 is a fine measure of how accurate the star is observed.
Different camera-models has a different way of saving the information. The astronomical software must split the image in four colour layers 1 2 3 4, and the astronomical user of the sensor must then translate that to the colours. In the case of EOS 550D the colour sequence is R G1 G2 B, but it has to be controlled by the user. [Exercise: Fill in the table with your colour sequence].

Colour layer #	1	2	3	4
EOS 550D	R	G1	G2	B
My camera				

The EOS 550D resembles situation (d) in the table to the right.

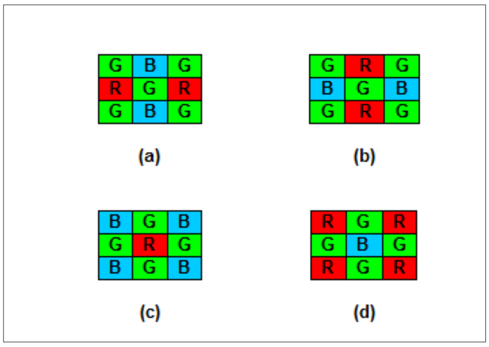


Image processing and aperture photometry.

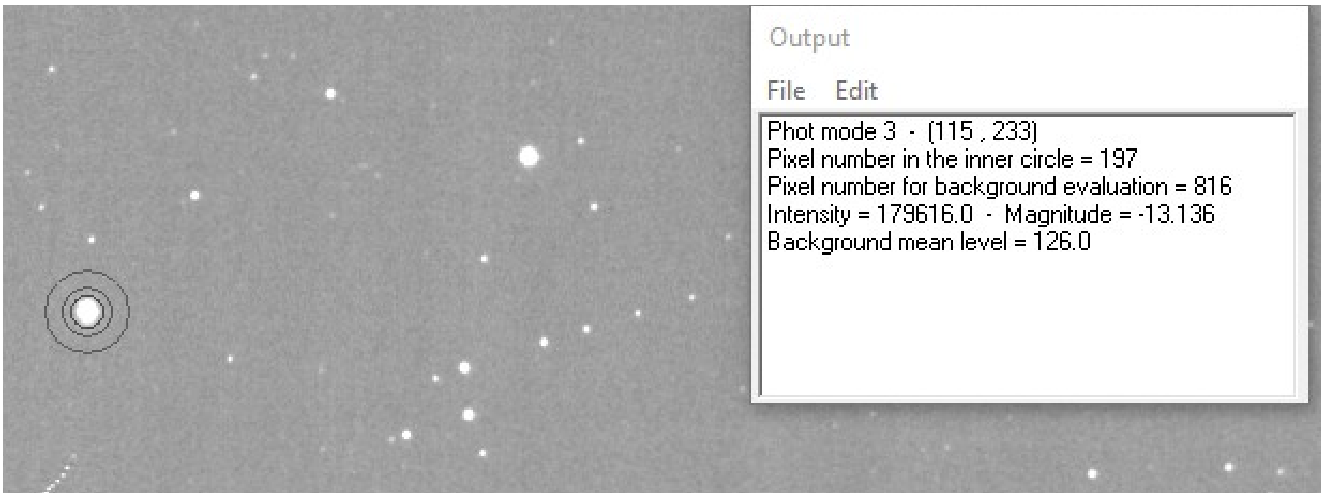
It is customary to take a sequence of star images (not only one). The number of images can be considerable, but here an example of 2 images are discussed to simplify the explanations.
The 2 images are transformed form the .cr2 format of the EOS 550D to the images i1 and i2 in CFA-format. They are then split into 8 images: @i11, @i21, @i31, @i41, @i12, @i22, @i23, @i42
The numbering is so, that the last image (@i42) is the blue layer of the second image.
Let us take a look at this image. Each pixel has a ADU value.

The lowest value is at a certain bias-value (2048 in the EOS550D case).
The theoretical biggest value is 16383 (2^14 -1, because the sensor is 14 bit), but in practical life a saturated image has the value 15300 ADU. So after dark subtraction 13252 ADU is absolutely maximum. A value above 11000 ADU is probably close to saturation.
In this first discussion it is advisory to use dummys for the photometric concepts called bias, dark, flat and hot-pixel-maps. The author took one of the 8 split images (with their format information) and filled it with the following values:

	Value
Bias or offset	2048
Dark1, dark2, dark3, dark4	0
Flat1, flat2, flat3, flat4	10000

The importance of making good flats is discussed later.
The importance of taking darks every night is mainly to make a reliable map of hot-pixels[1].

The next step in image-processing is to subtract bias and dark from the @i-images and divide the resultant image with the normalized flat (flat /10000). The result is 8 images: @j11, @j21 @j31, @j41, @j21, @j22, @j32, @j42.
The following step is to align the images, so that the stellar positions in the first image are the same as in the second. This may seem needless with 2 images and a very stable telescopic mount, but with 32 images and a cheap mount as the authors Az-Gti from Skywatcher, it is important to take differential rotation into account with the software. The aligned images are called @k11, @k12, @k13, @k14, @k21, @k22, @k32, @k42.
Now let us look at the two images @k31 and @k32. We add these two green images, and find the target star and the comp star. The target star on the image is R Crb.

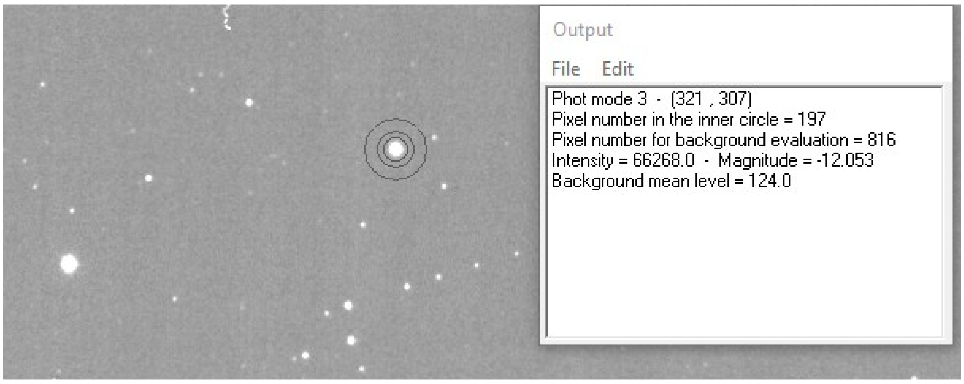


The software has the feature to place an aperture with 3 circles around the target star[2]. The inner radius r1 is so big, that the inner measuring circle contains all the light from the star[3]. The outer ring (between r2 and r3) measures the background mean level. In this case the background from the city and the moon is 126 ADU/pixel.

1 The reason for this is, that aperture photometry measures the dark and background locally in a ring around the star as described later. Therefore dark subtraction is not critical, when doing aperture photometry. This is very different from making pretty astronomical pictures.
2 IRIS-MENU : Analysis → Aperture Photometry
3 A radius r1=2*FWHM is usually a good choice. In IRIS the Full With Half Maximum is found by drawing a rectangle around the star by the mouse, and then right click -> PSF

Since the inner circle contains 197 pixels, the intensity of the star is the sum of all the ADUvalues from the measuring circle minus 197 * 126 ADU. This intensity is 179616 ADU as can be seen in the output window.
The instrumental magnitude of the target star is
g2 = -2.5*log(179616 ADU) = -13.136 Note[4]

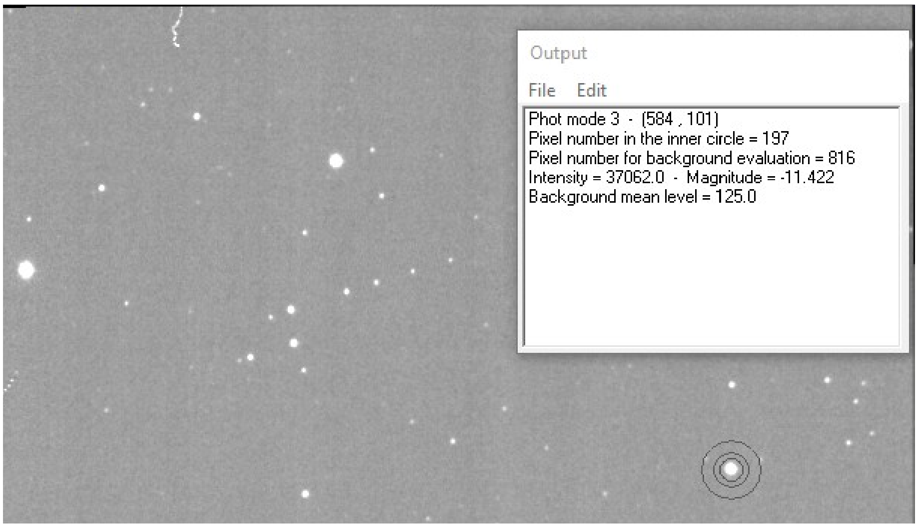
Here is the same figure for the comparison star HD 141352



A similar procedure for the this star gives an instrumental magnitude of g=-12.053.
Since the comparison star is a known constant shining star with Vcat = 7.427 magnitude, the magnitude of the target star can be calculated

TG = Vcat – g_comp + g_target = 7.427 -(-12.053) + (-13.136) = 6.344 mag. (Equation 1)

This is the figure for the check-star HD 140913 with Vcat=8.065 mag.



A similar calculation gives an observed magnitude of TG= 8.058 mag, a value that only deviates 0.007 mag from the catalogue value. The reader is encouraged to make this calculation himself. These 3 numbers describes one observation at a certain time (JD-number).

#NAME	DATE (JD)	MAG	MERR	FILT	TRANS	MTYPE	CNAME	CMAG	KNAME	KMAG	AMASS	GROUP	CHART	NOTES
R Crb	2458332.3920	6.344		TG	no	std	74	7.427	81	8.058			X186030	

4 The magnitude is negative, because it is much brighter than the (hypothetical) faint star with intensity I = 1 ADU. The Suns magnitude is V=-26.7, because it is much brighter than the standard star Vega (with V=0.03)

Transformation from TG and TB to Johnson system

This is the problem mentioned in the article heading.
The procedure for calculating TG as described above can be repeated for the blue layer and for the red layer, if catalogue values in Johnson B and Cousin R are available for the comp star and the check star. These observations are called TB and TR, and the observations can be send to AAVSO in the “extended format” as shown in the example above.
There is only one problem with this: The blue observations TB are very far away form the observations made by the other observers, that uses monochrome CCD and filter-wheels with the B V and R filters. The observations needs to be *transformed* from the tricolour system to the BVR. This is a classical situation caused by the differences in spectral response of the filters.
Before we continue our case story, a historical intermezzo is presented:

Transformation from Tycho2 to Johnson system.

After the presentation of The Millennium Star Catalogue (2000) with the parallaxes of 118.000 stars in the Hipparcos catalogue, and photometry in blue and visual for 2.5 mill star in the Tycho2 catalogue, the same problem appeared. How can we transform the Tycho colours BT and VT to the Johnson system? Høg et al (2000) writes:

> *The two Tycho passbands are close to Johnson B and V, and approximate transformations are given in ESA97, Vol.1, Sect. 1.3. It is however, recommended to use BT and VT directly since the transformation is dependant especially on luminosity class and redning which are usually unknown.*

The reason for this recommendation is further stressed by the fact, that the Tycho2 catalogue contains observations made with the very same instrument on the northern and the southern hemisphere unaffected by atmospheric absorption. The internal accuracy[5] is 0.013 mag i VT for stars brighter than 9th magnitude.
But of course the authors presented the transformation[6] that has been used quite extensively ever after:

$$V - VT = -0.090 * (BT - VT) \quad \text{(Equation 2)}$$

$$(B - V) - (BT - VT) = -0.150 * (BT - VT) \quad \text{(Equation 3)}$$

This formula contains two numbers:

The green magnitude transformation coefficient T_v= -0.090

and the colour transformation coefficient T_{bv}= -0.150

It is seen from the two equations that, if we have two stars (the target star and the comp star) with the same colour (BT-VT), then it can be concluded that the transformation correction is 0. The transformation correction is what is on the left-hand side of the equations above.

If the two stars differ in colour, it is only the colour-difference Δ(BT-VT) between the two stars that is involved in the transformation correction. This conclusion can be of good use, when we turn to our case study, the transformation from Tricolour DSLR observations to the Johnson system.

5 http://www.nbi.dk/~erik/Tycho-2/letter.pdf
6 My reference is http://www.aerith.net/astro/color_conversion.html

Photometric transformations.

In the example in the intermezzo the transformation depends on the colour (BT – VT).

In the tri-colour DSLR observation two instrumental colours (x and y) are calculated from the 3 instrumental colours b g r , where g is the average of the two green instrumental magnitudes

$x = (b-g)$ and $y = (r-g)$ (Equation 4)

Let us first concentrate on the blue colour x. The red colour y is discussed later.

The transformation problem is to find the 2 slopes s1 and s2 in the equations

$V - g = s1 * x + \text{z-point1}$ (Equation 5)

$(B-V) - (b-g) = s2 * x + \text{z-point2}$ (Equation 6)

This is solved graphically by observing an open cluster of stars with well-documented V and B magnitudes. Stetson[7] has made observations like this in selected fields with an accuracy of 0.003 mag, but these stars are rather faint (fainter than 10 mag). If the telescope and the detector allows that, it is a very good method. In my case the "telescope" is a Canon lens f=200 mm and f/8. It is very well suited for stars brighter than 9 mag, so the Tycho2 values are used, with its 0.01 mag uncertainty; and then transformed to the Johnson system afterwards with the mentioned transformation. Equation 2 & 3.

Following Arne Henden AAVSO equation 5 and 6 can be modified at little, if the uncertainty in the catalogue-values are smaller than the observed values.

$(b-g) = T_{bv} (B-V) + Z_{bv}$ (Equation 7)

$(V-g) = T_{v\_bv}(B-V) + Z_g$ (Equation 8)

$(B-b) = T_{b\text{-}bv}(B-V) + Z_b$ (Equation 9)

Comment[i]

The observations

Images of M67 was taken on 2018-03-18 with a Canon 550D camera with at 200 mm lens f/8 and 200 ISO on Skywatcher AZ-GTI mount from Virum, DK (north of Copenhagen). 99 Images each of 30 sek were taken, and they were reduced with IRIS ver 5.59.

7 https://www.aavso.org/apps/vsd/stdfields

The mount and the camera had external power-supply to avoid battery-problems. The images were transferred to the laptop with a 3 m long USB cable, and the Canon EOS-Utility was used for focusing and the procedure for taking the pictures. They were stacked and reduced as mentioned earlier, and the final addition of the four colour images were done with the ADD_NORM procedure, so that if the limit of 32700 were exceeded in one pixel, the image was normalized to this value. This was indeed the case for all four images, but it also meant that the two green images had a different normalization factors, because the maximum pixel-value was not exactly the same in the two resultant images.

63 stars were observed, and compared with Johnson B and V (calculated from the Tycho standard values).

From the graphs below the following transformation is achieved[8]:

(g2-g1) = 0.058 ± 0.029 mag
It is the 0.029 mag, that shows the accuracy of the measurement. Δg= 0.015 mag for the green channel.

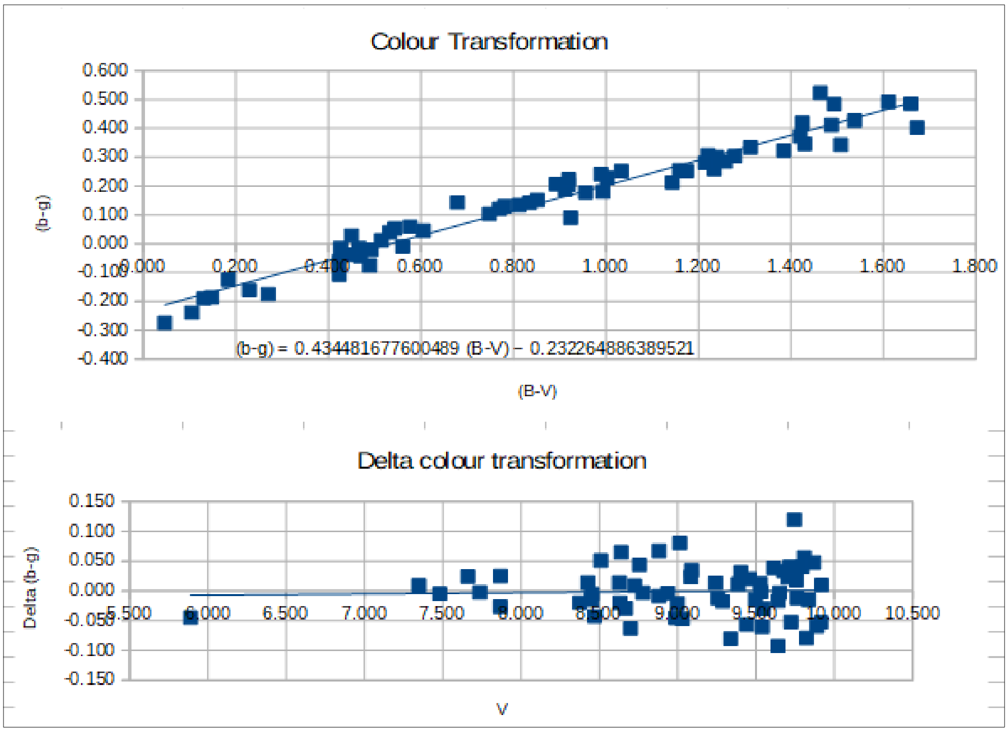
(b-g) = 0.435 (B-V) – 0.232 ± 42 mmag
(V-g)=-0.125 (B-V) + 18.712 ± 46 mmag
(B-b)= 0.444 (B-V) + 18.936 ± 49 mmag

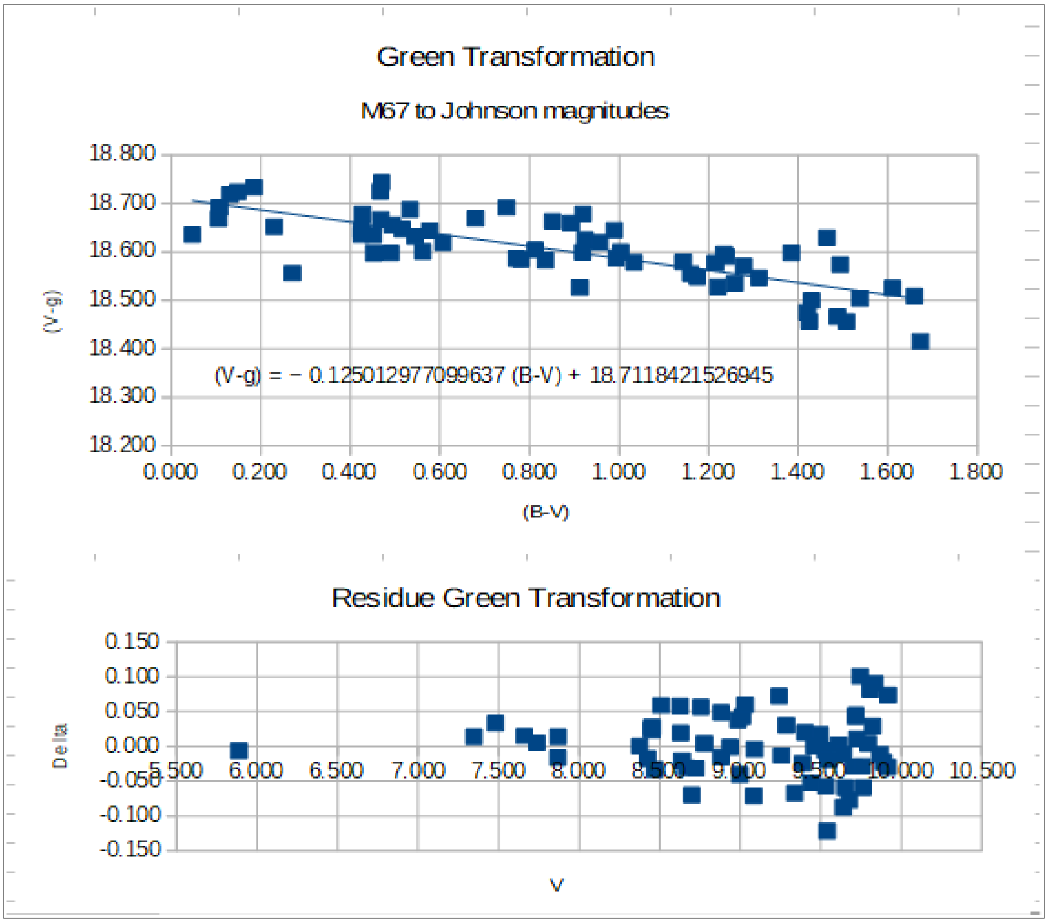
The transformation coefficients is thus

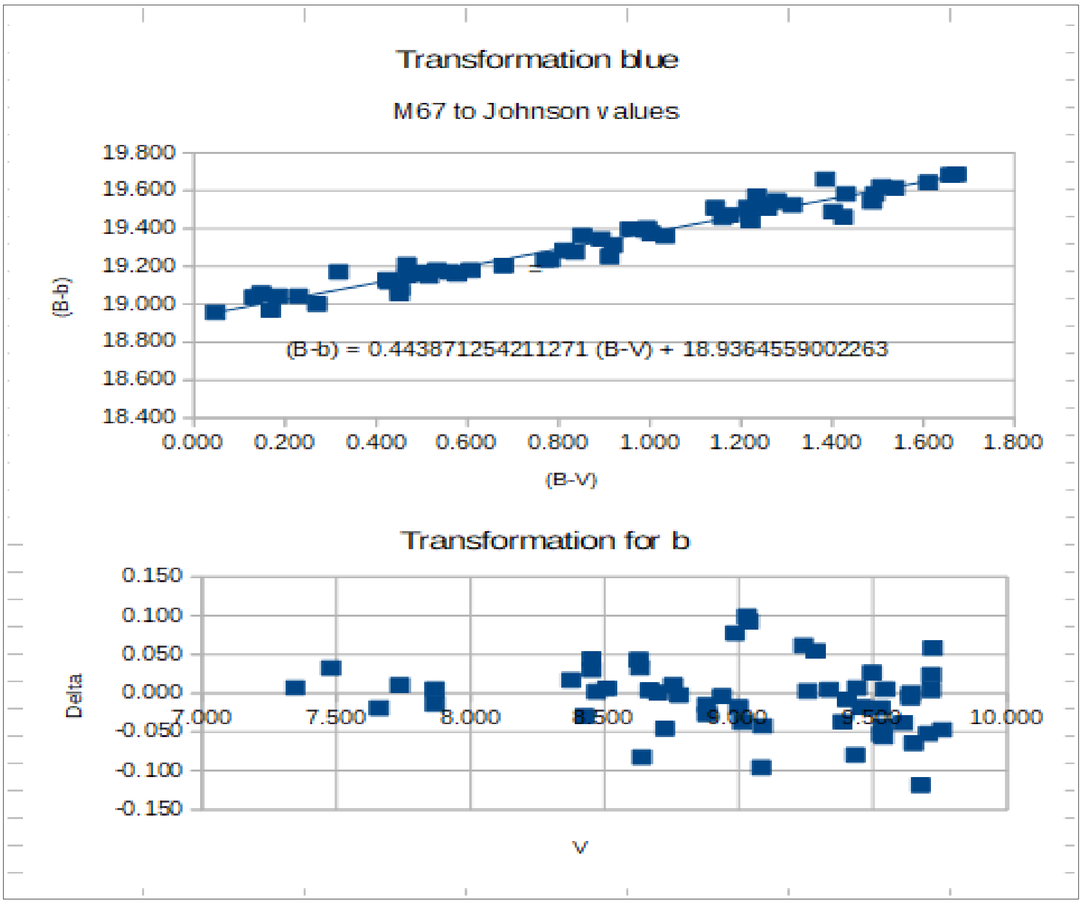
(V-g)= - 0.287 (b-g) + 18.645
(B-b)= 1.021 (b-g) + 19.173

The uncertainty in the coefficients -0.287 og 1.021 is at least some %

8 Capital letters B V denotes catalogue -values, small letters g b r denotes instrumental values.


Colour Transformation
0.600
0.500
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
-0.300
-0.400
0.000 0.200 0.400 0.600 0.800 1.000 1.200 1.400 1.600 1.800
(b-g)
(b-g) = 0.434481677600489 (B-V) − 0.232264886389521
(B-V)
Delta colour transformation
0.150
0.100
0.050
0.000
-0.050
-0.100
-0.150
5.500 6.000 6.500 7.000 7.500 8.000 8.500 9.000 9.500 10.000 10.500
Delta (b-g)
V


Green Transformation
M67 to Johnson magnitudes
18.800
18.700
18.600
18.500
18.400
18.300
18.200
0.000 0.200 0.400 0.600 0.800 1.000 1.200 1.400 1.600 1.800
(V-g)
(V-g) = − 0.125012977099637 (B-V) + 18.7118421526945
(B-V)
Residue Green Transformation
0.150
0.100
0.050
0.000
-0.050
-0.100
-0.150
5.500 6.000 6.500 7.000 7.500 8.000 8.500 9.000 9.500 10.000 10.500
Delta
V



Example.

Let us look at the two stars in M67

TYC816-2496-1 (star 685) and

TYC813-2738-1 (comp 739)

The difference between the two green observations for the star 685 is

Δg= g2-g1= -11.636-(-11.730)= 0.047 mag

This is not the uncertainty af the measurement, because there is an offset, as can be seen in the other to stars in the table.

The green instrumental magnitude is

g = (g1+g2)/2 = (-11.636+(-11.730))/2= -11.683

Let us suppose, that we don't know the catalogue-values for the star. Then we can *calculate* the Tri-colour magnitude from the instrumentalmagnitudes of the star and the comp-star:

M67			Comp*	Check1
	Time \ Star #	685	739	868
r	2458196.360	-12.391	-11.486	-10.209
g1	2458196.360	-11.730	-11.209	-9.945
g2	2458196.360	-11.636	-11.134	-9.847
b	2458196.360	-11.004	-10.998	-9.760
Δg		0.047	0.037	0.049
g		-11.683	-11.172	-9.896
Star ID:	TYC	816-2496-1	813-2738-1	814-2304-1
V-cat	Johnson	6.682	7.347	8.638
B-cat	Johnson	8.342	7.814	9.089
TG	Obs Tricolour	6.835	7.347	8.622
TB	Obs Tricolour	7.808	7.814	9.052
Diff V		0.153	0.000	-0.016
Diff B		-0.534	0.000	-0.037
TRANSFORMATION				
(b-g)		0.679	0.174	0.136
Δ (b-g)		0.506	0.000	-0.037
T_V*Δ(b-g)	-0.287	-0.145	0.000	0.011
T_B*Δ(b-g)	1.021	0.516	0.000	-0.038
V	Observed	6.690	7.347	8.633
B	Observed	8.324	7.814	9.014
	σ			
Diff V	0.026	0.008	0.000	-0.006
Diff B	0.049	-0.017	0.000	-0.075

The first observation (without transformation correction) is calculated so:

TG= V_comp – g_comp + g_star = 7.347 - (-11.172) – 11.683 = 6.835

TB= 7.814 - (-10.998) -11.004= 7.808

In this case the catalogue-values are known, so we can see that the differences Obs-Cat are rather big (0.153 mag and -0.534 mag in V and B)

Transformation:

The observed colour is

for the star (b-g)= -11.004 - (-11.683) = 0.679

for the comp (b-g)=-10.998 - (-11.172) = 0.174

The difference in colour is Δ(b-g)= 0.679 – 0.174= 0.506

With this value the transformation correction can be calculated:

(V-TG) = -0.287 Δ(b-g) = -0.287 * 0.506 = -0.145

So the transformed V magnitude for the star is

V = 7.808 – 0.145 = 6.690 mag

With a deviation from the catalogue-value of only 0.008 mag.

This value should be communicated to the AAVSO as transformed V (and not TG as before).

The B magnitude for the star is calculated in a similar way.

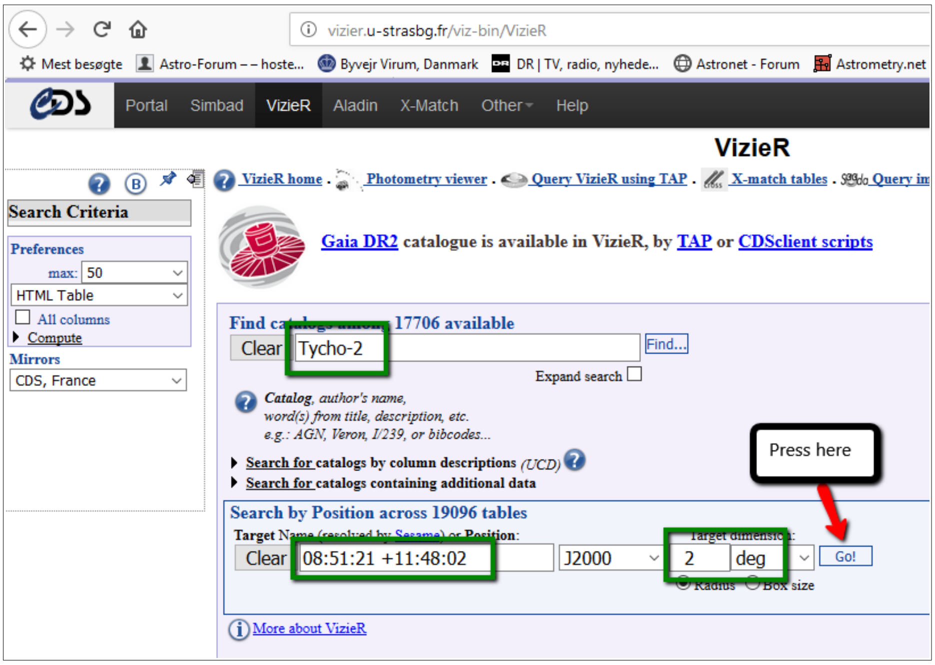
The V and B magnitude for the Comp-star is calculated in a similar way. Since the catalogue-values are known for the Check-star, it is possible to calculate the errors and thus estimate the error of the star. It is only in this artificial example, that we know the catalogue values for the star. In the general situation this is naturally not possible. That is the whole point.

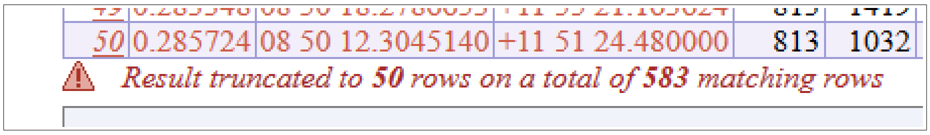
The need for transformation is obvious, but it is also seen that especially for the B magnitudes, the corrections are big. It is not easy to reduce the errors (see the comp stars B magnitude with an error of 0.075 mag). This is due to the big transformation-factor 1.021 for B. This means that (B-V) is approximately 2 times the instrumental colour magnitude (b-g).

How to find Standard magnitudes Tycho-2 in VizieR

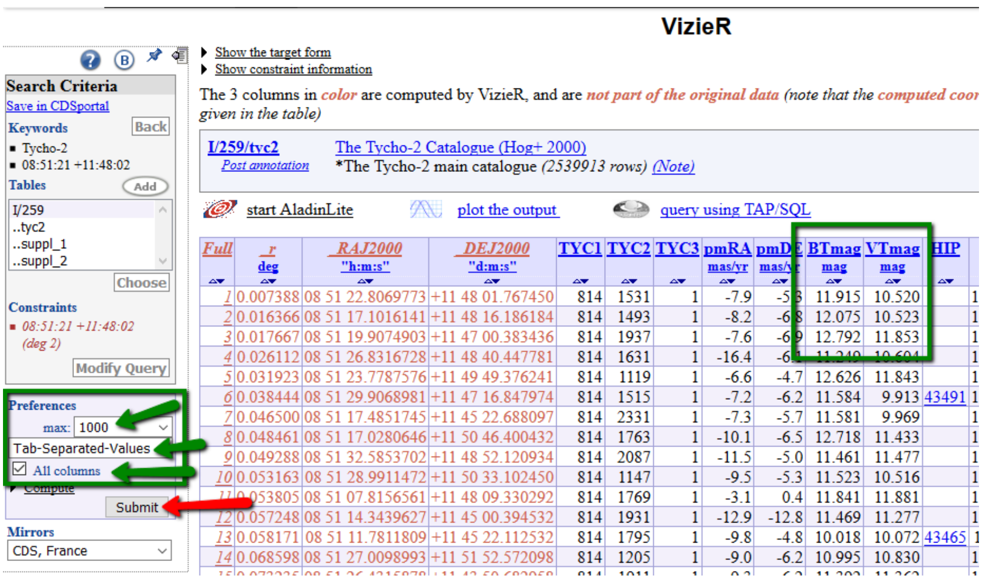
15. oktober 2018 ST A case study

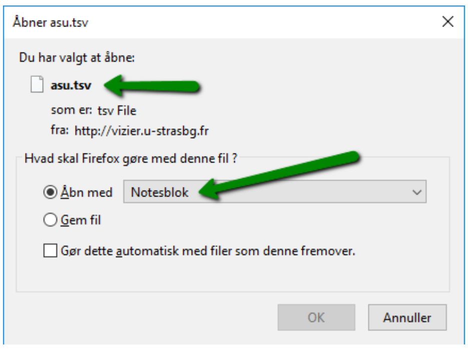
The question:
How can I find standard magnitudes VT and BT from the Tycho-2 Catalogue for the M67 standard field? RA 08:51:21 Dec +11:48:02 in a radius of 2 degrees from the centre?
The answer:
The catalogue is in VizieR http://vizier.u-strasbg.fr/viz-bin/VizieR



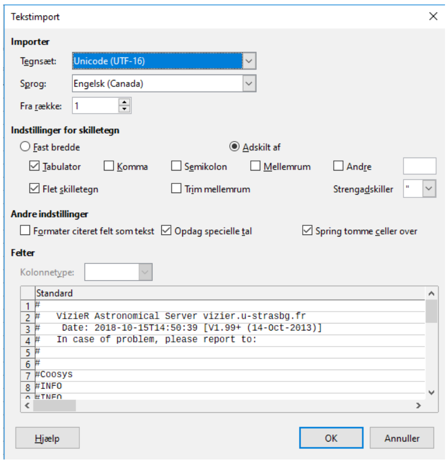


The search criteria is changed to a Tab-separated format (max 1000).





And the result is copy-pasted into LiberCalc (Insert special)



90							
91	q_pmRA	q_pmDE	BTmag	e_BTmag	VTmag	e_VTmag	rox
92			mag	mag	mag	mag	
93	----	----	------	------	------	------	--
94	0.4	0.4	11.915	0.107	10.52	0.048	
95	0.6	0.1	12.075	0.14	10.523	0.051	
96	0.4	0	12.792	0.271	11.853	0.177	
97	0.9	1.1	11.249	0.064	10.604	0.053	
98	0	0.8	12.626	0.263	11.843	0.189	
99	1.2	0.9	11.584	0.078	9.913	0.031	
100	1.3	0.5	11.581	0.079	9.969	0.033	

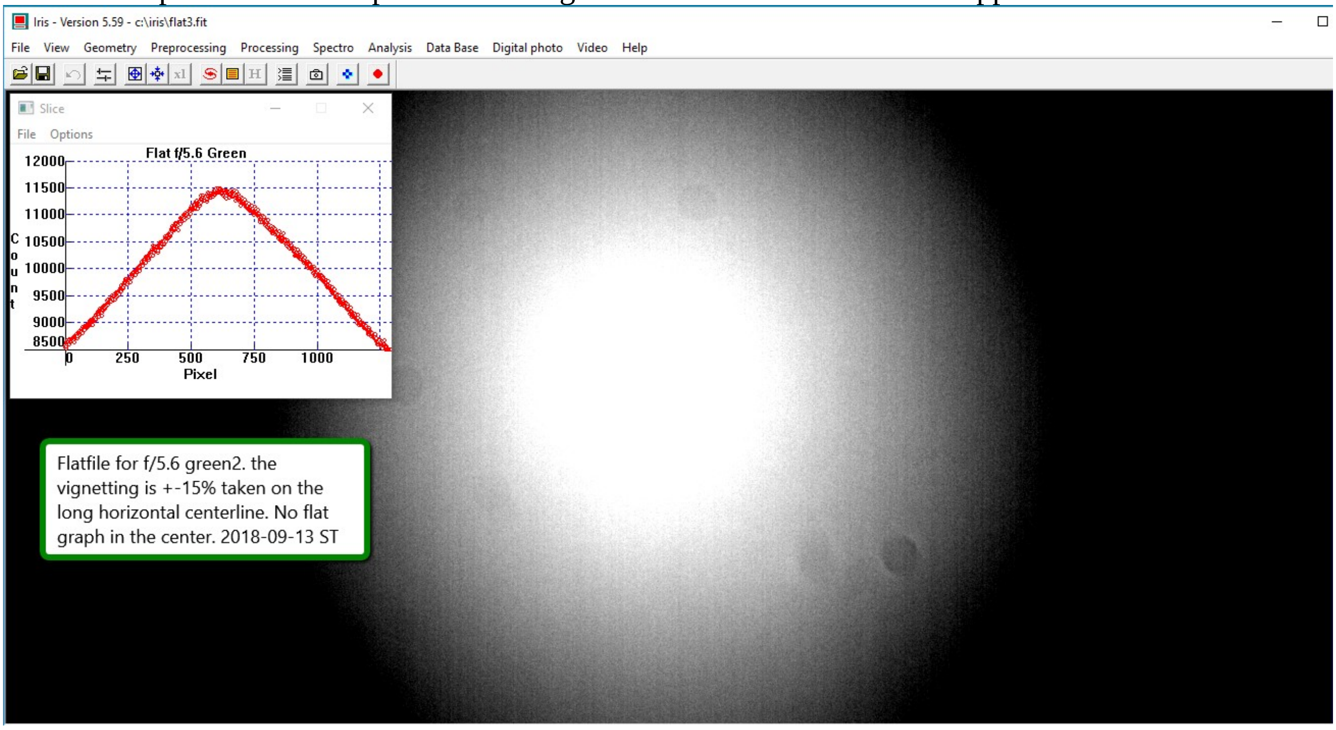
This is then a part of the resulting spreadsheet:
The many columns are due to the selected “All columns” option.
They can safely be deleted.
2018-10-15 ST

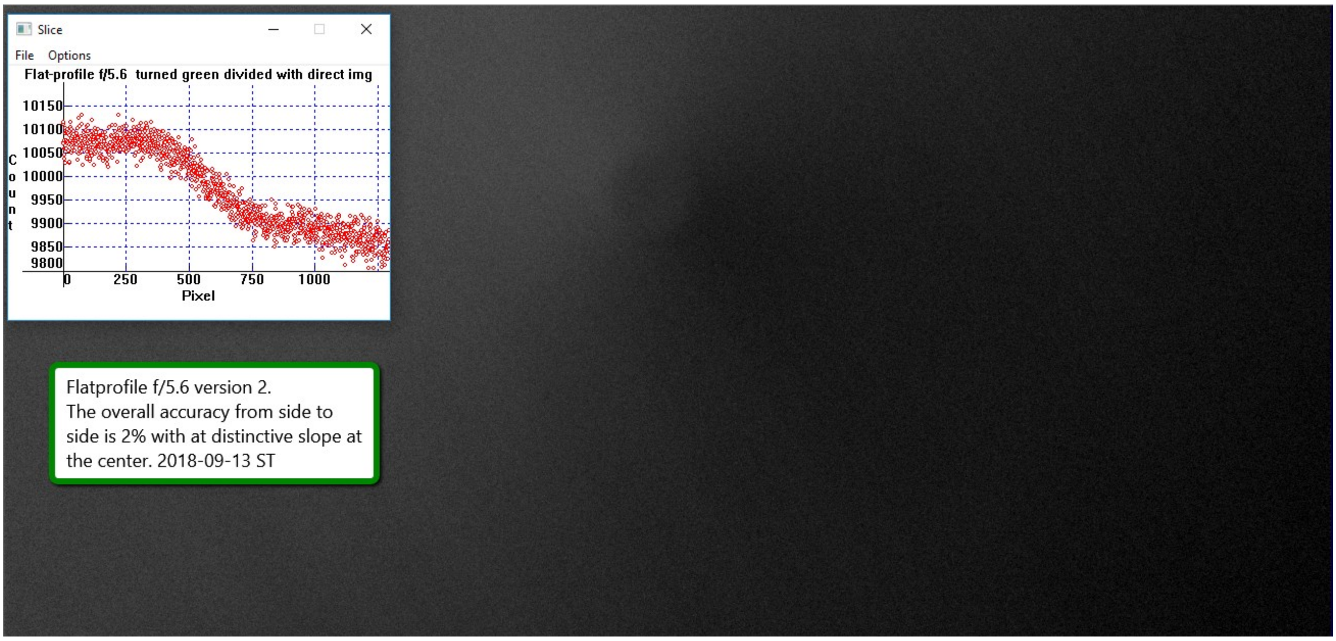
The spreadsheet

APPENDIX Flat field correction

I have made two flat-field - corrections with my Canon Zoom Lens EF 80-200 mm 1:4.5-5.6 II

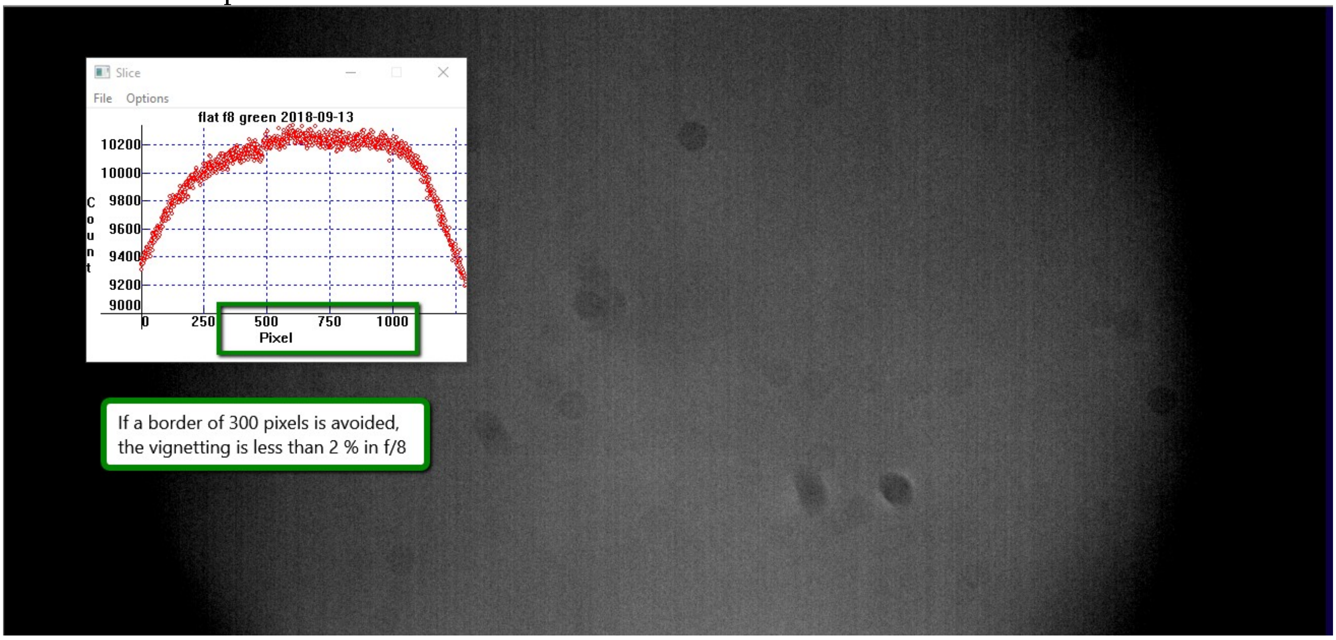
First attempt:
I tried to use the lens full open f/5.6.
The vignetting was very pronounced (± 15%) from side to side.
The standard procedure is to turn the camera 90 degrees, and divide the direct image with the turned image. When I made the image division (Image profile) there was a 2% difference from side to side, with at slope in the central part of the image. That is where the stars are supposed to be.

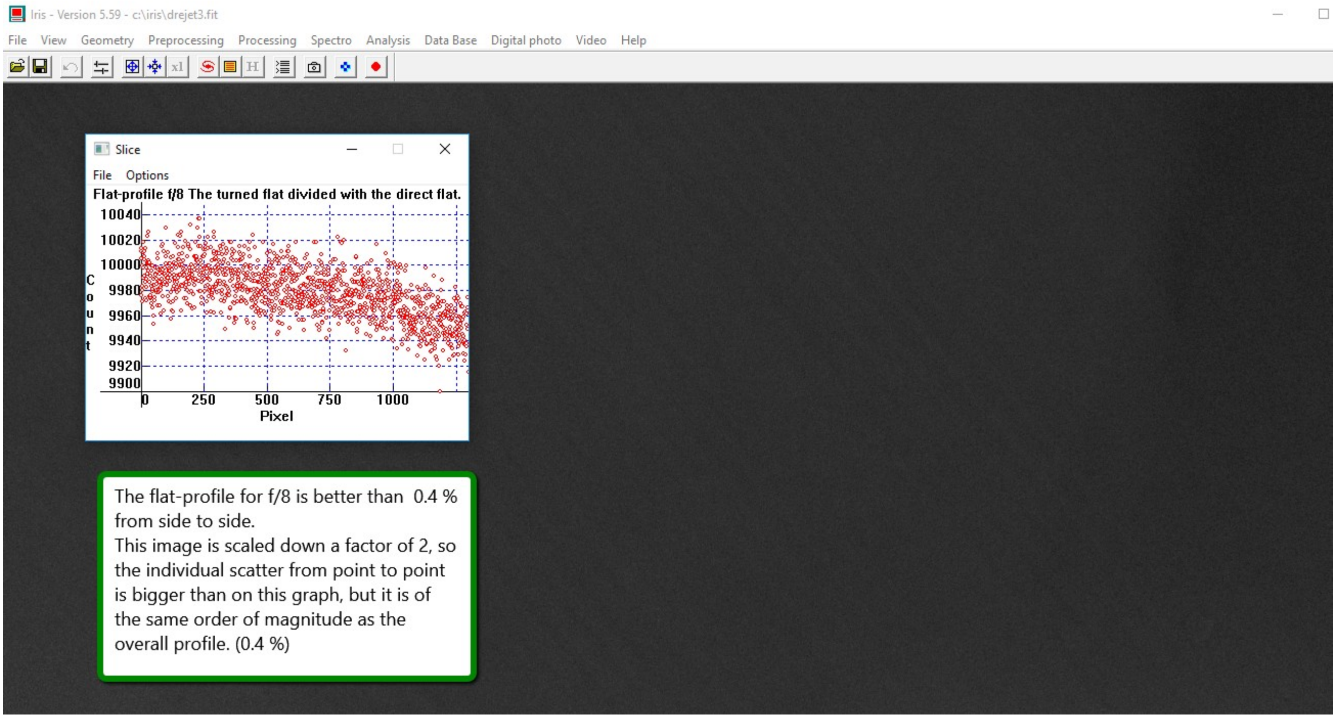




Second attempt:

I stopped down the lens to f/8. That was much better.
The vignetting was only ± 4% and the central part of the image showed less than ± 1%.
That should be possible to calibrate 10 x





It can be seen on the Profile for f/8, where one flat is divided with the turned flat, shows less than 0.4 % differences from side to side.

So the conclusion is the old story:
Stop down your lens, to get rid of the vignetting.

The light source is a halogen lamp that lights up my white wall. This white wall is seen through a white piece of plastic. The first picture shows the lamp and the camera. The second picture is taken during daytime. To avoid the obvious inhomogeneity in luminosity, the flats should be taken at night so the lamp is the only light-source.

Søren 2018-09-20

[i] A final remark on the standard charts for DSLR-photometry.

When comparing the accuracy of the Stetson-fields with the AAVSO standard-field charts, I find it remarkable that the classical transformation field M67 does not have the same small errors on the AAVSO standard-field chart. The standard-field contains only stars fainter than 10 mag. This is rather faint for DSLR photometry with at photographic lens. The errors are typically 5-10 times worse than in the Stetson-fields, where an accuracy of 0.003 mag is achieved in V and B.

https://www.aavso.org/apps/vsp/photometry/?fov=20&B=on&north=up&maglimit=16&title=M67&ra=132.838375&Rc=on&Ic=on&east=left&dec=11.800667&special=std_field

Maybe better standard fields for DSLR-photometry could be established. [The Summer Beehive(IC4665) and The Winter Beehive (M44 or NGC 2632)].