Chapter 2

Amateur Astronomical Spectroscopy

Introduction

The goal of astronomical spectroscopy is to produce a wavelength calibrated line profile of the spectrum of an astronomical object, usually a star. From this line profile of the spectrum image, wavelengths can be measured as well as equivalent widths. Stellar and supernova classifications can be done. Doppler shifts can be measured and radical velocities calculated. Elemental lines can also be identified and their strengths measured. All these data can be gleaned from a single image of a spectrum. No wonder spectroscopy is so powerful.

This chapter will discuss the equipment used and techniques for producing a good astronomical spectrum image. Chapter 7 will discuss the software and processing of the spectral images in detail. While certain combinations of equipment will produce better results than others, when starting out with low-resolution spectroscopy almost any combination can be used to produce good first results. Low-resolution work will not provide accurate wavelengths no matter how good the technique. It can be used to identify major elemental lines and even classify supernovae. To determine accurate wavelengths, high-resolution must be used. There is still a great deal that can be before going to high-resolution spectroscopy, however. It is suggested that one start with low-resolution spectroscopy and master that before trying higher resolution work. Part of this is because probably 75 % of the effort is in the software processing. Most of this is the same regardless of resolution. Obtaining low-resolution spectra and processing them is an excellent way to learn spectroscopy. The other part is one can start with low-resolution spectroscopy for a few hundred dollars. Venturing into high-resolution will require several thousand dollars worth of equipment.

J.L. Hopkins, *Using Commercial Amateur Astronomical Spectrographs*, The Patrick Moore Practical Astronomy Series, DOI 10.1007/ 978-3-319-01442-5_2,

Astronomical Spectroscopy Equipment

Telescopes and Mounts

As mentioned earlier almost any telescope can be used, reflector or refractor, ALT/AZ or Polar mounted and a variety of focal lengths. For low-resolution work on bright stars, exposures will be is the sub-second range so tracking is not important. For high-resolution work and where fainter objects are imaged, time exposures will be required. A solid aligned mount is required for high-resolution work. Computerized ALT/AZ telescope will also work fine. The biggest disadvantage of the ALT/AZ mount is a clearance problem when using a LISA or Lhires III or even an ALPY 600 spectrograph. This is especially a problem when observing near the zenith, which is where the best observations are. A Polar mount will allow a large area beneath the telescope when observing near the zenith. For a mount a tripod will work, but if it needs to be set up each observing session, that effort can get old fast. A better approach is some kind of permanent mount. Using a permanent pier and Polar mount, once adjusted, will save many hours and make the observing sessions much more pleasurable.

Naturally the larger the aperture the more light (more photons) is available to be spread out into a spectrum and thus shorter exposures can be used or fainter stars observed. For the equipment listed, a 16″ aperture is about maximum for optimum spectroscopy. Larger instruments can be used, but there is a fast diminishing of returns. The Lhires III is optimized for a 12″ aperture. The Star Analyser is supposed to work best at f/5, but experience shows it works well at f/10 too and probably most focal lengths. The Star Analyser can also be used directly on a telephoto lens of a DSLR camera. The Lhires III works well at f/10 or f/6.3.

At the Hopkins Phoenix Observatory a simple, but permanent roll-off-roof observatory is used. The observatory is 8-foot square and 7-foot high with a fixed pier with polar mount and 12″ LX200 GPS telescope. This observatory is used for high-resolution work with the Lhires III (Figs. 2.1 and 2.2).

Fig. 2.1 Hopkins Phoenix observatory

Fig. 2.2 Permanent pier and 12″ LX-200 GPS telescope

A simpler setup was developed for low-resolution work with an 8″ LX90 telescope and Star Analyser. No observatory. The exact dimensions of the following are not critical. A 1-foot deep 2-foot square hole was dug and filled with concrete. A 4-foot long by 12-inch diameter cardboard Sono tube was then inserted into the concrete. A 5-foot long 3-inch diameter steel water pipe, threaded at the upper end was inserted into the center of the Sono tube and also filled with concrete. A 3 inch threaded pipe flange was then screwed onto the top of the pipe. A 10-inch square by quarter inch thick aluminum plate was then screwed to the flange. The LX90 wedge was then attached to the aluminum plate. This has proved to be an excellent arrangement. Once the wedge was aligned the telescope can be installed and removed easily. This arrangement requires little setup time. An extension cord provides AC power to a power strip to power the telescope and computer. If the telescope is to be used for several nights, it is left on the wedge. To protect it from the weather a 20-gallon commercial black plastic garbage bag is installed over it with a rope tying it at the base (Figs. 2.3 and 2.4).

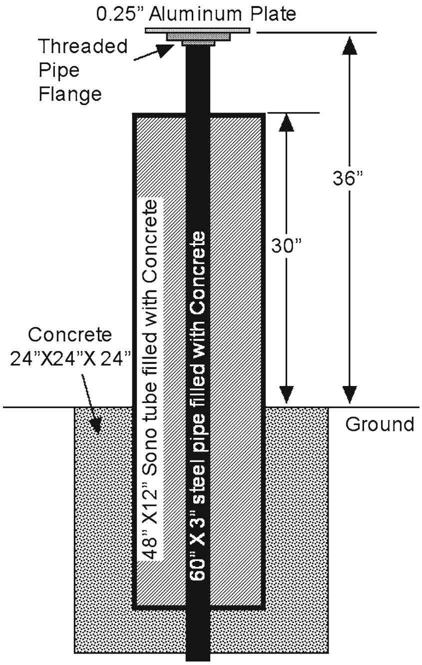


Fig. 2.3 Simple pier for 8″ LX90 and star analyser

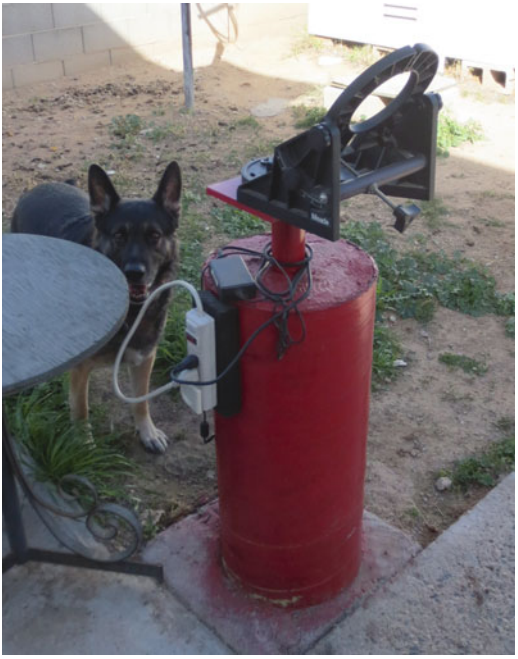


Fig. 2.4 Wedge and pier

German Sheppard guard dog Blackie stands guard over the equipment (Fig. 2.5).

Fig. 2.5 8″ LX90 telescope on pier

Digital Cameras

When starting out with low-resolution spectroscopy most any digital camera can be used including DSLR and web cam cameras. A 16-bit monochrome camera will produce an optimum results (best sensitivity, dynamic range and resolution) and is essential for quality high-resolution work. An 8-bit monochrome or 24-bit color camera will work for low-resolution spectroscopy, but they will have a dynamic range of only 256 whereas the 16-bit cameras will have a dynamic range of 65,536.

CCD Versus CMOS

A digital camera has a small chip that is a CCD (charge coupled device) or CMOS (complimentary metal oxide semiconductor) chip. The CMOS chips work well, but the CCD is the preferred type of sensor for most astronomical work. Both CCD and

CMOS work by the photoelectric effect where photons knock off electrons in a cell. The CCD chips are more sensitive in the longer wavelength infrared region. This region is where a lot of work is done on the hydrogen alpha and helium I lines. The CMOS chips are popular in DSLR and other non-astronomical digital cameras. They have a higher data transfer and lower noise that is needed for general camera use. The CCD excels for astronomical use with its better long wavelength response and higher sensitivity to low light conditions.

The CCD and CMOS chips contain rows and columns of pixels in the form of a matrix. Each pixel detects and reports the intensity of photons hitting it. New cameras can have over 1,000 rows and 1,000 columns for total number of pixels greater than one million. When photons hit the pixel, electrons are knocked off and fill a pixel well. The charge in the pixel well is then read and converted to an Analog to Digital Unit (ADU) count. The well is then emptied and ready for the next exposure. Color cameras have 3 or 4 different colored filers over the pixel matrix. For this reason color cameras have much lower resolution than that of a monochrome camera with the same total number of pixels. The filters also reduce the amount of light each pixel receives so the color camera is also less sensitive than a monochrome camera (Fig. 2.6). The following image shows a section of a CCD chip pixel matrix.

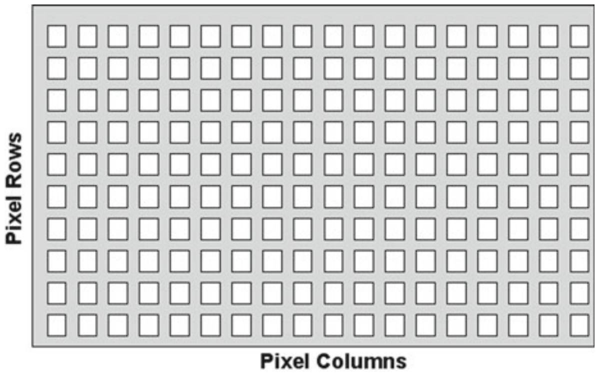


Fig. 2.6 CCD chip pixels

Each of the white squares is a pixel well. For color CCD chips it takes 3 or 4 pixels to produce one color point. Typically the maximum ADU count for a color pixel with a color CCD camera is 256 or 8 bits. Monochrome CCD chips use each pixel for a spot or point. This means the monochrome CCD chip has a resolution of 3 or 4 times that of a color chip of the same size. In addition, monochrome CCD cameras typically are 16 bit cameras and produce pixel ADU counts of from 0 to 65,535 meaning they have a much greater intensity dynamic range.

While most any CCD camera can be used with a Star Analyser spectrograph, it is essential that a 16-bit monochrome camera be used for high-resolution work. The Meade DSI Pro II and Orion G3 monochrome cameras both have the same CCD chip. The DSI series is no longer available, but the G3 is available now and has a built in regulated and adjustable TEC cooler. The pictured DSI camera is a DSI Pro II monochrome camera (Fig. 2.7).

DSI Series and Orion StarShoot Cameras

Fig. 2.7 Meade DSI Pro series

One can tell the difference between the DSI Pro and DSI Pro II by the color of the case. The DSI Pro is black and the DSI Pro II is blue. The DSI Pro II also has a bigger CCD chip. The Pro series are monochrome cameras and the DSI without the Pro are color cameras. The Pro series has a sensitivity 230 % and resolution 400 % more that the Color DSI Camera. The Pro series comes with a sliding filter bar. It is best to replace that with a low profile adapter and dark slide, as seen above, available from ScopeStuff (http://scopestuff.com/). The Orion G3 is a better buy now and can be found on sale from Orion for $399 (Fig. 2.8). ATIK also has good cameras, but tend to be more expensive (Fig. 2.8).

Fig. 2.8 Orion StarShoot G3 camera

ATIK 314L+ CCD Camera

Another popular CCD camera with a bigger chip for spectroscopy is the ATIK 314L+. At over $1,600 it is a bit expensive compared to the DSI and Orion series. Another drawback is the larger chip requires a bigger camera and camera space is limited on the Lhires III. Some observers have been able to use them, however. It may require a smaller guide camera so all the cameras can fit. The ATIK 314L+ uses a Sony ICX285AL CCD chip (Fig. 2.9).

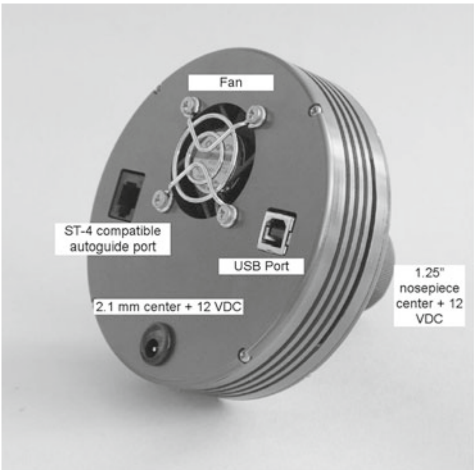


Fig. 2.9 ATIK 314L+ monochrome CCD camera

Table 2.1 shows the specifications for the CCD chips used for the Meade DSI series cameras as well as the Orion StarShoot camera and the ATIK camera.

Table 2.1 CCD chip specifications

CCD specifications
DSI
Color (4 Channel)
Ye, Cy, Mg, G
CCD ICX404AK
1/3″ Chip
510 × 492 pixels
(250,920 total pixels)
9.6 mm × 7.5 mm pixel size
16 Bit ADC
DSI II
Color(4 Channel)
Ye, Cy, Mg, G
CCD ICX419AKL
1/2″ Chip
753 × 582 pixels
(438,246 total pixels)
8.3 mm × 8.6 mm pixel size
16 Bit ADC
DSI Pro
Monochrome
CCD ICX254AL
1/3″ Chip
510 × 492 pixels
(250,920 total pixels)
9.6 mm × 7.5 mm pixel size
16 Bit ADC
DSI Pro II/Orion StarShoot G3 Monochrome
Monochrome
CCD ICX429ALL
1/2″ Chip
753 × 582 pixels
(438,246 total pixels)
8.3 mm × 8.6 mm pixel size
ATIK 324L+
Monochrome
CCD ICX285AL
2/3″ Chip
1,392 h × 1,040 v pixels
(1,447,680 total pixels)
6.45 mm × 6.45 mm pixel size
16 Bit ADC

Figure 2.10 shows the spectral response curves for the Meade DSI series and Orion StarShoot cameras. Figure 2.11 shows the spectral response curve for the ATIK camera.

CCD Chip Spectral Response Curves

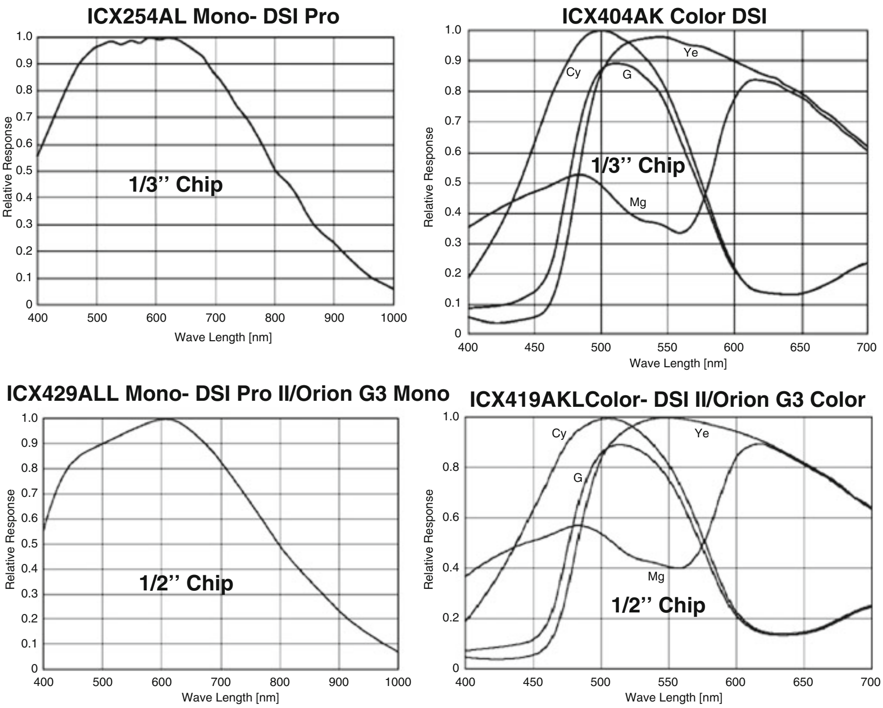


Fig. 2.10 DSI and Orion Star Shoot CCD spectra response curves

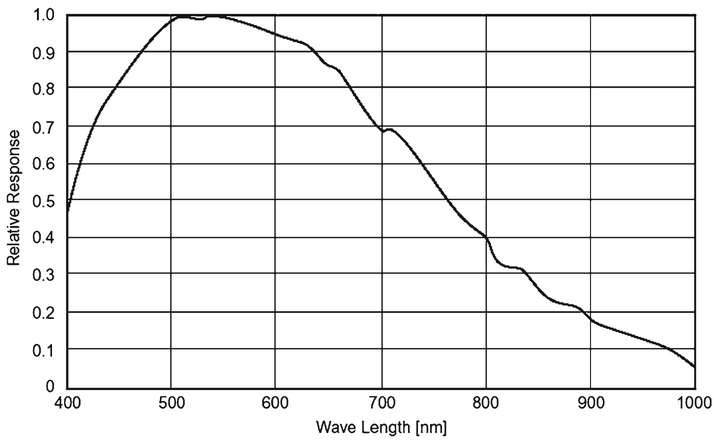


Fig. 2.11 ATIK 314L+ ICX285AL CCD spectra response curve

Spectrographs

Both a prism and/or diffraction grating can be used to produce a spectrum of the visible region of the electromagnetic spectrum. Prisms were used for early spectroscopy, but in order to have sufficient resolution, the prism-based spectrographs tend to get very big and thus usually will only work with large telescopes. Diffraction grating spectrographs can be made much smaller and are more suitable for smaller telescopes. A good example is the Lhires III. The Lhires III uses a Littrow design where the light passes through the same lens twice, first as a collimator and then as a focuser, in a folded optical arrangement.

A diffraction grating is a glass plate or film that has many parallel lines scribed on its surface. The number of lines per millimeter (l/mm) is one factor that determines the possible resolution of the spectrograph. The more line per mm the higher the possible resolution. For the discussed spectrographs the number of lines vary from 100 to 2,400 l/mm. There are two types of diffraction grating, reflection and transmission. In addition the transmission gratings can be used with or without a slit. For those observers in light polluted areas, a slit will essentially eliminate the sky background. Using a slit with a grating enables one to do good astronomical spectroscopy from urban backyards.

In this chapter, the Star Analyser, DIY (Do-It-Yourself), ALPY 600. LISA, Lhires III and eShel spectrographs will be briefly discussed. In Chaps. 3, 4, 5 and 6, the Star Analyser, DIY, ALPY 600, and Lhires III spectrographs will be discussed in detail.

Star Analyser Spectrograph

The Star Analyser spectrograph has a 100 l/mm blazed transmission grating. Note the Rainbow Optics spectrograph is very similar and most of what is discussed regarding the Star Analyser also applies to the Rainbow Optics unit. Both of these spectrographs are used for low-resolution work. Both the Star Analyser and the Rainbow Optics unit have a resolution of 200 or less. The Price of the Star Analyser is under $200 US$ whereas the Rainbow Optics spectrograph is around $250. Both of these spectrographs are normally used in a slitless mode. More information on the Rainbow Optics spectrograph can be found at:

http://www.starspectroscope.com/

and the User Manual for the Star Analyser at:

http://www.patonhawksley.co.uk/staranalyserusermanual.html (Fig. 2.12).

Fig. 2.12 Star analyser spectrograph, credit: Shelyak instruments

DIY Spectrograph

The Do-It-Yourself (DIY) spectrograph has an 1,800 l/mm reflection grating and is fiber optic coupled. The DIY Spectrograph has been available on eBay off and on for $200 US$. This includes everything needed to produce a spectrum line profile except a means of coupling to a telescope to use starlight for the spectrum (Fig. 2.13).

Fig. 2.13 DIY spectrograph

ALPY 600 Spectrograph

In February 2013 Shelyak Instruments announced a new low-resolution spectrograph called the ALPY 600. ALPY is not an acronym, but was conceived in Europe in the Alps. The ALPY 600 uses a grism arrangement. The grism consists of a 600 l/mm transmission grating with a small prism in front of it. This arrangement increases the resolution. The ALPY 600 has a resolution of over 500. The unit can be used with or without a slit. The basic unit has a rotating plate on the front of the spectrograph that allows a slitless mode and several different slit selections. The selectable positions are a 25 mm hole, 50, 100 and 300 mm wide slits plus a 3 mm hole clear position for slitless mode. The unit can be used on a telescope or on a bench via a fiber optic cable. The unit is designed to provide a spectrograph in price and performance between a Star Analyser and LISA spectrograph. The system has three modules. A basic module can be purchased first at minimal cost and other modules added as desired. The other modules consist of a guiding module and wavelength calibration module. The price of the ALPY 600 Is $825 US$ (shipping and exchange rate). All three modules can be purchased for around $2500 US$. The guiding and imaging CCD cameras are not included. User Manuals for the ALPY 600 Modules can be found at (Fig. 2.14):

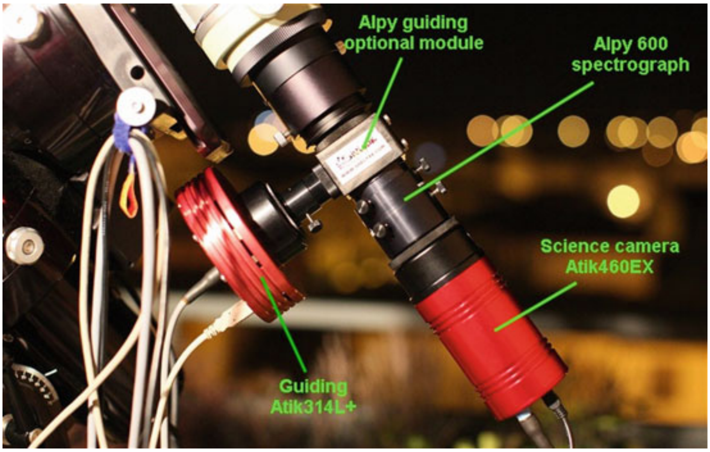


Fig. 2.14 ALPY 600 spectrograph, credit Shelyak instruments

Basic Unit:
http://thizy.free.fr/shelyak/alpy/DC0016A_Doc_Alpy_600_EN.pdf
Guiding Unit:
http://thizy.free.fr/shelyak/alpy/DC0017A_Doc_Alpy_Guiding_EN.pdf
Calibration Unit:
http://thizy.free.fr/shelyak/alpy/DC0018A_Doc_Alpy_Calibration_EN.pdf

LISA Spectrograph

Shelyak also has a low to mid-resolution 600 l/mm reflection grating slit type spectrograph called the LISA, **L**ong **I**maging-slit **S**pectrograph for **A**stronomy. The resolution is between 600 and 1000. The price for the LISA, less CCD cameras and white calibration unit, is around $4,800 US$. The white calibration unit is an additional $500 US$. The LISA User Manuals can be found at (Fig. 2.15):

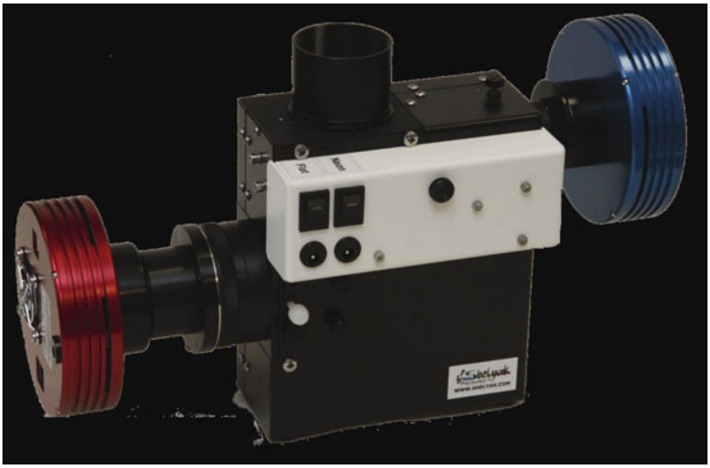


Fig. 2.15 LISA spectrograph, credit: Shelyak instruments

http://thizy.free.fr/shelyak/Lisa/DC0015A%20LISA%20Pack%20User%20&%20Reference%20Manual%20%28EN%29.pdf

and

http://thizy.free.fr/shelyak/Lisa/DC0012A%20-%20LISA%20User%20Guide%20-%20En.pdf

Lhires III Spectrograph

For mid-resolution and high-resolution spectroscopy a Lhires, **L**ittrow **Hi**gh **Res**olution Spectrograph, III with both 600 and 2,400 l/mm reflection gratings spectrograph will be discussed in detail. The Lhires III is optimized for the 2,400 l/mm grating, but 150, 300, 600 and 1,200 l/mm gratings are available optionally at around $500 USS each. The Lhires III has a resolution of over 17,000 with the 2,400 l/mm grating. The Lhires is available, less CCD cameras for $4,800 US$. This is perhaps the best choice for high-resolution spectroscopy. The LHIRES III Spectrograph User Manual can be found at (Fig. 2.16):

Fig. 2.16 Lhires III spectrograph, credit: Shelyak instruments

http://thizy.free.fr/shelyak/LhiresIII/DC0004A%20-%20Lhires%20III%20User%20Guide%20-%20English.pdf

eShel Spectrograph

The top of the line spectrograph from Shelyak is the eShel unit. This is an eschell type spectrograph that uses higher order spectra for a wider coverage of the spectrum. This is a fiber optic coupled spectrograph. The price of this spectrograph varies from $15,000 to $25,000, which is way out of reach for most amateurs and thus will not be discussed in detail. The eShel Spectrograph Users Manuals can be found at (Fig. 2.17):

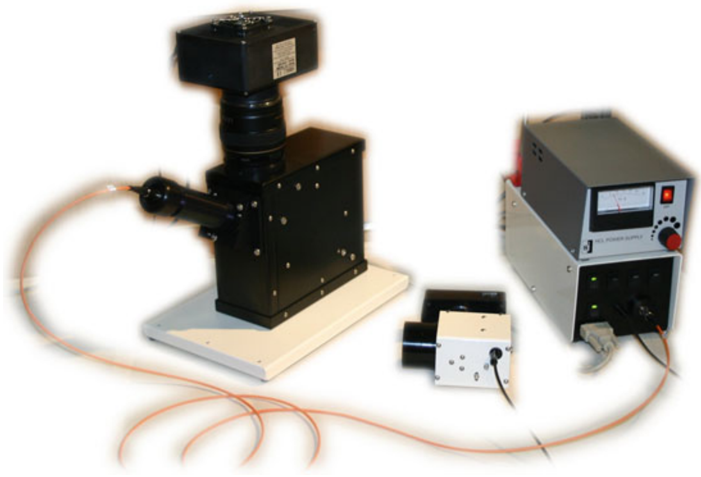


Fig. 2.17 eShel spectrograph, credit: Shelyak instruments

http://thizy.free.fr/shelyak/eshel/DC0010C%20eShel%20Installation%20&%20Maintenance%20Manual.pdf

and

http://thizy.free.fr/shelyak/eshel/DC0009B%20eShel%20User%20Guide.pdf

Taking Spectra

There are some procedural basics that apply to both low and high-resolution spectroscopy. High-resolution usually requires exposures in several minutes, even for bright stars, whereas low-resolution exposures are typically in seconds or milliseconds.

It is suggested that when starting out in spectroscopy that the observer try visual astronomical spectroscopy to get familiar with the spectral orders. This is done with low-resolution spectroscopy and will be discussed with the Star Analyser. Colorful spectra will be seen which can be inspirational.

When a spectrum is created there will be multiple versions of it on each side of the zero order spectrum or star image. Each successive spectrum will be fainter. There will be first order, second order and so on spectra on each side of the zero order spectrum. Normally the first order spectrum should be the spectrum used as it will be the brightest spectrum. For the Star Analyser spectrograph the transmission grating used is blazed in such a way as to make the first order spectrum on one side of the zero order spectrum much brighter than the first order spectrum on the other side. If in doubt which is which, look on both sides of the zero order spectrum and use the brighter one. Rotate the image so the zero order spectrum so to the left and the first order spectrum is to the right. This will produce the proper order of shorter (blue) wavelengths to the left and longer (red) wavelengths to the right. With color cameras this is obvious, but not so with monochrome cameras.

Note: In this Book, most spectra images are monochrome. Some spectrum processing software allows a monochrome spectrum's calibrated line profile to display a synthesized color spectrum based on the line profile wavelength calibration.

Spectral Order

As mentioned earlier and because a diffraction grating will produce multiple spectra, the Star Analyser transmission grating will produce spectra on both sides of the zero order and on just one side with the Lhires III reflection grating, it is important to use only the first order spectrum and in the case of a transmission grating, the brighter first order spectrum. With the Lhires III and 2,400 l/mm grating only the first order spectrum will be seen, however, if other gratings are used, e.g., the 150 l/mm, 300 l/mm, 600 l/mm or 1,200 l/mm gratings, higher order spectra can be seen, but will be dimmer. It is important to use the first order spectrum as it will be the brightest. The following Figure shows the spectrum image at the top with the zero order spectrum in the middle and the two first order spectra on each side with the brightest one to the right. The corresponding line profile of the image is seen below the spectrum image (Fig. 2.18).

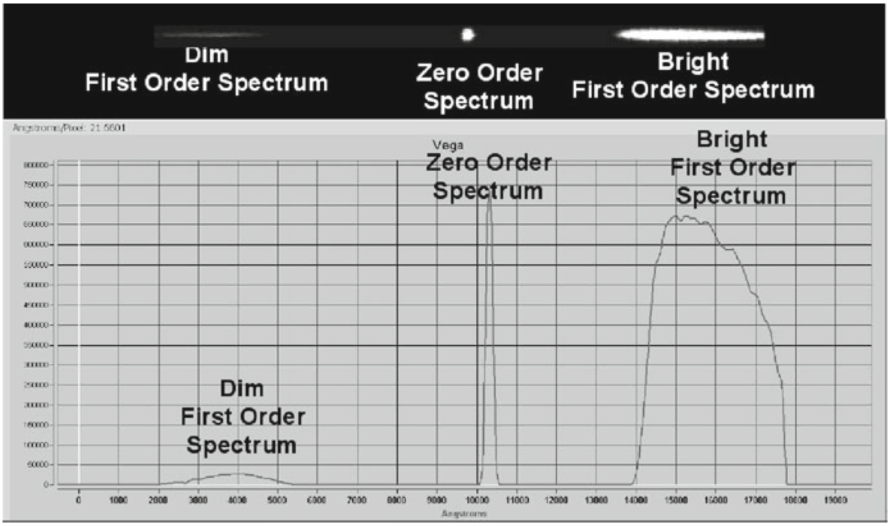


Fig. 2.18 Zero and first order spectra

Exposure

What exposure should you use? There are several factors involved, the brightness of the object, the telescope aperture and the camera sensitivity. There are two points to consider, the saturation point and linearity break point.

Saturation

The saturation point is a function of the dynamic range of the CCD. For a 16-bit CCD the saturation point is 65,535 counts or 2^16 and for 8/24-bit CCD cameras it's 255 counts or 2^8. Each of those actually has one more count, but that is zero. Exposure beyond the saturation point will not produce any more counts. Saturated spectral line profiles will appear with a flat top. While this will not hurt the CCD camera, it should be avoided. Note, the zero order spectrum may be saturated, but because it is not used for any intensity work it is not a consideration.

Linearity

For the best result the exposure should produce a first order spectrum pixel peak ADU count with a high value, but within the linearity range of the CCD. The point where linearity breaks is different for each CCD camera. Typically the break point is around 45,000 ADU counts for a 16-bit camera and 200 for an 8/24-bit camera. To determine a camera's linearity break point a simple experiment can be done. Set up a fixed light source that produces a peak ADU count of 10,000 for a 16-bit camera and 50 for an 8/24-bit camera. Ideally the light source should be producing a continuous spectrum, such as with an incandescent light. Increase the exposure times and note the peak ADU counts. Plot the exposure time vs. ADU counts. The plot should be a straight line (linear) until the break point is reached. At the break point the line will show a knee and further exposure time increase will not produce a corresponding linear ADU count (Fig. 2.19).

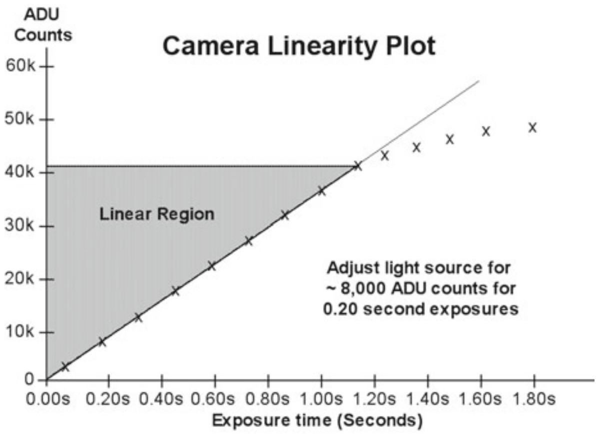


Fig. 2.19 Linearity break determination

Hot Pixels

For exposure times of one second or less, the image should not have any hot pixels. For longer exposures, they can be a problem. A hot pixel is one that has been turned on completely to saturation due to thermal noise and not photons. If the hot pixel occurs within the spectrum image, there will be a large spike in the line profile. These are obvious and can be deleted in the line profile. However, it is better to eliminate as many hot pixels as possible by using a dark frame. To create a dark frame cover the CCD or telescope so no light gets to the CCD chip. Take an image. The exposure should be at approximately the same CCD temperature as the spectrum exposure and the same exposure length. The dark frame is then subtracted from the spectrum image file. The spectrum image is then ready for spectroscopy processing (Fig. 2.20).

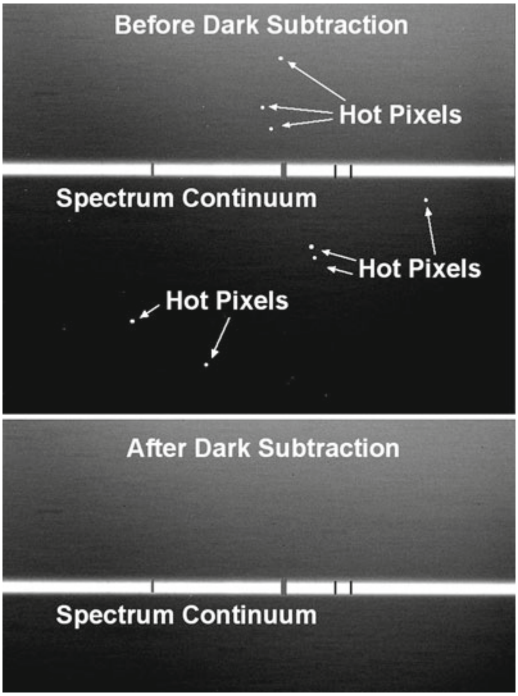


Fig. 2.20 Hot pixels and dark frame subtraction

Pixel Maps

Remember a CCD camera detector is composed of rows and columns of pixels in the form of a matrix. When an exposure is taken, each pixel charge is read and converted to a corresponding ADU count and assigned a matrix coordinate (Y-row and X-column) with that value. A pixel map showing the ADU counts of a specified area of the image can be produced with most imaging software and with the RSpec spectrum processing software. For the first example, the pixel Y = 197, X = 532 has an ADU count of 16,433. In the second example a map is not produced, but a read out of the maximum pixel ADU for a selected area of the image can be seen. The important thing here is to adjust the exposure so that the maximum pixel ADU count for the first order spectrum is less that the 65,535 (2^16 for 16-bit detectors) saturation count and ideally within the linear region of the CCD detector.

Most image processing software programs allow a means of examining the pixel map. The AutoStar Suite has an Image Processing section that can be used to examine the pixel ADU intensity counts (Figs. 2.21 and 2.22).

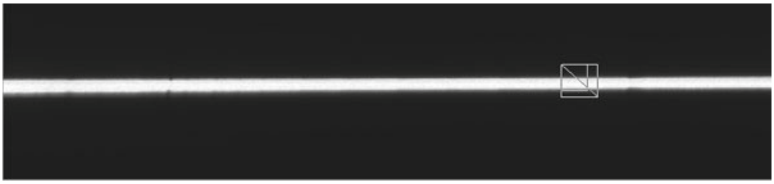
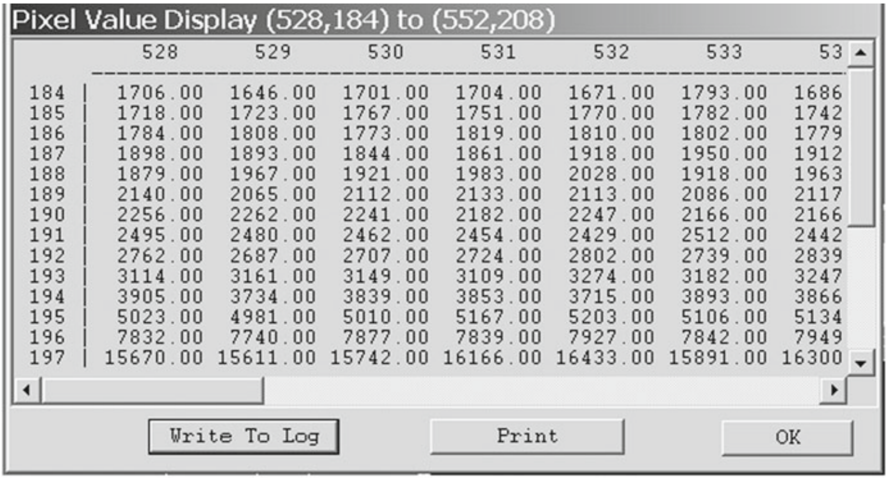


Fig. 2.21 Pixel map area selection with AutoStar image processing



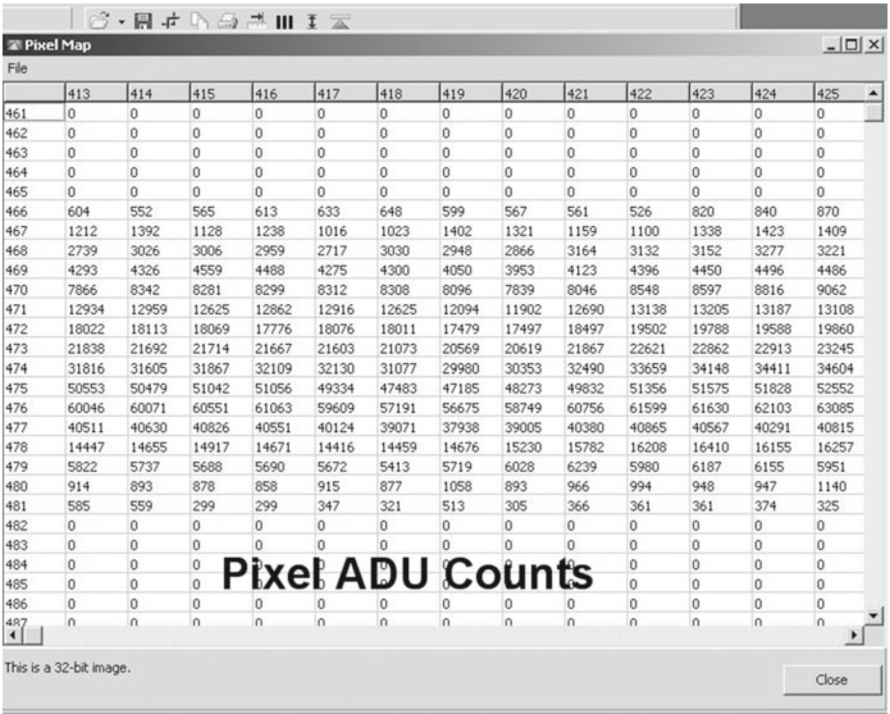
Pixel Value Display (528,184) to (552,208)

	528	529	530	531	532	533	53
184	1706.00	1646.00	1701.00	1704.00	1671.00	1793.00	1686
185	1718.00	1723.00	1767.00	1751.00	1770.00	1782.00	1742
186	1784.00	1808.00	1773.00	1819.00	1810.00	1802.00	1779
187	1898.00	1893.00	1844.00	1861.00	1918.00	1950.00	1912
188	1879.00	1967.00	1921.00	1983.00	2028.00	1918.00	1963
189	2140.00	2065.00	2112.00	2133.00	2113.00	2086.00	2117
190	2256.00	2262.00	2241.00	2182.00	2247.00	2166.00	2166
191	2495.00	2480.00	2462.00	2454.00	2429.00	2512.00	2442
192	2762.00	2687.00	2707.00	2724.00	2802.00	2739.00	2839
193	3114.00	3161.00	3149.00	3109.00	3274.00	3182.00	3247
194	3905.00	3734.00	3839.00	3853.00	3715.00	3893.00	3866
195	5023.00	4981.00	5010.00	5167.00	5203.00	5106.00	5134
196	7832.00	7740.00	7877.00	7839.00	7927.00	7842.00	7949
197	15670.00	15611.00	15742.00	16166.00	16433.00	15891.00	16300

Write To Log Print OK

Fig. 2.22 AutoStar suite image processing pixel map

Other software also provides means to examine the pixel ADU intensity counts. The spectrum processing program RSpec as an option to show the pixel map and intensity ADU counts for a spectrum image (Fig. 2.23).



	413	414	415	416	417	418	419	420	421	422	423	424	425
461	0	0	0	0	0	0	0	0	0	0	0	0	0
462	0	0	0	0	0	0	0	0	0	0	0	0	0
463	0	0	0	0	0	0	0	0	0	0	0	0	0
464	0	0	0	0	0	0	0	0	0	0	0	0	0
465	0	0	0	0	0	0	0	0	0	0	0	0	0
466	604	552	565	613	633	648	599	567	561	526	820	840	870
467	1212	1392	1128	1238	1016	1023	1402	1321	1159	1100	1338	1423	1409
468	2739	3026	3006	2959	2717	3030	2948	2866	3164	3132	3152	3277	3221
469	4293	4326	4559	4488	4275	4300	4050	3953	4123	4396	4450	4496	4486
470	7866	8342	8281	8299	8312	8308	8096	7839	8046	8548	8597	8816	9062
471	12934	12959	12625	12862	12916	12625	12094	11902	12690	13138	13205	13187	13108
472	18022	18113	18069	17776	18076	18011	17479	17497	18497	19502	19788	19588	19860
473	21838	21692	21714	21667	21603	21073	20569	20619	21867	22621	22862	22913	23245
474	31816	31605	31867	32109	32130	31077	29980	30353	32490	33659	34148	34411	34604
475	50553	50479	51042	51056	49334	47483	47185	48273	49832	51356	51575	51828	52552
476	60046	60071	60551	61063	59609	57191	56675	58749	60756	61599	61630	62103	63085
477	40511	40630	40826	40551	40124	39071	37938	39005	40380	40865	40567	40291	40815
478	14447	14655	14917	14671	14416	14459	14676	15230	15782	16208	16410	16155	16257
479	5822	5737	5688	5690	5672	5413	5719	6028	6239	5980	6187	6155	5951
480	914	893	878	858	915	877	1058	893	966	994	948	947	1140
481	585	559	299	299	347	321	513	305	366	361	361	374	325
482	0	0	0	0	0	0	0	0	0	0	0	0	0
483	0	0	0	0	0	0	0	0	0	0	0	0	0
484	0	0	0	0	0	0	0	0	0	0	0	0	0
485	0	0	0	0	0	0	0	0	0	0	0	0	0
486	0	0	0	0	0	0	0	0	0	0	0	0	0
487	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 2.23 RSpec pixel map

The image processing portion of the Orion Camera Studio software allows examination of the spectrum image when the cursor is positioned (Fig. 2.24).

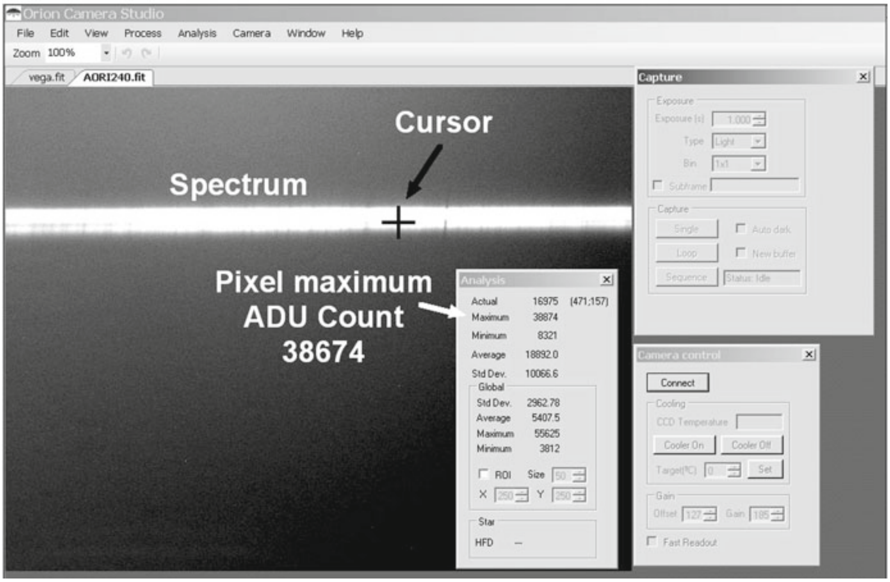


Fig. 2.24 Orion camera studio pixel count

The spectrum processing program VSpec has a means of examining the pixel ADU intensity counts similar to the Orion program (Fig. 2.25).

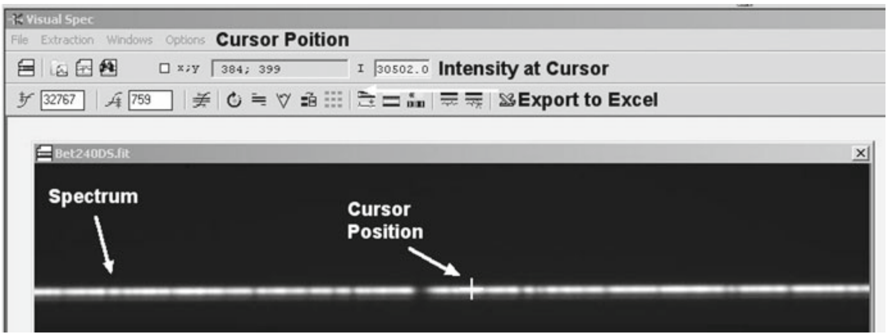


Fig. 2.25 VSpec pixel count

Dark Frames

A dark frame is an image taken at a specific exposure and temperature with no light falling on the CCD chip. Since no photons are hitting the detector, any pixels that show an intensity ADU count are hot pixels or bias pixels. The hot pixels will appear as bright points in the image. When a spectrum image is taken at the same exposure time and temperature, the same pixels will be hot pixels. The dark frame can be used to subtract those hot pixels (and bias pixels). This can be seen very nicely on long exposures. Before the dark frame subtraction, the image may have multiple bright points. While the hot pixels that are located far from the spectrum are of no concern, any hot pixels lying on or near the spectrum can make the spectrum appear to have an emission line at that point. It is therefore very important to subtract the dark frame. Note, there is also a bias frame, but when subtracting the dark frame, the bias frame is included and thus also subtracted.

With typical low-resolution spectroscopy images that are no longer than 1.0 s, dark frames are usually not needed. Since high-resolution imaging requires exposures in minutes or longer, dark frames should be taken. As noted above, the dark frames should use the same exposure time and approximate temperature of the detector as when the spectrum image is taken. These can be taken before or after the wavelength calibration and spectrum images. The dark frame is then subtracted from the spectrum image prior to the spectrum processing. For the best results, but not always needed, several dark frames of the same exposure and temperature are taken and then averaged. The averaged dark frame is then used. These dark frames can be reused if the CCD temperature and exposure times are the same.

Flat Frames

Flat frames are used to calibrate the CCD or CMOS detector for uniform sensitivity. The sensitivity from pixel to pixel can vary. This is true for both CCD and CMOS detectors. The CCD chips use a common Analog to Digital Converter (ADC) to convert the electric charge to a digital number. CMOS chips have an ADC on each pixel. While the CMOS arrangement provides a faster readout time, it also introduces a variation in the ADC gains from pixel to pixel. Correcting the pixel-to-pixel sensitivity if very important for astrophotography and photometry. It is of lesser importance for spectroscopy. With astrophotography slight imperfections in the optical train and of course the famous dust donuts, faint donut shaped objects in the image, can ruin the image. Flat frames can be used to correct those problems. With photometry, doing a flat frame correction can increase the accuracy of the magnitude determination. The value of flat frame correction for spectroscopy is debatable. Many observers skip using flat fields particularly for low-resolution work.

Because there is a slight variation in the pixel-to-pixel sensitivity of a CCD or CMOS chip, a pixel map that corrects the variation can be used. This will calibrate the chip so all pixels appear to be of uniform sensitivity, i.e., the same light produces the same ADU count for each pixel. Unlike dark frames, flats are much more complex.

To keep things straight some definitions are in order. First, the flat image taken is called the raw flat image. That image must have a corresponding dark frame subtracted. The resulting image is then the flat field. If the flat field is examined using a pixel map all the pixels will be seen to be about the same ADU count, but the values will vary. What is wanted is a flat calibration frame (Fig. 2.26).

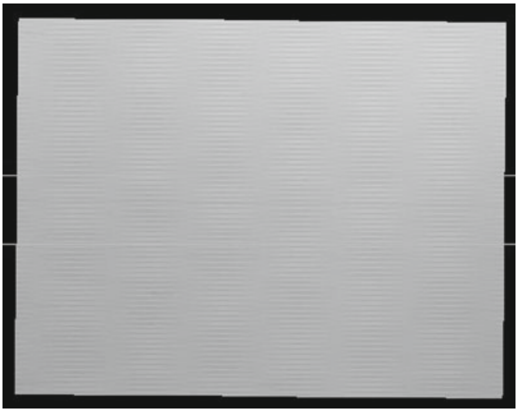


Fig. 2.26 Raw flat image

The following Figure shows a pixel map of the raw flat image where pixel intensity ADU counts vary around 40,000 (Fig. 2.27).

	430	431	432	433	434	435	436	437	438	439	440
432	38097	37967	38174	37791	38306	38242	38254	38128	38280	38052	38411
433	40647	40627	41065	40766	40506	40648	40740	40249	40592	40760	40492
434	37974	37756	37827	37760	37907	38133	38258	38144	38188	38245	38294
435	40648	40612	40574	40386	40618	40543	40638	40627	40535	40148	40380
436	37537	37821	37974	37956	38007	38224	38352	38061	37834	38106	38256
437	40312	40769	40277	40648	40460	40772	40572	40278	40641	40339	40514
438	37872	37544	37452	38138	38046	38082	38265	38103	38080	38537	38084
439	40959	40382	40462	40297	40401	40412	40000	40305	40532	40292	40526
440	37685	37795	37803	37644	37750	38080	38097	37746	37963	37836	38066
441	40775	40499	40653	40923	40610	40816	40824	40350	40365	40098	40549
442	37815	37697	37933	38014	37834	37931	38249	38085	38020	38226	38324
443	40571	40606	40859	40588	40631	40620	40472	40356	40118	40537	40326
444	38201	38009	37789	38233	38202	38083	38007	38004	38283	38588	38223
445	40823	41068	41397	40830	40798	40652	40243	40490	40580	40582	40660
446	38013	38151	38195	38053	38105	38098	38066	38037	37687	37753	38041
447	40429	40592	40747	40349	40410	40314	40690	40138	40257	40065	40305
448	37574	38060	38218	37649	37754	37846	38099	38039	37833	37876	38112
449	40490	40561	40605	40349	40582	40335	40037	40289	40354	40105	40303
450	37822	37935	37459	37765	37678	37720	37968	38064	38016	37801	37782
451	40264	40025	39953	40263	39844	40097	40045	40280	40353	40079	39993
452	37464	37314	37536	37571	38114	38049	37934	37718	37828	37725	37508

Fig. 2.27 Raw flat image pixel map

A calibration flat frame is created by first calculating an average value of all pixel ADU counts. That average number is divided into each pixel's intensity ADU count. This produces a new pixel map with all the ADU counts around 1.00. The following Figure shows the flat frame pixel map. This is a pixel map of the normalized image and is the flat frame that is used to calibrate an image. This is the calibration flat frame. The calibration flat frame is then divided, not subtracted, into the spectrum image. Dividing each of the spectrum image's pixels by a number around 1.00 will make a small correction in the count and adjust the pixel map for uniform pixel sensitivity (Fig. 2.28).

	281	282	283	284	285	286	28
169	1.09	1.08	1.09	1.09	1.09	1.09	1
170	1.00	1.00	1.00	1.00	1.00	1.00	1
171	1.09	1.09	1.08	1.08	1.08	1.07	1
172	1.00	0.99	0.99	0.99	0.99	0.99	0
173	1.08	1.09	1.08	1.08	1.08	1.08	1
174	1.00	0.99	1.00	1.00	1.00	0.99	1
175	1.06	1.08	1.08	1.08	1.08	1.08	1
176	0.99	1.00	0.98	0.99	0.99	0.99	1
177	1.08	1.07	1.08	1.08	1.08	1.07	1
178	0.98	0.99	0.98	0.99	1.00	0.98	1
179	1.08	1.08	1.08	1.08	1.08	1.07	1
180	1.00	0.99	0.99	0.99	0.99	0.99	1
181	1.08	1.09	1.09	1.10	1.08	1.08	1
182	0.99	0.99	1.00	0.98	1.00	1.00	1

Fig. 2.28 Flat frame pixel map

RAW flat frames are taken by uniformly illuminating the CCD chip with a continuous spectrum from an incandescent light. Do not use a fluorescent light. With high-resolution spectroscopy because CCD sensitivity is wavelength dependent, several raw flats should be taken with the grating set for different bands. Take flats every 500 Å from 4,000 Å up to 8,000 Å. These are raw flat images. Exposure times should be used so that the pixel intensity ADU counts are about 50 % of the saturation count. For 16-bit ADC cameras the count should be between 25,000 and 45,000. For 8-bit ADC cameras the counts should be around 125.

The raw flat image must have dark flats of the same exposure time and temperature subtracted from each raw flat image. The results will still not be ready to be used, however. Most imaging programs handle the flats by normalizing the image. This is done by taking the raw flat image pixel ADU count average for the whole chip and dividing that number into each pixel ADU count. This produces a pixel map with ADU counts around a value of 1.00. This is the real calibration flat frame. This map is then divided into the main images (after darks have been subtracted from the main image) to correct all the pixels for varying sensitivity. To take a raw flat and divide it into the main image without the darks or normalizing it is very bad and will produce an image that is severely corrupted.

The value of the extra effort to take and use flats for spectroscopy can be debated. A similar averaging calibration without flats can be done two ways, movement in the slit and binning. The spectrum image is typical a dozen or more pixels in height. This and any movement back or forth in the slit of the star image will increase the number of pixels and height of the spectrum image. Since the line profile sums these column ADU counts, any small variations tend to average out (Figs. 2.29 and 2.30).

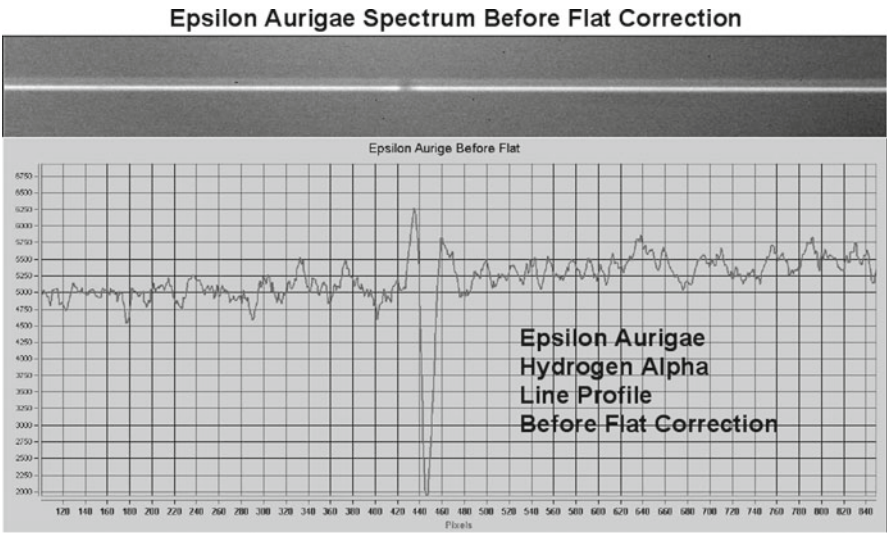


Fig. 2.29 Spectrum and line profile without flat frame correction

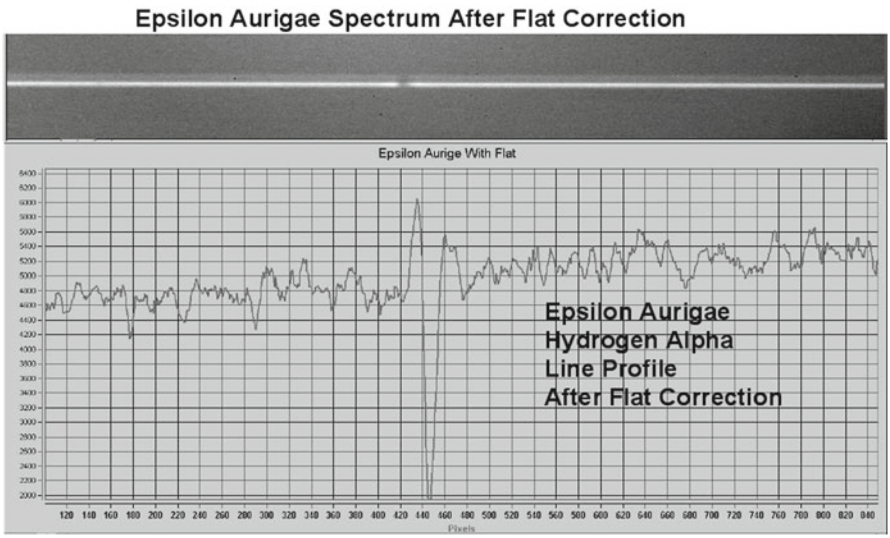


Fig. 2.30 Spectrum and line profile with flat frame correction

Note, some imaging processing programs make this very simple, but be careful that you know for sure what is happening. For example some programs allow you to load the spectrum image and do a calibration by loading a dark frame and flat. The question is which flat, the raw flat image, flat field or calibration flat frame? Usually the flat is the raw flat image. Some imaging programs do all the work for you and you just need to take the raw flat and the program makes and uses the calibration flat. Experiment to make sure you know what is going on.

Image Rotation

As with low-resolution spectroscopy it is also very important that the spectrum image be horizontal for high-resolution work. The orientation of the spectrum should be adjusted by rotating the spectrum imaging camera. With low-resolution work rotating the grating with respect to the camera is needed. If an important image is produced and later found to have a titled spectrum, it may be too late to correct the spectrum at the spectrograph. In such a case most spectrum processing software allows the image to be rotated with software. This is a last resort and while this rotation does work, it can trim the spectrum and produce strange artifacts. Additionally it is very important to make sure the longer (red) wavelengths are to the right in the image. If reversed the spectrum imaging camera should be rotated 180°. It is also possible to rotate the spectrum 180° with software, but best to have the orientation correct when imaging the spectrum. The following Figure shows an extreme of a high-resolution spectrum image tilt (Fig. 2.31).

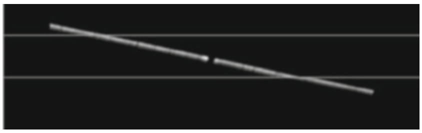


Fig. 2.31 Spectrum image orientation

Background or Sky Subtraction

For spectra of astronomical objects it is important to subtract the background or sky from the image. Most spectrum processing software has this option. A specified number of pixel rows above and below the horizontal spectrum delimiting lines are used to sum pixel columns in those rows and then subtract that number from the sum of the pixel columns delimited by the horizontal lines. This reduces the “floor” of the line profile. Typically 10 pixels above and below are used. It should be noted that the background subtraction should not be used for the neon line calibration. This is for two reasons. First there should be no background or at least an insignificant background. Second the pixels above and below the delimiting lines for the neon spectrum are still the neon spectrum and will result in eliminating or seriously diminishing the neon lines in the line profile.

Horizontal Binning

A spectrum's signal-to-noise can sometimes be improved by using horizontal binning. With the RSpec program this is where adjacent pixels to the right in a row are averaged to create a new pixel value. The degree of binning can be selected. Usually Bin 2, Bin 3, Bin 4, Bin 5 or Bin 6 are available for use. While binning will reduce the wavelength precision with high-resolution images slightly, it may still be of value in reducing the spectrum noise. Low-resolution images with a Star Analyser will show smoother profiles and no significant change in resolution. For the best wavelength calibration with high-resolution images, the minimum or no binning should be used. The following Figure shows an example of Bin 2 horizontal pixel binning. The numbers in the boxes (pixel cells) are intensity ADU counts (Fig. 2.32).

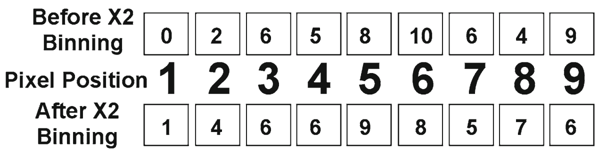


Fig. 2.32 Horizontal binning (Bin 2)

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