

First steps with a Slit Spectroscope

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Ok, you've taken the quantum leap and moved into your first slit spectroscope. Your initial experiences may have been with a grating (Star Analyser/ Rainbow Optics/ Baader) and you quickly find setting up and using a slit spectroscope, both on the bench and on the telescope is a completely different ball game.

Hopefully these notes will ease the way forward and provide some meaningful stepping stones on the journey.

We won't talk at this stage about guiding or "target acquisition", (The notes on Using AI's reticule in the files area is a good primer on this subject) instead we'll concentrate on getting the spectroscope set-up ready for serious use and highlight the necessary steps along the way.

It really doesn't matter which design of slit spectroscope you have, it can be a Classical DIY, or a Littrow. These notes will apply to both and equally to commercial/ professional instruments like the SBIG SGS, Sheylak LHiresIII/ LISA, Baader DADOS and the Spectra-L200.

The construction of a spectroscope has the common elements:

- An entrance Slit
- A collimator lens
- A diffraction grating/ prism (with or without adjustment)
- An imaging lens (the same lens as the collimator in a Littrow design)
- And finally the imaging camera/ eyepiece.

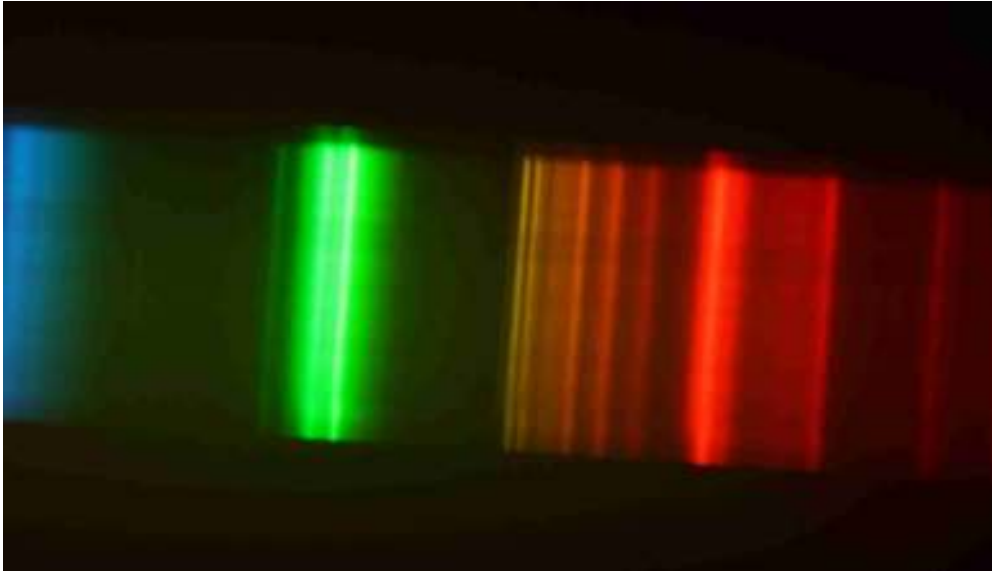
(It's worthwhile mentioning up front that the SimSpecV4 spreadsheet is an excellent aid to evaluating your spectroscope and the interaction between the target star, the entrance slit gap, the grating and the imaging camera when considering resolution etc. Spend a bit of time playing around with the various SimSpec inputs and understanding what the results are telling you. We'll refer back to SimSpecV4 as we move up the learning curve...)

Moving along...

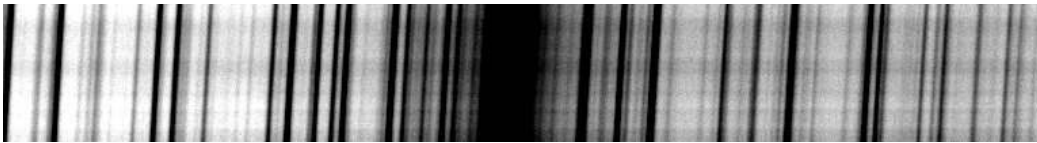
I'm going to make the assumption that the spectroscope you're using has been assembled and built correctly – the positioning of the entrance slit is correct for the collimator, the grating rotation can be controlled (micrometer head) and is repeatable, and the alignment of the optics can give a visible spectrum in your eyepiece/ camera.

(If this is not the case, refer to your DIY/ Supplier Instructions for procedures to fix/ adjust the instrument.)

I also strongly recommend that you orientate the spectrum central to your CCD frame and horizontal across the larger axis. This reduces the "tilt" angle and possible loss of resolution. (The absorption/ emission lines within the spectrum height will probably end up showing a "slant". This is normal. It can easily be corrected with your normal processing)



Low resolution Spectrum shown “tilted” across the camera field



Hi-resolution Spectrum corrected for tilt but still showing “slant” of the lines

There are three basic steps which MUST be done:

- Focus the imaging camera
- Calibrate the grating rotation (if available)
- Focus the target (star) onto the entrance slit.

That’s it! Achieve these three things and you have a capable instrument for spectroscopy.

Focus the imaging camera

Preamble

The size (width) of the entrance slit generally defines the quality of the spectrum produced.

The spectral image is made up of “strips” each the width of the slit for every individual wavelength. To maximise the resolution and clarity of the spectrum the imaging camera must have a pixel size less than 50% the slit gap. (This is driven by the Nyquist sampling - <http://www.dspguide.com/ch3/2.htm>).

For an “average” minimum slit gap this then means that the slit will appear (under ideal conditions) as an image 2-3 pixel wide.

Understanding the above helps us appreciate the importance of getting the slit image into accurate focus.

Depth of focus tolerance (CFZ)

We also have the inherent depth of acceptable focus which is dependent on the f ratio of the imaging lens. To keep the image quality within the accepted $\frac{1}{4}$ wave accuracy the “critical focus zone” (CFZ) is:

f ratio	tolerance (micron)
10	220
8	141
5	55
4	35

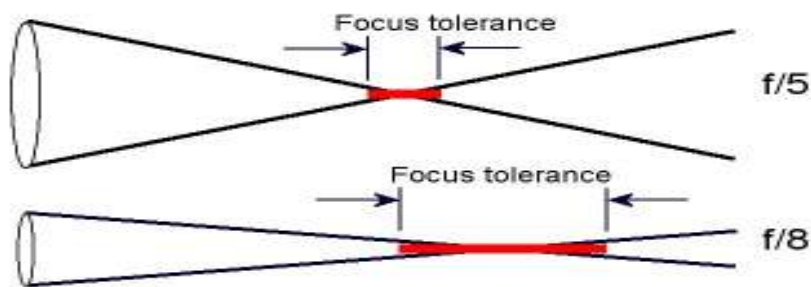


Diagram of the CFZ

This effectively defines our allowable “error band” on the focusing.

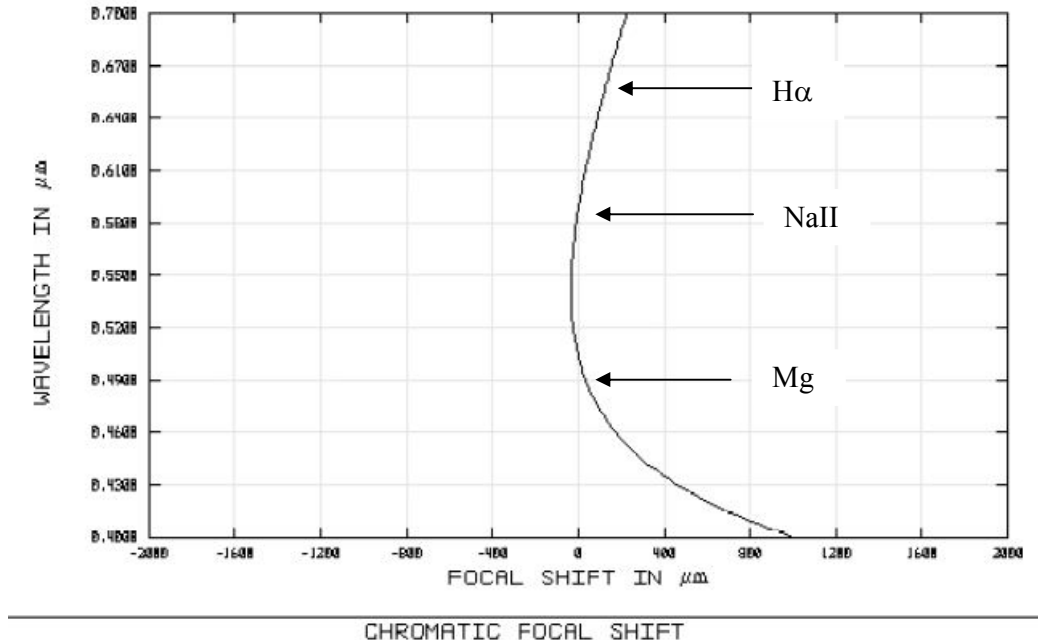
Aberrations

The next issue is the quality of the imaging lens being used. Most small spectroscopes use doublet achromat lenses. These suffer from various aberrations; astigmatism, distortion, chromatic colour and the quality of image produced will depend on the accuracy of the lens. Most lenses will resolve around 10-20 micron. (The old lines/inch resolution charts etc.). This can be factored into the spectroscope design in SimSpecV4.

Aberration - Chromatic

One of the most important aberrations for us is chromatic aberration, where the blue, green and red regions of the spectrum come to a focus at different points along the optical axis. What this means to us is that the imaging camera needs to be able to be moved relative to the imaging lens depending on which region of the spectrum we are recording.

The graph below (taken from the Edmund Optics website) shows the typical amount of re-focusing required when an achromat doublet is used.



You can see from the three arrows (approx wavelengths Ha, NaII, Mg) the variation.

Taking Ha (650nm) as the “base”:

The yellow (550nm) would require the CCD to move forward by around 200 micron, and the blue (490nm) a reduced forward movement of 100 micron.

(Comparing this required movement with the CFZ at f10, you may be able to get satisfactory results across the whole spectral range by setting the focus to a mid point between red and yellow.)

Bear in mind the T thread on your adaptors has a thread pitch of 0.75mm (750 micron/ 360 degree rotation). This would mean a rotation of $(200/750)*360 = 90$ degrees for the yellow, and $(100/750)*360 = 45$ degrees for the blue.

In the Sheyak LhireIII, the collimating lens can be moved to provide fine focus corrections.

Aberration – Field Curvature

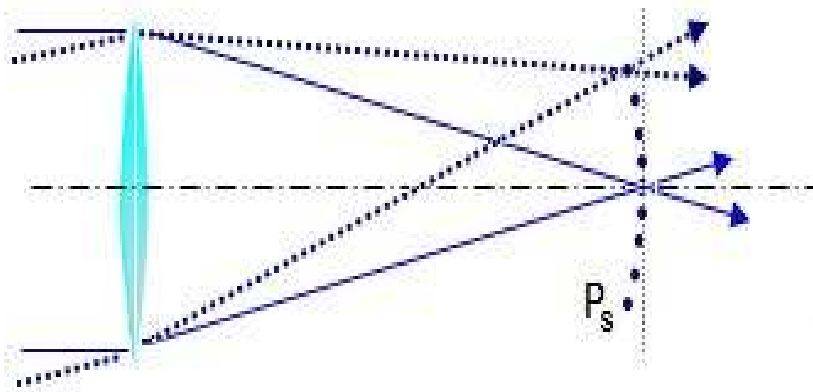
The second, and sometimes the most important aberration is field curvature.

The “best” off axis image lies along a spherical curved surface (Petzval surface) the radius of which is approx (this varies with the lens) 1/3 the focal length. This means for a 200mm focal length lens the Petzval surface radius would be around 65mm.

(You’ve probably come across this problem when you used a grating in the converging beam – the zero order star image has to be out of focus to bring the spectrum into best focus.)

As the CCD sensor has a flat surface it cannot focus all parts of the Petzval curve at the same focus setting. The further you image away from the optical axis, the further you go out of focus. This gets even worse when you consider the larger chips in the DSLR. (Note: the best focus point moves towards the lens.)

LENS PETZVAL SURFACE



See <http://www.telescope-optics.net/curvature.htm> for further details.

For a 200mm lens and an approx Petzval curve of 65mm:

Off axis distance (mm)	Change in focal plane (microns)
0	0
2	-31
3	-69
4	-123
5	-193 (CFZ limit)
6	-278
7	-378
8	-494
9	-626
10	-774
11	-938

From the above data you can see the “sweet spot” i.e. a field of view within the CFZ limit is around 10mm diameter.

For a DSLR, the frame width is 22mm. At the extreme edges of the image, the spectrum will be well out of focus. This will severely impact on the clarity and resolution of the spectrum recorded.

You need to consider both these aberrations when determining your “best focus” for your CCD. Focus on your region of interest and accept that extreme edge of your frame may record at a lesser resolution.

1. Setting the camera focus

This is initially best done on the bench. You need to illuminate the slit with a suitable light source. A piece of greaseproof paper/ tracing paper over the inlet port gives a good diffuse light. As you'll probably be moving on to calibrating the grating rotation, use an energy saving fluoro lamp. Position the lamp a metre or so from the inlet port such that it fully illuminates the slit.

The slit gap, if adjustable, should be set reasonable narrow (around 50-70 micron). If you use a fixed slit plate, start with the widest available gap.

The adaptors necessary to set the camera CCD at or close to the design back focal position should already be in place. Provision for camera rotation (to reduce "tilt" should also be available.

(Some suppliers – e.g. SBIG and Shelyak, supply custom made spacers for various cameras)

Set up the camera to give a 0.5 sec exposure (this will vary camera to camera, and we'll reset the exposure again later)

If you can access the zero order image (by rotating the grating to a position where it acts as a front surface mirror) then use this setting for the initial focusing. Otherwise adjust the grating until you get an image of the slit on the CCD.

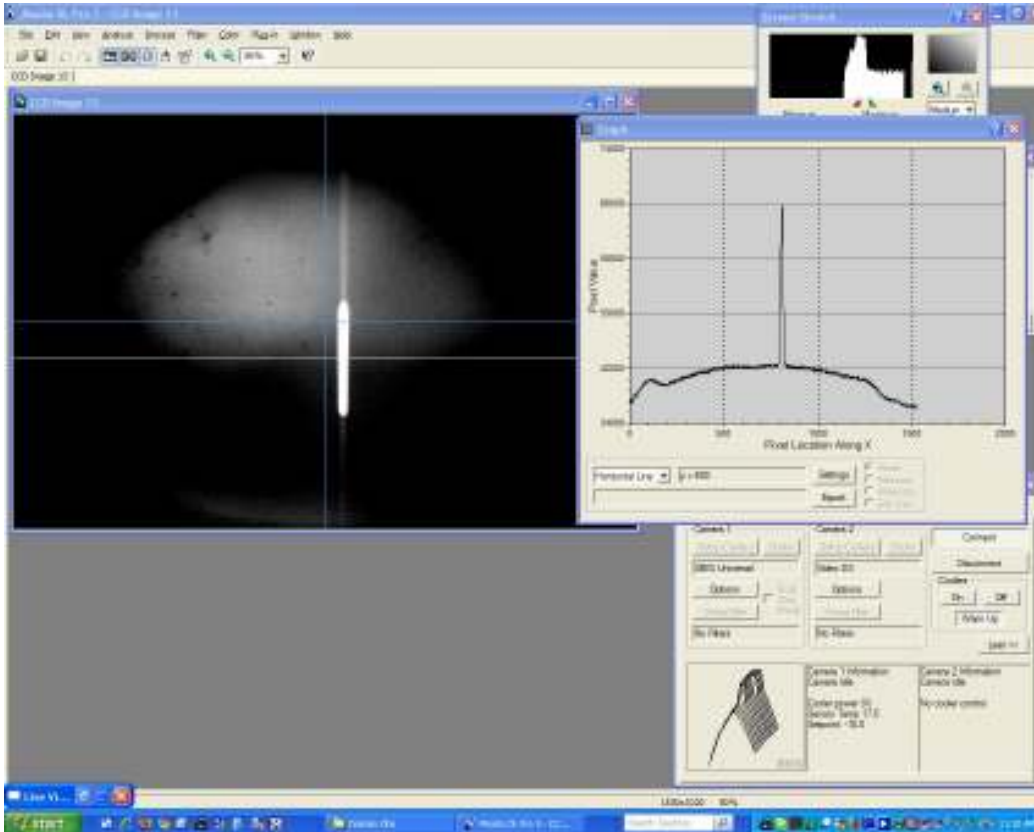
Check and adjust the camera position to bring the image close to mid frame. (This may require fine adjustment of your grating tilt angle or pick-off mirror (Littrow)).

Now vary the exposure to get a well exposed image of the slit (zero order) or a tight clean emission line. Overexposing the image will swamp the detail.

The image should show a bright vertical "band" – probably slightly out of focus. The next job is to make adjustments of the camera spacers to bring this image to best focus.

Trial and error. If you use T-thread adaptors, you can rotate them to see the impact (don't worry too much about the "tilt" angle – this can be corrected at the end.)

By the time you finish, the slit gap (zero order) should appear as a clean, crisp, tight bright line in the centre of the CCD chip. If you're using a bright emission line, then again this should appear regular, and the edges of the slit gap clean in sharp focus.



Digression.....

When you have achieved this good focus, close the slit gap (if adjustable) or change to the smallest slit gap setting. Check that the focus is still clean and tight.

Use your image processing software to show the profile across the slit image. You can then measure the FWHM (full width half max) of the slit image.

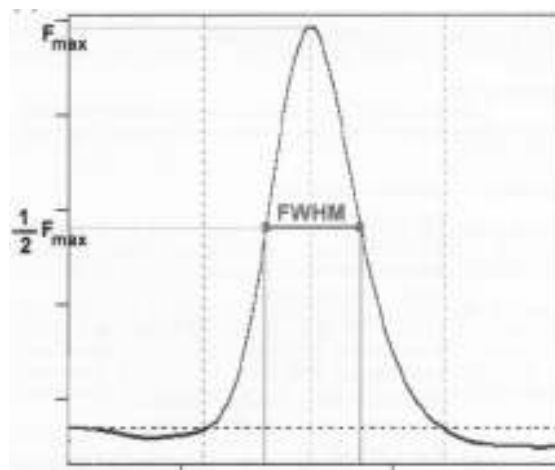


Diagram of FWHM

Just record the maximum intensity value, take 50% and measure the width in pixels at that point. The minimum usable width would be a FWHM of 2-3 pixel. Multiply our

reading by the size of the pixel (i.e. 6.45micron pixel) – this will give you the effective slit gap in microns.

(Note that this recorded gap size may not agree with the actual slit gap on the slit plate. The difference is caused by the design of the spectroscope – the collimator having a different focal length from the imaging lens e.g. Classical design or the various aberrations within the spectroscope optics. This can be demonstrated in SimSpec V4.)

Telescope			Spectrograph			Camera		
6	6	350 mm	6	6	250 mm	6	6	6.45 mic
7	7	3500 mm	7	7	250 mm	7	7	1360
8	8	F/D (F#)	8	8	10.0	8	8	54%
9	9	13.0	9	9	20.0	9	9	7 e-14
10	10	6.3	10	10	15 microns	10	10	8.1 e-14
11	11	6.92	11	11	15 microns	11	11	1
12	12		12	12	250 mm	12	12	4.75
13	13	31	13	13	250 mm	13	13	300 sec
14	14	6.75	14	14	21.7	14	14	12
15	15	15	15	15	8.4	15	15	3600 sec
16	16	63.57 microns	16	16	15 microns	16	16	
17	17		17	17	0	17	17	
18	18		18	18	20 microns	18	18	
19	19		19	19	1280	19	19	
20	20		20	20	1	20	20	
21	21		21	21	20.0	21	21	
22	22		22	22	21.5	22	22	
23	23		23	23	0.25	23	23	
24	24		24	24	6495	24	24	
25	25		25	25	1.17	25	25	
26	26		26	26	3.4	26	26	
27	27		27	27	6600	27	27	
28	28		28	28	6185	28	28	
29	29		29	29	6731	29	29	
30	30		30	30	336	30	30	
31	31		31	31		31	31	
32	32		32	32		32	32	
33	33		33	33		33	33	
34	34		34	34		34	34	
35	35		35	35		35	35	
36	36		36	36		36	36	
37	37		37	37		37	37	
38	38		38	38		38	38	
39	39		39	39		39	39	
40	40		40	40		40	40	
41	41		41	41		41	41	

Here we see the entrance slit width was 20 micron (G19), the camera pixel size set to 6.45micron (K6), and the resulting slit image was 30.57micron (C40). The end result being 50% greater than the physical slit width!

If the camera has been rotated to achieve focus (i.e when rotating T thread spacers) it needs to be reset back to the horizontal without changing the focus.



I find in the T thread configuration that the TS rotary adaptor #TST2We (above) works very well and only takes up 5.5mm of back focus. (<http://www.teleskop->

express.de/shop/index.php?manufacturers_id=39) this can be combined with an #TS-EOSs “zero length” T2 adaptor to save space when a DSLR is used.

(The inner section of the standard T2 adapter on the front of the DSLR body can be rotated by slightly loosening the three small grub screws (remember to retighten them when your finished!!))

Once we have achieved this good focus it will be fixed for that camera/ spectroscope combination. The only change will occur when we compensate for chromatic or field curvature variations.

2. Calibrate the grating rotation (if available)

In most high resolution spectroscopes the grating can be rotated on its axis to change the central wavelength recorded by the imaging camera. On some low resolution instruments the grating is fixed and is set to give as wide as possible spectral range to the camera. With a fixed grating the calibration of spectral pixel position to wavelength only requires analysis of the image width and will be constant for any combination of imaging lens and camera. Note; it is the convention in spectroscopy to present the spectrum with the blue region (shorter wavelengths) towards the left hand side of the image/ graph. This may require you to flip the camera image.

To accurately position the grating, the adjustment is done usually with a micrometer head. (The end of the micrometer shaft bears on the grating support and as the micrometer shaft moves it rotates the support and hence the grating. Depending on the mechanical arrangement, the total movement of the micrometer can be between 12 and 20mm)

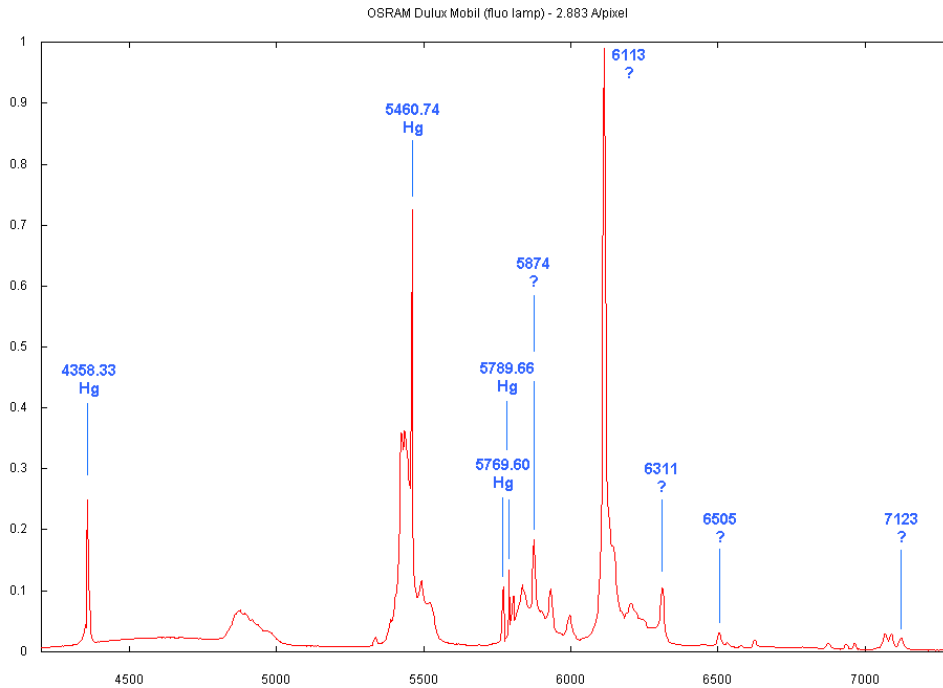
If you can set the micrometer to show the zero order image in mid frame of your CCD, this provides an ideal starting point. Move the grating to and fro each time recording the micrometer reading when the zero order is exactly on centre. These reading should obviously be the same. Note this reading for future reference.

As you move away from the zero image (adjusting the micrometer head inwards) you'll find initial a “gap” where there is no spectrum recorded; keep adjusting until a bright spectrum is found.

The first region to be seen will be the blue of the 1st order spectrum. This 1st order spectrum is the one we want to use. Further adjustment will take you further into the spectrum, the green, yellow and finally the red.

Calibration - reference lamp

We can start with an energy saving fluoro lamp (compact fluorescent light bulb)



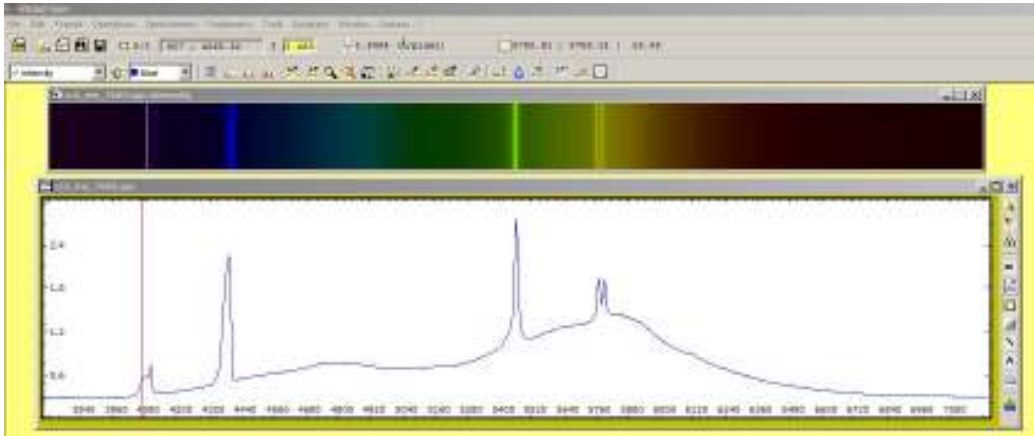
This annotated fluoro spectrum (Buil) is typical of the energy saving lamps. You see we have a few easy emission lines that can be used for calibration purposes.

Line Description	Ångstrom
Hg	4358.33
Hg	5460.74
Hg	569.60/ 5789.66
Red	6113

Set up the lamp as previously explained.

Set-up and confirm the focus of the imaging camera.

Carefully rotate the grating (adjusting the micrometer) until you can find a region of the spectrum you recognise. Move the grating to bring the first bright line (in the blue) onto centre frame – record the micrometer reading. Move up to the bright green line and again record the reading.



This is a typical screen dump of the green fluoro line positioned central to the CCD frame.

Repeat this for the yellow double. (depending on the grating resolution, these may appear clean pair of lines 10\AA apart. A neat visual guide to the resolution of your instrument.) Move up the spectrum to the brightest red line and measure again. Keep rotating the grating going until the red “bump” starts to fade. This is close to the end of the first order (and brightest) spectrum.

Then retrace your steps back through the red to the yellow, green and onto the blue recording the micrometer readings for each. Repeat this exercise a few times and average the individual readings.

These readings will form the basis of our instrument calibration curve. We will need to generate a new calibration curve when we change gratings or micrometer.

The reading can now be entered into a spreadsheet showing wavelength ν 's micrometer reading. We can also graph the results.

This now allows us to pre-set the micrometer to display any chosen centre wavelength on the CCD.

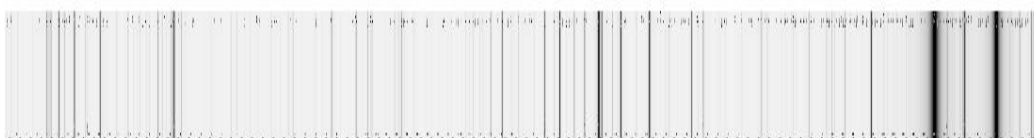
We can for instance set up a table of the readings for all the Balmer lines and accurately position them, as required, in the centre of our CCD.

Using an annotated solar spectrum we can do the same calibration, in more detail right across the visible spectrum.

Set the spectroscope up (with or without attachment to the telescope) and point the entrance towards the bright daytime sky. This will show the solar spectrum.

The highly detailed solar spectrum by Lunette Jean Rösch is highly recommended.

<http://ljr.bagn.obs-mip.fr/observing/spectrum/>

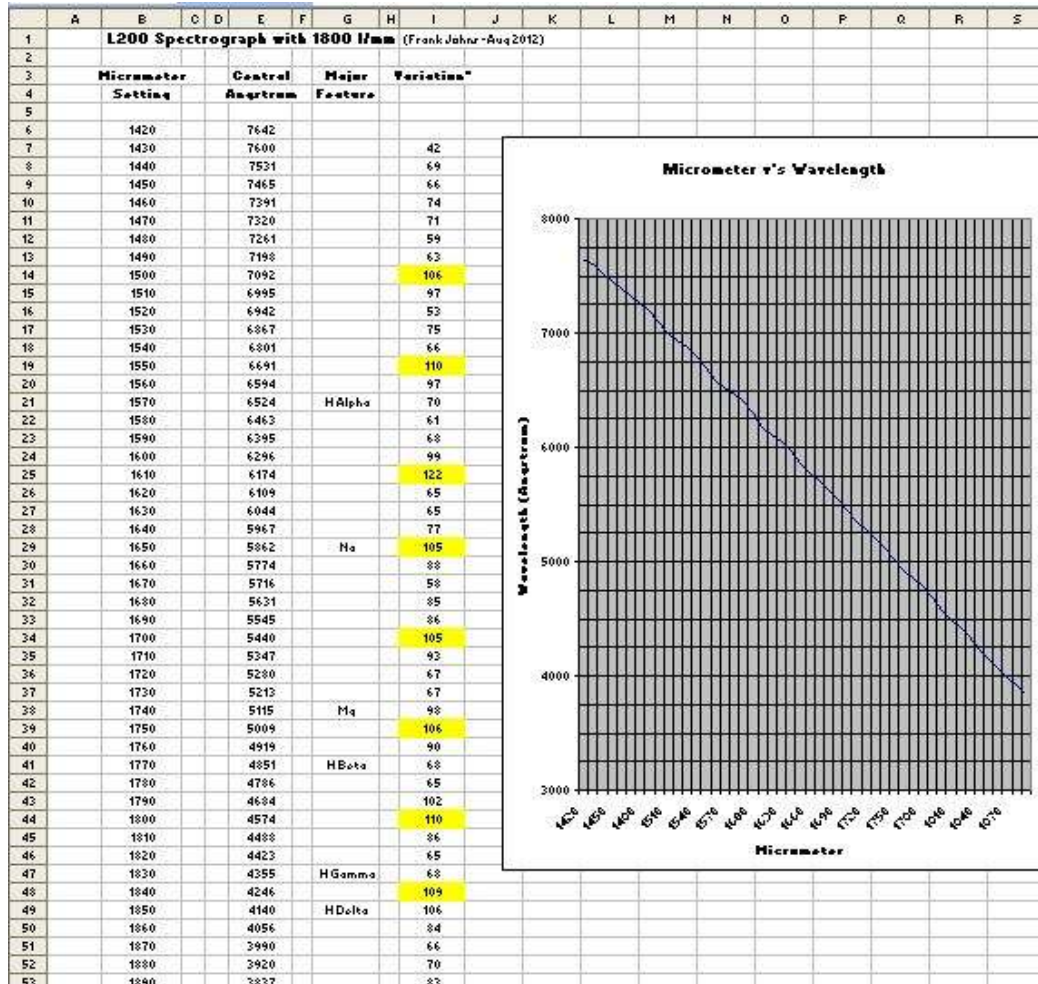


The above section shows the solar lines between 5800-5900 (Na doublet)

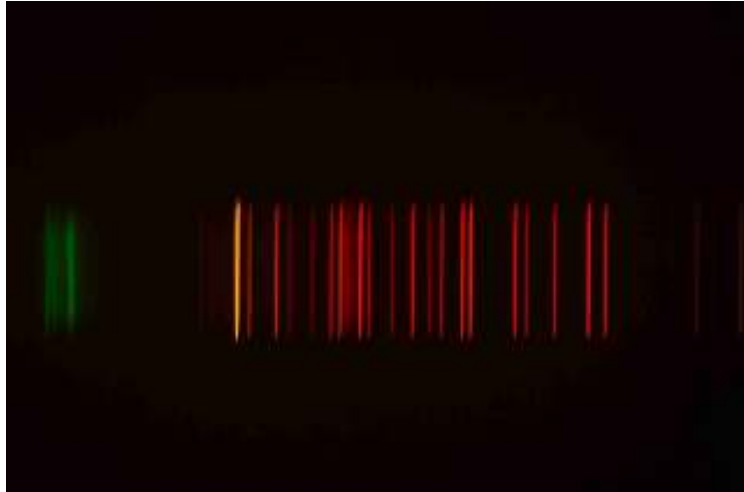
Even greater detail is given on the solar spectrum obtained on the BASS2000 website: http://bass2000.obspm.fr/solar_spect.php?step=1

The following illustration shows a typical micrometer calibration curve, based on a solar spectrum. (Thanks to Frank J.)

It is important to do this calibration and keep the results with the instrument. When you actually use the spectroscope at night on the telescope it will come in very, very handy.



We can also use a standard neon reference lamp. Some spectroscopes have these built in e.g Shelyak LhiresIII/ LISA, Spectra-L200. The illustration below shows the typical “neon forest” seen with a low resolution grating.



Neon forest- neon emission lines used for calibration

3. Focus the target (star) onto the entrance slit.

So far we've been able to do the focus and calibration set-ups in the comfort of the study / kitchen table or sitting outside enjoying the sun. Now we have to get serious.

NOTE: You will not succeed in focusing your target star on a narrow (20 micron or so) slit gap if your telescope and mount are not capable. The mount must be able to hold all the equipment in a good balanced condition and be able to be guided to "lock on" to the target star for at least 10-20 mins.

The telescope must be well collimated and the focuser robust enough to hold the weight of the spectroscop and camera(s) with NO sag or movement.

Look back at the CFZ section. The same tolerance applies to the target star focus onto the front of the slit.

The write up on AI's reticule ("Setting up AI.PDF" in the files area) gives some insight into the possible procedures you can use to get the target star onto the slit.

If you know, or can measure, the backfocus distance from the nosepiece adaptor to the entrance slit (usually around 55mm), you can first focus at this distance using an eyepiece on a suitable extension/ adaptor.

Start by using a bright star – they are easier to find (!) and give a bright zero order/ spectral image.

Using the zero order star image

With the spectroscop rigidly attached and the target star in or very close to the slit gap, set the grating to the zero order micrometer reading and bring the star image into the middle of the slit gap height. The closer the image is to the center of the slit height, the closer it is to the optical axis (and hopefully the centre of the CCD chip). Take an exposure to confirm the star is actually there. Drop the exposure time until the image is well exposed – not over-exposed. Use ONLY the focuser on the telescope. (Don't touch the imaging camera!) Bring the star image height in the slit gap down to the smallest height you can.

Take exposures after every adjustment.

Move the star image from one side of the slit (using the fine controls on your mount) to the other to ensure you are actually seeing the “central” core and not just one of the edges. Depending on the seeing conditions this size should be similar to the optimum entrance slit gap used. (Simspec V4 will allow you to do this quick calculation.) If the star size at focus (FWHM) is say, 50micron, then this would represent a height of $(50/6.45) = 8$ pixels – probably 10 pixels accounting for the aberrations etc. on the CCD.

This will be the height of the spectrum produced by your target star.

No zero order image

Similar to the above, but we are now relying on the minimal height of the star’s spectrum to guide us. The exposure required will obviously be much longer.

Again, move the star image from one side of the slit to the other to ensure you are actually seeing the “central” core and not just one of the edges.

Summary:

The success of your spectroscopic results will depend very much on the stability of the telescope/ mount/ spectroscope combination. This means in real terms that the spectroscope should be fitted and aligned (and well supported) and not moved on and off the telescope unnecessarily. (Many amateurs “dedicate” a telescope to their spectroscope work.)

Likewise moving the imaging camera on and off the spectroscope means checking and re-checking focus and alignment every time; it’s much easier in the longer term to have a dedicated camera for the spectroscope.

Getting precise focus of the target star on the entrance slit and the spectrum (or at least the region of interest) in the imaging camera, is a critical step in achieving maximum resolution and repeatability of results. Spend the time, get it right.

Slit spectroscopy isn’t easy. The challenges can be daunting at times. When it all comes together, the satisfaction of seeing your results makes up for all the effort.

Just remember –

“Astronomical Spectroscopy – the final frontier” –to boldly go where few amateurs have gone before!

Ken Harrison

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(Many thanks to the various Astronomical Spectroscopy group members who have contributed to this article. Errors are mine!)