AAVSO Guide to Getting Started in Spectroscopy

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Contents

1. Introduction

This guide is intended for those who are interested in getting started with astronomical spectroscopy and for observers who already have some experience with imaging. Our hope is to familiarize you with what is required to acquire and process spectroscopic data. The following sections will provide an overview of the equipment and software used to acquire and process astronomical spectra, describe the process for configuring and checkout of your equipment, and provide instruction on acquiring, processing, assessing quality, and submitting your spectra in the AAVSO AVSpec database. Excellent equipment-specific and software-specific resources are available elsewhere. For a comprehensive discussion of principles discussed in this guide, we strongly recommend the book “Successfully Starting in Astronomical Spectroscopy” by François Cochard.

It is important to note that submitting spectra into AVSpec does not require all the processing and calibration steps discussed here. After users have submitted an initial reference star spectrum for approval, subsequent spectra may be submitted to the database with minimal processing. The submission requirements are simply that the spectrum be dark-corrected, extracted into a one-dimensional spectrum, and wavelength calibrated. While many science applications require more thoroughly processed spectra, minimally processed spectra have scientific value and is the preferred option for submission into AVSpec.

The AAVSO encourages observers to get started with spectroscopy and with tools such as the spectroscopic processing and analysis software listed in Section 5. Fully processed spectra can be produced quickly and relatively easily with most of this software. More information on submitting to the database and a complete discussion of the technical requirements can be found at https://app.aavso.org/avspec/help

2. Acknowledgements

This Manual was written by Dr. Ryan Maderak, Benedictine College with contributions from Joe Daglen, Ken Hudson, and Dr. Stella Kafka, AAVSO Executive Director. We are grateful to Scott Donnell for valuable discussions and updates of this guide, leading to clarifications of the terminology used here.

3. Types of Spectrometers

Amateur spectrometers are of three general types: slitless, low-resolution, and high-resolution.

3.1. Slitless

A slitless spectrometer is the most basic, easiest, and least expensive way for amateurs to become involved in spectroscopy. With a spectroscopic grating filter such as the SA200 fitted to the front of a DSLR camera or placed in the filter wheel of your imaging telescope, you can obtain spectra of many of the brighter objects in the field of view like that obtained by an objective prism.

Full field spectra such as this can be used in a variety of observing programs including Be star searches, monitoring changes in spectral features of long period variable stars, and detecting and identifying elements in comets. More information on the type of projects you can engage in with a spectroscopic grating filter can be found at: https://www.rspec-astro.com/

3.2. Low Resolution

A low-resolution spectrometer typically has a slit and provides a full image of a spectrum from about 380 nm to 750 nm or more. A slit has the advantage of passing light only from a selected object and provides increased spectral detail while allowing the entire spectrum to be imaged.

The spectral profile produced by this type of instrument allows you, for example, to detect the presence and measure the abundances of elements in nebula, detect the presence of a circumstellar disk or shell, and observe changes to the spectrum of a nova or supernova over time. More information on projects you can engage in with a low-resolution spectrometer can be found at: https://www.aavso.org/spectroscopy-observing-section

3.3. High Resolution

A high-resolution spectrometer also has a slit and provides high detail over a narrow wavelength range centered on interesting features. These instruments allow you to measure speed toward or away from the observer, the rotation rate of a star, and changes in a circumstellar shell or disk that provides understanding into the physical process in these and many other interesting objects. More information on projects you can engage in with a high-resolution spectrometer can be found at: https://www.aavso.org/spectroscopy-observing-section

4. Equipment

4.1. Principles of Spectrographs

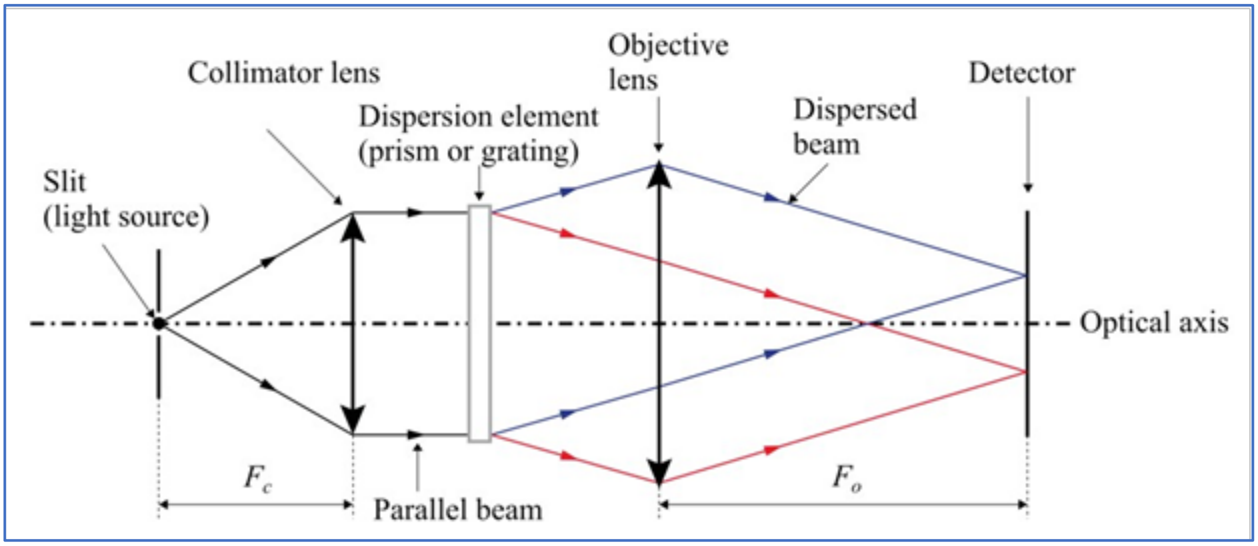

Figure 1- Diagram of a Spectrograph (courtesy of Francois Cochard)

4.1.1. Components of a Spectrograph

4.1.1.1. Slit

The slit acts as the light source for the imaging sensor. It restricts the angular size of the object/source and produces the initial dispersion through diffraction. The slit isolates the source, and the width of the slit determines the spectral resolution. In a fiber-fed spectrograph, the fiber acts as a slit.

4.1.1.2. Collimator

The collimator lens transforms the divergent light from the slit into a collimated (parallel) beam necessary for the dispersion element. Poor collimation will result in vignetting (loss of light from edges of the beam) which will reduce signal or even reduce wavelength coverage.

4.1.1.3. Dispersion Element

A prism disperses light due to the wavelength dependence of the index of refraction with blue light being dispersed at a greater angle than red. Prisms have the advantage of higher throughput than gratings but with much lower dispersion.

A diffraction grating is a glass plate with many finely ruled grooves - typically hundreds of lines per mm - each of which acts as a diffraction source. Interference between light from each groove increases resolution by making each wavelength “sharper”. In contrast to prisms, gratings disperse red light more than blue. Gratings also produce multiple diffraction orders that can be used. While the basic design described here a transmission grating is assumed, there are also reflection gratings that behave in much the same way.

4.1.1.4. Objective Lens

The objective lens focuses light from the dispersion element onto the detector. Poor focus will result in decreased spectral resolution (discussed immediately below), in much the same that a poor focus with an imager results in reduced spatial resolution.

4.1.2. Dispersion and Resolution

As alluded to above, there is a distinction between dispersion and resolution. *Dispersion* describes the extent to which the light is spread out, that is, by how much wavelengths are separated, and is usually stated in units of angstroms/pixel. *Resolution* describes the smallest spectral feature that can be clearly distinguished. Resolution is equal to the full width at half maximum (FWHM) of a "thin" spectral line. Resolution is often given in terms of the ratio of the wavelength to the resolved difference in wavelength and, for low resolution, is referred to a wavelength central to the wavelength range (e.g. R = 500 at $\lambda = 500$ nm).

$$R = \frac{\lambda}{\Delta\lambda}$$

Generally, R < 5000 is considered low resolution, 5000 < R < 10,000 is considered medium resolution, and R > 10,000 is considered high resolution.

As noted previously, resolution is determined in part by the size of the slit, and in part by the dispersing element. Slit spectrographs sometimes have slits of multiple sizes that can be selected or a vernier which allows adjustment of the slit size. But resolution is also influenced by the natural random processes affecting light as it passes through the telescope and spectrograph optics. These processes give spectral lines their Gaussian profile.

The resolution is typically determined from the FWHM of emission lines in wavelength calibration spectra (e.g., Neon or Argon lamp) which are very "thin." It can also be determined using the absorption lines of a slowly rotating star, such as the Sun. Spectral lines in stellar atmospheres are affected by other processes, but for "weak" lines in slowly rotating stars, the observed line width and shape is set by the instrument, not the star and can be used to determine the instrument's resolution.

It is also important to note that seeing conditions have no impact on spectral resolution. If seeing is poor, then less of the star's light passes through the slit, and so the spectrum will simply have less signal for a given exposure time. The light will be dispersed the same and the resolution will be unaffected.

4.1.3. Spectrum Orientation (Blue on Left – Red on Right)

The convention for astronomical spectrometry is to orient your equipment so that the 2D spectrum is oriented horizontally on your imaging sensor and with the blue end of the spectrum on the left. Your processed 1D profile will then also have shorter (blue) wavelengths to the left and the longer (red) wavelengths to the right. See Section 6 for details.

4.2. Equipment Considerations

4.2.1. Slit Size

The size of the slit contributes, along with the dispersing element, to the resolution of the spectrum, with narrower slits producing higher resolution and wider slits lower resolution. The width of the slit also determines the amount or light passing through and therefore the integration time of the image. It is important to attempt to match the slit width of the spectrometer to the seeing-average size of a star on the slit to maximize the throughput of the slit and produce images with the largest possible signal to noise ratio. The FWHM of a star image on the slit can be determined from:

$$FWHM(\mu m) = S(arcsec)\left(\frac{fl(mm)}{206265}\right)X1000$$

where S is the average seeing in arcseconds, fl is the telescope focal length in mm, and FWHM is the full width half maximum of the focused star image at the slit. For example, a telescope of focal length 1682 mm will produce a star image of FWHM 24.46 microns at the slit. For a spectrometer with a 23 micron slit, this would be a good match as most of the star's light is entering the slit and the integration time for acquiring the spectrum will be the shortest possible.

If the FWHM of the star at the slit is much larger than the slit, then less of the light of the star is passing through the slit and the image on the camera sensor is fainter and a longer integration time will be required to compensate. Possible actions to take to get the best match of the telescope focal length to the slit size are 1) Introduce a focal reducer or focal extender to modify the telescope focal length, 2) Use a different slit size if that option is available, or 3) Do nothing and accept the consequences of the mismatch between the star image size and the slit size. All of this assumes you are attempting to match an existing telescope's focal length to the spectrometer slit size. If you are planning on acquiring a telescope for your spectrometry, you then have the additional option of choosing a telescope with a native focal length close to that required to match the slit size.

Choosing either options 1 or 2 have their consequences as well. If you introduce a focal reducer or extender (Option 1) you also introduce the real possibility of introducing chromatic aberration that may affect instrument response. More on that in Section 7.4. If you choose a different slit size (Option 2) you will affect the resolution, with a larger slit producing lower resolution. You may need to experiment to find the option that works best for you.

4.2.2. Acquisition Camera

There are no special requirements for the CCD imager, so long as the pixel size is well matched to the resolution and the format is large enough for the wavelength range of the spectra. It is also helpful if the sensitivity is roughly uniform over optical wavelengths. In addition, the pixel size should be well-matched to the resolution - ideally 2 to 4 pixels per "resolution element," which in the case of spectra is the FWHM of a thin spectral line. For comparison, in the case of photometry, a resolution element is the FWHM of the star's seeing disk (but as noted above, seeing does not influence spectral resolution). To determine the number of pixels per resolution element in your spectra, simply divide the FWHM of a thin spectral line by the dispersion.

4.2.3. Guiding

This is perhaps the most challenging aspect of acquiring a spectrum, as the star must remain on the slit. This could in principle be accomplished with a standard off-axis guide camera, but instead you should guide on an image of the slit itself, and in fact need a camera in this position to center the star on the slit initially. Some spectrographs, such as the popular Shelyak Lhires III, have a reflective slit, allowing the slit to be directly imaged, and allowing guiding on the target star itself. Some guiding software, such as PHD2, provide for an overlay on the guiding image of a narrow rectangle aligned with the slit position – allowing the user to place a star on the slit even though the slit itself is not visible.

4.2.4. Flat Fielding

The principles of flat fielding for spectroscopy are discussed in Section 7.6.4. Spectrographs often have an internal flat field lamp (typically tungsten) which can be used for this purpose. The source only needs to be spatially uniform over the slit of the spectrograph. Spatial uniformity is not relevant for fiber-fed spectrographs, unless a second fiber is used to image the background sky spectrum, in which case it must be uniform over both.

4.2.5. Calibration Spectra

The principles of wavelength calibration of spectra are discussed in Section 8.5. Spectrographs often have an internal comparison spectrum lamp (typically Neon and/or Argon). The emission lines are identified, and their wavelengths entered, and a polynomial fit is applied to find the wavelength solution (assigning wavelength units to individual pixels of the CCD). Neon and Argon are usually used since those gases have a rich emission line spectrum in the optical. In general, you should use a lamp with as many spectral lines as possible to get a good wavelength solution.

4.2.6. Focal Reducers and Extenders

A focal reducer or extender is used to modify the focal length of the telescope to provide a sampling as close to ideal as possible. More about these is Section 7.4

5. Software

You will use software to acquire your images, to process your images, and to analyze your images. In addition to software for your guide camera, you will need software to control and organize the images obtained by your acquisition camera. Your acquisition software should provide the capability to obtain not only your spectral images, but also your bias, dark, flat, and wavelength images.

Your processing software should provide the capability to apply corrections from the bias, dark, and flat field frames, make geometrical corrections to the spectral image, stack the images, extract the spectral profile, and perform a wavelength calibration. Other capabilities, such as applying an instrument response curve, scaling the profile, and cropping the wavelength range are important features in a processing software.

Although the above is enough for submitting your spectra in AVSpec, you may want to explore your spectra in more detail through various analyses such as fitting a Plank temperature curve to a star's spectral profile, identifying spectral lines and measuring their characteristics, or determining a doppler shift.

Software developed for amateur spectroscopy typically provide many of these features in a single package. Some of the often-used software available are:

1. RSpec – Developed for users of the SA100 and SA200 spectroscopic grating filters. RSpec imports spectra taken with a user's camera control software or a video camera. Some analysis such as identification of spectral features and profile matching is supported.

2. Demetra – Acquisition and processing software developed by Shelyak for the Alpy 600 and Lisa spectrographs. Demetra provides the capability to manage the image types (bias, dark, image, etc.) as well as automate the processing steps. No analysis capability is provided.

3. BASSProject - A product of the British Astronomical Society Spectrometry group, BASSProject provides capability to perform processing and many type of analysis.

4. ISIS – Integrated Spectrographic Innovative Software (ISIS) is processing and analysis software developed by Christian Buil. It provides capability for the user to control the processing at a finer level.

6. Spectrometer Configuration and Checkout

When you first acquire your spectrometer it is suggested you familiarize yourself with its components and operation – and make a few initial adjustments in an environment such as a desk or worktable in your home or office during the daytime.

6.1. Orientation and Focus

One of the first things you will want to do is to adjust the orientation and focus between the spectrometer and the acquisition camera, and between the spectrometer and the guide camera.

6.1.1. Alignment of Acquisition Camera Relative to Spectrometer

This adjustment is nothing more than rotating the acquisition camera so that the image of a spectrum is aligned horizontally in the image frame (i.e along the image X axis) and with the blue end of the spectrum on the left and the red end of the spectrum on the right. The acquisition cameras are typically monochrome, so it is not immediately obvious which side of the spectrum is blue and which is red. One way to do this is to take an image of the solar spectrum (i.e. aim the spectrometer out a window during daytime) and note the position of the solar Calcium H and K lines. Another method is to use a piece of spectroscopic grating film to view the spectrum of an LED lamp. The prominent emission lines will show their colors allowing you to determine which end is blue and which is red on the monochrome image. The reason for performing this alignment is to minimize error in the image processing process where, for example, pixels are summed vertically in constructing the 1D profile. If the spectrum is not well aligned with the pixel grid of the camera sensor, then this summing will not work out well. The reason for having blue on the left and red on the right is because that is the standard and what the processing software expect. If you later discover you have red on the left and blue on the right, you can probably flip the image horizontally prior to processing, but better to verify the blue-left, red-right orientation during initial setup.

6.1.2. Focus Between Acquisition Camera and Spectrometer

Next up is adjusting the focus between the acquisition camera and the spectrometer. For some spectrometers this may be a one-time adjustment without any capability to adjust the focus when mounted on the telescope. Using the solar spectrum or an LED lamp, adjust the distance mounted on the telescope. Using the solar spectrum or an LED lamp, adjust the distance between the acquisition camera and the spectrometer until the finest lines are in sharp focus. Fine-tuning this focus can be achieved if your acquisition software provides a measurement of the FWHM of selected spectral lines – in which case you adjust focus to achieve the smallest possible FWHM.

6.1.3. Guiding Camera relative to Slit

If you have an off-axis guider attached to the spectrometer, now is a good time to adjust the focus and orientation. The goal is to achieve focus on the slit and orient the guide camera so that the image of the slit is vertical in the field of view (i.e along the Y axis). Focusing on the slit assures that when a star is in focus in the guide camera it is also focused on the slit. Aligning the slit in the vertical direction of the guide camera field of view is not strictly necessary but mimics the general orientation of the slit on the sky – that is – along the declination direction. More about slit orientation during image acquisition in Section 7.2.

6.2. Testing Using Solar Spectrum

With the acquisition camera in focus with the spectrometer and oriented properly, you are ready to test the spectrometer performance by imaging the solar spectrum. Simply point the spectrometer toward a window (but not directly at the Sun) and adjust the acquisition camera exposure time so the largest ADU value in the image is less than about 80-90% of the camera's maximum value. You should see a continuous spectrum rich with fine absorption features.

6.3. Checking Configuration on the Telescope

Next step is to attach the spectrometer assembly to your telescope and adjust focus and orientation. Initially align your telescope along the meridian so the right ascension axis aligns with the horizontal and the declination aligns with the vertical. Mount your spectrometer assembly so that motion in right ascension corresponds to motion along the image x axis and motion in declination corresponds to motion along the image y axis. This should put the slit vertical, or perpendicular to the horizon. An image from the acquisition camera should show a spectrum aligned along the camera frame x axis (and parallel to the horizon).

What remains is to adjust the focus of the telescope and test the autoguider. Place a star in the guide camera field of view and adjust the telescope focus to produce the sharpest image possible. Some guiding software have tools to assist with focusing, so use them if available. Finally, activate the autoguiding and make any adjustments to the software configuration to produce the corrections necessary to maintain the star on the slit. If all looks good at this point, then you are ready to acquire your first spectrum.

7. Image Acquisition

7.1. Focusing

Being desirable to get as much light as possible from the target object through the slit, it is essential to ensure the telescope is focused on the slit. This may seem obvious, but keep in mind that focus can change throughout an observing session through temperature changes, mirror shifts, and other factors - and these focus shifts can have a non-trivial and negative effect on subsequent flux calibration. So, take the time to focus before each target session. With the telescope aimed at an illuminated wall or screen (so you can see the slit) verify that the slit is well focused in the guide camera and adjust as necessary. This would also be a good time to add an overlay, if your guiding software provides it, to outline the position of the slit since you may not be able to see the slit when aimed at the night sky. Then point your telescope to your target object and center it in the guider field of view.

7.2. Slit Orientation and Position of Target on the Slit

This next step is often omitted but is important as atmospheric dispersion, also known as differential refraction, affects the quality of your flux calibration. Atmospheric dispersion is the wavelength-dependent refraction of light perpendicular to the horizon with blue being refracted more and red less. Through the atmosphere every star appears as a tiny spectrum with the blue end toward the zenith. If your slit is aligned with the horizontal and centered on the green part of the spectrum, you will lose some light in both the blue and red ends of the spectrum. If you make no adjustment to the slit orientation for the reference star, it will be aligned at a somewhat different angle with respect to the horizontal (since it is in a different part of the sky) and the amount of blue and red light passing though the slit will be proportionately different compared to the target. This is what affects the instrument response since the acquired spectrum is affected differently than the reference spectrum upon which the calibration is based with the result that the shape of the continuum of the target spectrum will not be correct.

Since atmospheric dispersion is perpendicular to the horizon and decreases with decreasing zenith angle, the remedy for this problem is to observe objects when possible near the meridian where the zenith angle is smallest and orient the slit, so it is perpendicular to the horizon. Orienting the slit in this way results in the dispersion being along the length of the slit instead of its width, allowing most or all the dispersed light to pass though the slit. A simple way to orient the slit to be perpendicular to the horizon is to attach a small bubble level, such as a mason's line level, to your spectrometer. Wherever the telescope is pointing, if the bubble is level, the slit is perpendicular to the horizon.

Finally, center the target star on the slit both horizontally and vertically. The reason for this centering is that you will want to place your reference star in the same position. If you do not, then the target star and reference star spectra will be at different Y axis positions in the acquisition camera image. This is fine if you are confident that your flat image is uniform, but if you are in doubt its best to align both spectra in the image – and that is done by placing both at the same horizontal position on the slit.

7.3. Instrument Response and Reference Stars

For each target object you will want to acquire the spectrum of a reference star for the purpose of correcting for instrument and atmospheric effects. Instrument response refers to those aspects of your instrument (telescope, spectrometer, camera) that affect the amount of light registered by the camera sensor as a function of wavelength. That certainly is one factor, but the conditions of the atmosphere at the time the spectrum was acquired is another, with wavelength and zenith angle dependent extinction being the principal component of the other. Changes in atmospheric conditions as well as changes in instrument focus can affect the amount of light registered by the detector at each wavelength, so it becomes necessary to obtain a sample of the atmosphere and instrument conditions by imaging a reference star whose spectral profile is known at around the same time as the target object was imaged, at about the same zenith angle, and under the same instrument conditions (i.e., focus and slit orientation).

Ideally, the spectrum of the reference star is one obtained from the Miles library of standard spectra, but if one is not available, the next best thing is a generic spectrum of the same spectral type and class from the Pickles library. Although you could use a known spectrum of your target object for the instrument response correction, in most cases you will not have a Miles library spectrum for your target object, so better to adopt a standard methodology of obtaining spectra of a reference star and use it for your flux calibration.

A useful tool for selecting a reference star near your target object is the Miles Search tool (an Excel file) and associated Miles list of reference stars that can be downloaded from:

http://quasar.teoth.it/html/varie/MILES_SEARCH_V1_4.zip

To ensure you have a good reference spectrum for your target object it is advised to obtain a spectrum of the reference star both prior to and after obtaining the spectrum of the target object. In this way it is possible to obtain an averaged response profile that reflects conditions near the midpoint of the target object acquisition sequence.

7.4. Effect of Focal Modifiers on Instrument Response

The effect of atmospheric dispersion and orientation of the slit was discussed in Section 7.2 and its effect on instrument response was described. A similar effect can occur with the use of focal modifiers, either reducers or extenders, because of the inherent dispersive effects of the glass the light is passing through. Adding a focal reducer or extender may be beneficial in terms of matching the size of the star image to the slit size, but at the potential cost of introducing chromatic aberration. Whether the chromatic aberration is transverse or longitudinal, or a combination to the two, the effect is similar to the effect of atmospheric dispersion with less red and blue light entering the slit compared to green. If the focus and slit orientation is the same for both reference star and target images, then the effect will be the same for both and the instrument response is more accurate.

The issue now is that to address atmospheric dispersion you rotate the camera for both the reference star image and target images to maintain the slit perpendicular to the horizon. But to address the issue of chromatic aberration you need to keep the slit orientation the same for the reference and target images. Seems hopeless, but there are things you can do to resolve this dilemma. First, if you are using a focal modifier you can determine how much, if any, chromatic aberration it is contributing. You can get some idea by selecting a star near the zenith where atmospheric dispersion is almost zero and obtain a few spectra while rotating the slit by 90 degrees relative to the focal reducer/extender to assess the amount of transverse chromatic aberrations, and a few more while adjusting the focus in or out to assess the longitudinal component. Differencing these spectra from one another should reveal whether chromatic aberrations is present and how much it affects the instrument response. If chromatic aberration is present and affects the instrument response, then one approach is to remove the focal modifying element and accept the larger star image on the slit and corresponding longer integration times and reduced signal to noise. Another way-forward is to maintain the slit orientation and focus for both reference star and target but being careful to select a reference star near the target, at approximately the same zenith angle, and as close to the meridian as possible which results in the slit orientation being approximately the same for both the target and the reference star. In this way you address the chromatic aberration from the focal modifying element while minimizing the effect of atmospheric dispersion in your instrument response for that target. Yet another option is to increase the size of the slit, but at the expense of decreased resolution. You must make the choice based on your equipment and observing goals.

7.5. Exposure Time and Number of Images

The next consideration in obtaining spectra for the target and reference images is the exposure time for individual images and the number of images to acquire for each. The exposure time for the individual images should be such that the maximum ADU is below the maximum ADU of the camera and typically below 80 or 90 percent. Multiple images when stacked has the effect of increasing the signal to noise ratio (SNR) of the final image which is necessary for confident detection of faint spectral features. Multiple images also provide a hedge against any one image being defective and unusable for any reason. But long exposure times and multiple images adds to the time elapsed between the reference and target images and increases the possibility of changes in focus and atmospheric conditions adversely affecting the instrument response. Your goal should be to obtain the quality of images required for your observing goals in the minimum amount of time.

If your reference star or target is bright and the exposure time is short to avoid saturation, there is the possibility that scintillation can produce an effect similar to atmospheric dispersion where the shape of the spectrum between exposures can be dramatically different. Here you want to take a number of separate images and combine them to average out this effect.

7.6. Acquiring Image and Wavelength Calibration Images

Once you have acquired images for your target and reference star, all that remains is to generate images that will be applied to the target and reference images to account for noise and image artifacts and to apply wavelength scaling to the image. All of the following image and wavelength calibration images should be obtained, if possible, at the same temperature as of the target and reference images.

7.6.1. Bias Images

Bias images are images taken with zero exposure time and provides a measure of the component of noise that is constant for images of any exposure time. Bias images are used when dark images are scaled to match the exposure time of the spectrum image. Every image has noise that has a component that is constant across all exposure times (bias current) and a component that varies with exposure time (dark current). To scale the dark current to match the science image exposure time you have to first remove the bias component, otherwise it would be scaled as well. If the dark Image exposure time is the same for the target, reference star, flat image and wavelength calibration image, then bias images are not needed. But you will find this often is not the case and will need to obtain a set of bias images. Obtain multiple bias images (10 – 30) to stack into a master bias image with increased SNR.

7.6.2. Dark Images

Dark images are taken with an exposure time at least as long as the longest exposure time for all your other images and preferably longer by 10 or 20 percent. This allows the dark images to be scaled downward to match exposure time for your other images as needed. It is not advisable to scale upward as this requires an extrapolation and can introduce error. As with the bias images, obtain multiple dark mages (10 – 30) to allow for stacking and creating a master dark frame. The number of images you obtain is up to you but keep in mind that the reduction in SNR of the master image is determined by the square root of the number of images stacked. Stacking 10 images increases SNR by a factor of 3.2, stacking 30 images increases SNR by 5.4, and stacking 100 images increases SNR by 10, so you must balance your desire for increased SNR with your patience in collecting the required number of images.

7.6.3. Bias and Dark Libraries

Taking bias and dark images for every imaging session takes time and if your imaging camera is temperature controlled you may want to consider building a library of bias and dark images. You can create a set of bias frames along with sets of dark frames at a single long exposure or a set of shorter exposures – all at specified temperature set points. These frames are then available for image calibration during subsequent observing sessions. It is advisable to refresh this library periodically to account for any changes in your camera's behavior as it ages.

7.6.4. Flat Images

A flat image is obtained when a uniform source of white light enters the slit. The resulting image is used to adjust for differences in response of the camera's sensor due to image variations introduced by the spectrometer optics and in the response threshold of individual pixels in the sensor. As with the bias and calibration images, it is advisable to obtain multiple images to form a master flat image. This is because these three types of images (bias, dark, and flat) are used to modify the target and reference star images, and each will add some noise in doing so. Using master frames formed from a stack of multiple images reduces the effect of this added noise.

If your spectrometer does not include a built-in or add-on component to generate flat images, you can generate them simply by allowing a source of white light to enter the telescope optics and subsequently thought the spectrometer slit to be recorded on the camera's sensor. This flat image is essentially a mapping of the response of the spectrometer and camera to a uniform illumination.

7.6.5. Wavelength Calibration Images

A wavelength calibration images is a spectrum obtained from a light source containing known absorption or emission features and used to assign a wavelength scale to the spectral profile. The position of identified features of known wavelengths in the calibration image is used to determine a mapping between image coordinates X position and the wavelengths of the features identified in the calibration image. This mapping is then applied to the target and reference star images to obtain the desired wavelength scaling. Features in the target image can subsequently be identified by their wavelengths.

A wavelength calibration image is not applied to the target images as are the bias, dark, and flat frames and so multiple wavelength calibration images are not needed. Further, if using a calibration lamp, it is not strictly necessary to ensure the maximum ADU of the calibration image stays below the maximum and it may be desirable to exceed the exposure time at which saturation occurs for some of the lines. One reason to do this is, for example, to increase the intensity of faint lines in the blue end of the spectrum at the expense of over-exposing a few bright lines at the red end. If there are enough unsaturated lines remaining in the red end, then the software performing the calibration should be able to exclude the saturated red lines and perform a good fit on the remaining lines in the spectrum. Another possibility is to take multiple calibration exposures and stack them to increase the SNR of the faint lines on the blue end. Experiment with both methods and find out which one works best for you.

7.7. General Imaging Sequence

The imaging sequence suggested here is intended to provide the best possible calibrated spectral profile of your target. Of course, you can choose an imaging sequence tailored to your unique circumstances or observing goal, but whatever you do be sure you understand the ramifications. The imaging sequence presented here is:

- Wavelength Calibration Image
- Reference Star Images
- Target Images
- Reference Star Images
- Wavelength Calibration Image
- Flat Images
- Bias and Dark Images (unless using a library)

7.7.1. Wavelength Calibration Image

Obtain a wavelength calibration image (or images) prior to the first reference star image and following the second reference star image. The reason is that temperature or mechanical (flexure) changes can affect the wavelength calibration image by displacing the position of the spectral features from the calibration lamp. Having wavelength calibration images before and after the reference and target images allows for a check of the quality of the wavelength calibration images.

7.7.2. Reference Star Images

Images of the reference star are obtained immediately before and immediately after the target images. Maintaining focus, slit orientation, and position of images on the slit is essential for successful instrument response. As with the wavelength calibration images, reference star images before and after the target images provides a check on the focus, slit orientation, and slit position. One can be discarded in favor of the other if hopelessly flawed, or they can be averaged to provide a reference star image representing conditions at the midpoint of the target sequence. If you are rotating your slit between reference and target images, be sure focus is not affected. A mechanical rotator ring that allows rotation of the spectrometer while ensuring focus can be used here.

7.7.3. Target Images

Next are images of your target object. It takes time to acquire your target images and the zenith angle of your target is constantly changing, with the resulting effect on your instrument response. When possible, image your target when near the meridian where its zenith angle is a minimum and changing the least amount over time. If this is not possible, set the slit orientation to be perpendicular to the horizon near the midpoint of your target acquisition sequence to minimize the effect of atmospheric dispersion. Acquire as many images as required for your desired SNR while keeping the individual exposures below the camera's maximum ADU.

7.7.4. Reference Star Images

If your target requires a long integration time where its zenith angle changes appreciably, you may want to consider a different reference star for this step. The first reference star should have a zenith angle approximately that of the target at the beginning of the target acquisition sequence and the second with a zenith angle approximately that of the target at the end of the target acquisition sequence. Even though they are different stars, the resulting instrument response curves should be very similar since you would be using their respective Miles or Pickles standard spectra for the reductions.

7.7.5. Wavelength Calibration Image

This is the second of the two wavelength calibration images providing a check for any changes in temperature or hardware positioning possibly affecting the position of the spectral features on the camera frame.

7.7.6. Flat Images

By the time you have reached this point it is probably late enough in the evening where the ambient temperature has stabilized. You can obtain a set of flat images with reasonable confidence that they will well represent the optical and sensor response characteristics and their subsequent application to your reference star and target images will not introduce error. And if you are using a lamp in front of the telescope or an illuminated screen, you may need to point the telescope toward the horizontal or toward its park position. Either way, unless you have another target, you are done for the night and can start closing the observatory or packing up gear while the flats are being taken.

7.7.7. Bias and Dark Images

At this point you have completed all your reference star, target, and flat images and now know the longest exposure time used for the previous images and can select an appropriate exposure time for your dark images. If you are not using a library of bias and darks, this time can be used to finish closing the observatory, pack up gear, and make final logbook entries.

8. Calibration Data and Procedures

While we do not intend to provide a tutorial on how to process data with any particular software, we will use the very popular ISIS software (written by Christian Buil) to provide examples and

context. The ISIS website provides thorough manuals for processing data for each of Shelyak's spectrograph models and are a recommended resource.
http://www.astrosurf.com/buil/isis/isis_en.htm

8.1. Introductory Notes

Spectroscopy requires the same basic calibration data as for photometry, but with a few important additions (e.g., wavelength calibration spectra). Also, some of the calibration steps, while similar in purpose to the analogous ones for photometry, must be handled different (e.g., flat fielding). We describe the calibration procedures here, and they are presented in order, but note that there are additional steps, and we will put all of this in the sequential context of the overall processing procedure in Section 8.

We reiterate that what follows are the data necessary to produce a fully processed spectrum, but this does not constitute the AVSpec database submission requirements. The only calibration data absolutely required are darks and a wavelength comparison spectrum.

8.2. Calibration Data Dependent Only on the Acquisition Camera

Calibrations dependent only on the acquisition camera include biases and darks. Only a single set is absolutely necessary (for each camera binning configuration) per session, even for multiple spectrograph configurations.

8.2.1. Bias Frames

Biases are a snapshot of the acquisition camera background level at zero exposure time to be subtracted from all images. Best practice is to acquire a substantial number (10-20 or more) and then take the median of them (pixel by pixel) to produce a master bias. If observations span many hours, consider taking a set at both the beginning and end of the night.

ISIS can be used to both produce a master bias image and apply the correction (see their manual for details). Alternatively, you could first produce the master bias image using another image utility, and then simply supply that file to ISIS.

8.2.2. Dark Frames

Darks are integrated exposures with the shutter closed. Due to thermal noise, extra electrons accumulate in each pixel and introduce electronic noise to the data - this is called dark current. is temperature dependent and can be minimized by cooling the camera sensor. Most CCD cameras have built in thermoelectric cooling that can cool the chip from 20 to 30 °C below ambient. It is recommended that the CCD be cooled to at least 0 °C, if feasible without requiring more than about 80-90 percent of the cooler's power to maintain it. In addition, there may be "hot pixels" that accumulate charge at a higher rate. It is important to note that these may or may not scale linearly with exposure time, and so are best removed by creating a hot pixel map, which can be done with ISIS.

There are two approaches to applying dark frames:

1. If you have a defined and limited set of exposure times, you can simply take several darks at each exposure time (at least 10) and make a "master" dark for each by median combining them. Then subtract the master dark from the corresponding images of the same exposure time. This eliminates the need for a separate bias correction.
2. If you have many different exposure times you can take several long-exposure darks and scale them to the exposure time of your images. To do this you, take several long (30 minutes or more) dark exposures, bias subtract them, scale to the appropriate exposure time, and add the master bias in. This scaled dark is then subtracted from the image frame to create a dark and bias corrected image. The reason the bias is subtracted and then added back in after scaling is that bias is a constant for all exposure times, so it must be removed before the dark image is scaled to maintain its constant contribution. This procedure assumes the dark current is scalable (linear) with exposure length.

As with master bias subtraction, ISIS can be used to both create the master dark (if you did not do this with another image utility) and apply the correction; ISIS can also scale darks. Note that ISIS can also create a hot pixel map.

8.3. Calibration Data Dependent on Spectrograph Configuration

A calibration set for each of these types will be necessary for each combination of grating/ wavelength region/dispersion used.

8.4. Flats

Flats are well-exposed spectra of a continuous (thermal) source. As with biases, the best practice is to acquire a substantial number (at least 10) and average them to produce a master.

As is the case for photometry, flats are used to correct for pixel-to-pixel variations in effective detector sensitivity. This is done by fitting a polynomial curve to the flat field spectrum in the dispersion direction, in each row, and then dividing the flat by the fit to produce a "normalized" flat. All other spectra can then be divided by this normalized flat. In this way, only the pixel-to-pixel variation is removed, rather than other components of the instrumental response. After this row-by-row correction is applied, the spectrum can then be summed up in the direction perpendicular to the dispersion (i.e., by wavelength; roughly the column direction, if the CCD is well aligned).

Flats should not be used to correct for the total instrument response (which depends on the CCD sensitivity as a function of wavelength, the grating, etc.), because that assumes a uniform flux across all wavelengths. The instrument response correction will be described below.

Once again, ISIS can both produce a master flat and apply the flat field correction; you do not need to produce a normalized flat - ISIS takes care of this for you.

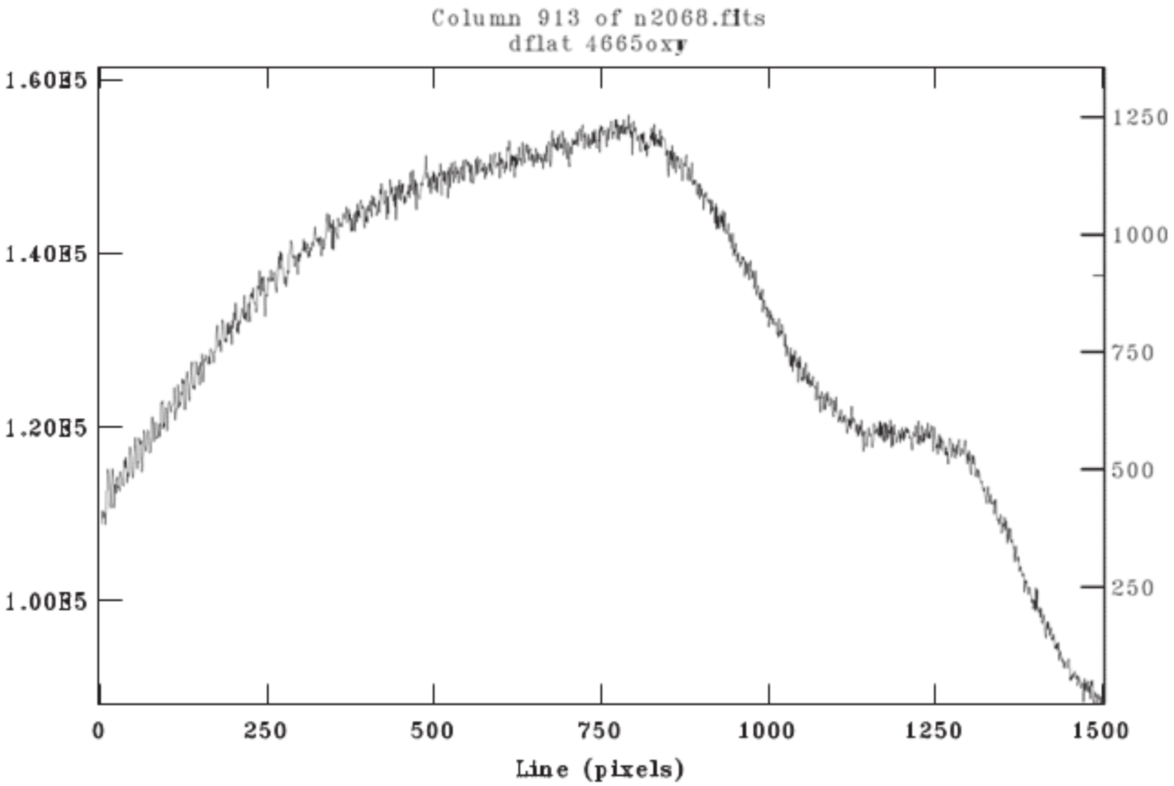

Figure 2- Plot along the dispersion direction, in a single row, for a raw flat-field spectrum, showing the pixel-to-pixel variation, as well as the overall and instrumental response. The spectral range is roughly 400 angstroms. To apply the flat field correction, a polynomial is first fit to this.

8.5. Wavelength Calibration

A spectrum of a source with known emission line wavelengths is used to find the wavelength scale (dispersion solution) for your spectra. Only one well exposed comparison spectrum is needed, but be careful not to overexpose and saturate strong lines, or else the line centers cannot be accurately determined.

The solar spectrum could be used if necessary. Simply take a spectrum of the daytime sky, which gives you the solar spectrum via scattered sunlight. Refer to a solar spectrum atlas for wavelengths of lines in the solar spectrum. Be careful to avoid using atmospheric absorption lines (aka telluric lines).

To apply the wavelength calibration in ISIS, you first supply an estimate of the dispersion and specify the order of the polynomial fit. The lowest order that fits the data well is best; even in the case where you have a large number (20 or more) of reliably identified comparison lines, a polynomial order greater than 5 – 6 is probably not appropriate. In the case where you have only a few lines, the order of the fit should be at least one degree less than the number of points (for example, for 3 lines, at most order 2 should be used). For identifying lines, it may be helpful to find a comparison line atlas (see for example http://iraf.noao.edu/specatlas/). But keep in mind that relative strengths of the emission lines depend in part on the specific lamp used, so pay attention to both the strength and the spacing of the lines. Note that ISIS also has some predefined calibration routines for specific Shelyak models and for specific wavelength ranges that greatly simplify the calibration process.

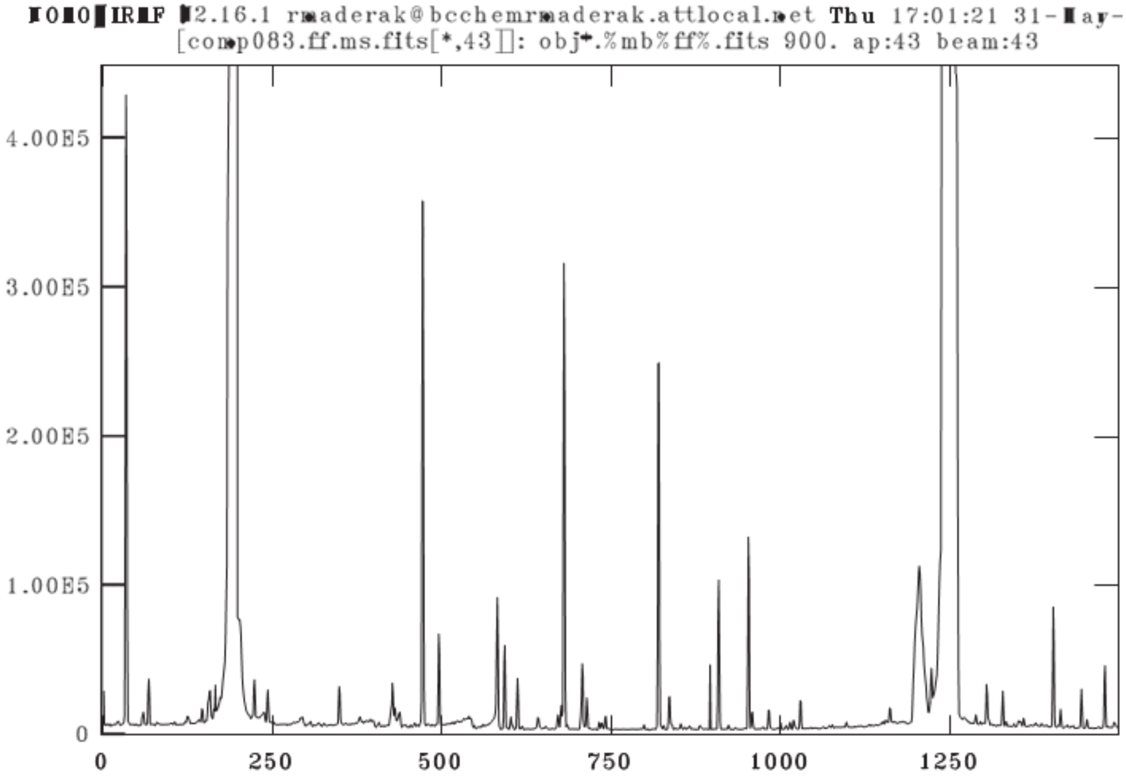

Figure 3- Plot along the dispersion direction for a comparison spectrum (Thorium-Argon lamp, near infrared, showing emission lines.

8.6. Sky Background

Spectra of the sky background should be acquired near each of your object spectra. The atmosphere produces various emission lines, and the sky might also contribute a scattered white light background, both of which should be subtracted out. For slit spectrographs, the portions of the slit not on a star image the background sky. This is ideal as the sky background from the slit can be subtracted without additional correction.

For slit spectra, ISIS performs sky subtraction by sampling then subtracting the sky background from user-defined intervals outside of the object spectrum. In the case of fiber fed spectrographs, you must either take a second spectrum of the same exposure length away from the star or use a second fiber to acquire a simultaneous sky (but note, if another fiber is used, you will need to apply a throughput correction to account for the different response of the two fibers). You would then simply treat the fiber(s) with the background sky exposure as if it were an additional object spectrum, then subtract it.

Note: for short exposures of bright objects, sky subtraction might not be absolutely necessary as the contribution is significant only for long exposures. Sky subtraction is important for long exposures and/or faint objects because the sky signal will be a substantial fraction of the object signal and the sky background is dependent on the observing conditions.

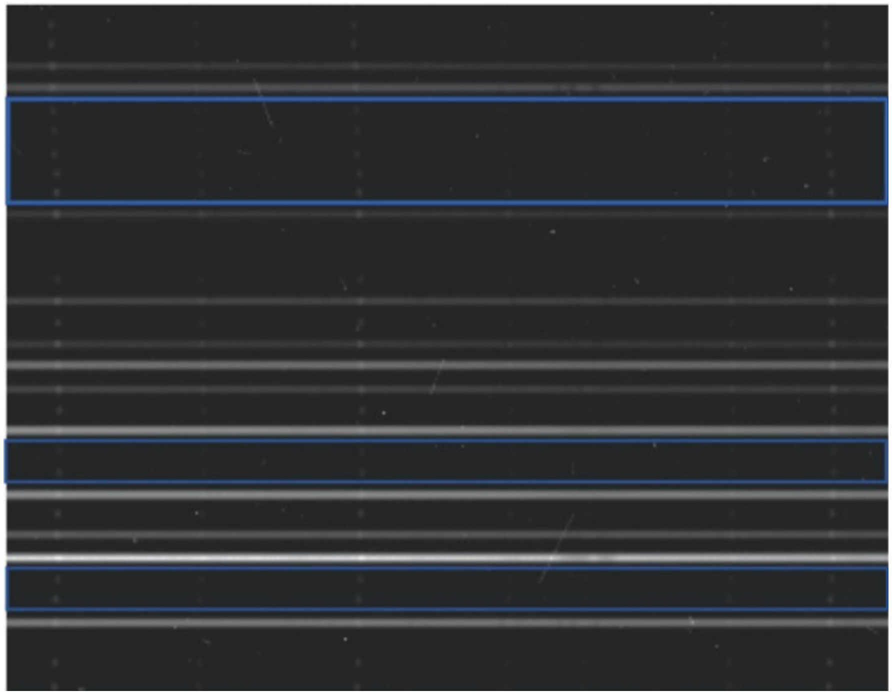

Figure 4- Raw multi-object fiber-fed image of an open star cluster, showing both object spectra and sky background spectra. Selected sky spectra are indicated by boxes. Note the bright sky emission line "dots" on both the sky background spectra and the brighter

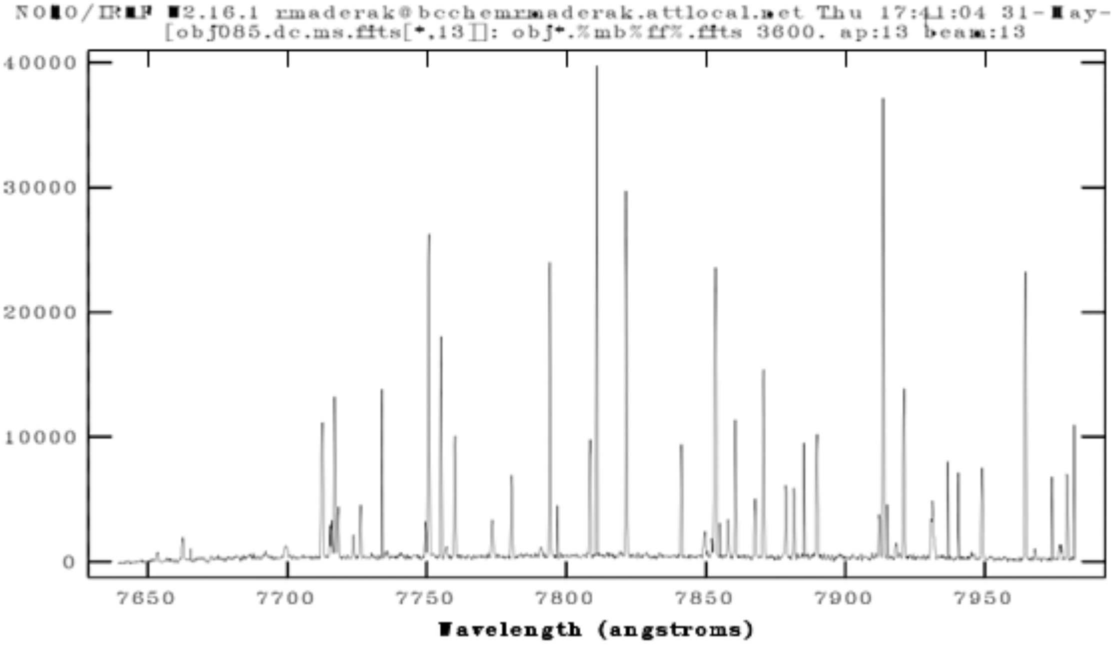

Figure 5- Sample sky background spectrum, showing sky emission lines

8.7. Instrument Response and Absolute Flux Calibration

Your telescope optics, detector, and spectrograph are each not uniformly sensitive to all wavelengths. This wavelength dependent variation in sensitivity is called spectral response or instrumental response and must be corrected for if your spectra are to be compared with others in a consistent, instrument independent way. For some stars, high quality reference spectra exist that have been carefully corrected for instrumental response and atmospheric extinction. These standards are usually very hot (early spectral types) because such stars have very few absorption lines. Dividing your spectrum by the reference spectrum (for the same star) will allow determination of your instrumental response, which can then be applied to other spectra. ISIS can both calculate the instrumental response, using a built-in library of reference spectra, and apply it automatically.

An important complication is that while the spectral response of your instrument system should be very stable, the spectral response of the atmosphere is not, and varies with airmass, humidity, etc. Observations of reference spectra should be taken with similar airmass to your target stars, and in principle should be taken every night, if not multiple times per night. In practice, except for more precise science applications, a reference spectrum taken at similar airmass is probably sufficient over multiple nights.

Absolute flux calibration is the process of converting the relative flux in your spectral profile into absolute units, such as ergs/cm2. To do this you would need to obtain spectra of flux calibration standard stars at the same airmasses (or in the same airmass range) as your target(s), on the same night, and under photometric conditions. This method is called spectrophotometry and is necessary for precise astrophysical applications, where the physical conditions of a target are to be determined such as temperature. Absolute flux calibration is not commonly performed even for professionally acquired spectra. Most spectra will use a relative intensity for the y-axis values. The AAVSO does not require absolute flux calibration for submission to the AVSpec database. An instrumental response in your processing steps is preferred but not required.

8.8. Additional Reference Data for Specific Science Objectives

8.8.1. Radial Velocity Standards

Spectra of stars with well-known radial velocities can be used to check your radial velocity scale, and if necessary, correct it. It is recommended that you acquire spectra of radial velocity standards if you intend to produce radial velocities on an absolute scale.

8.8.2. Solar Sky Spectrum

Because the atmosphere scatters sunlight, the solar spectrum can be acquired simply by taking a spectrum of a clear area of the daytime or twilight sky (all telluric absorption lines will of course be present). A solar spectrum can also be acquired by taking the spectrum of the Moon (reflected sunlight). If you intended to perform a spectroscopic chemical abundance analysis, then a solar spectrum is recommended, because solar abundances are often used as zero points for the abundance scale.

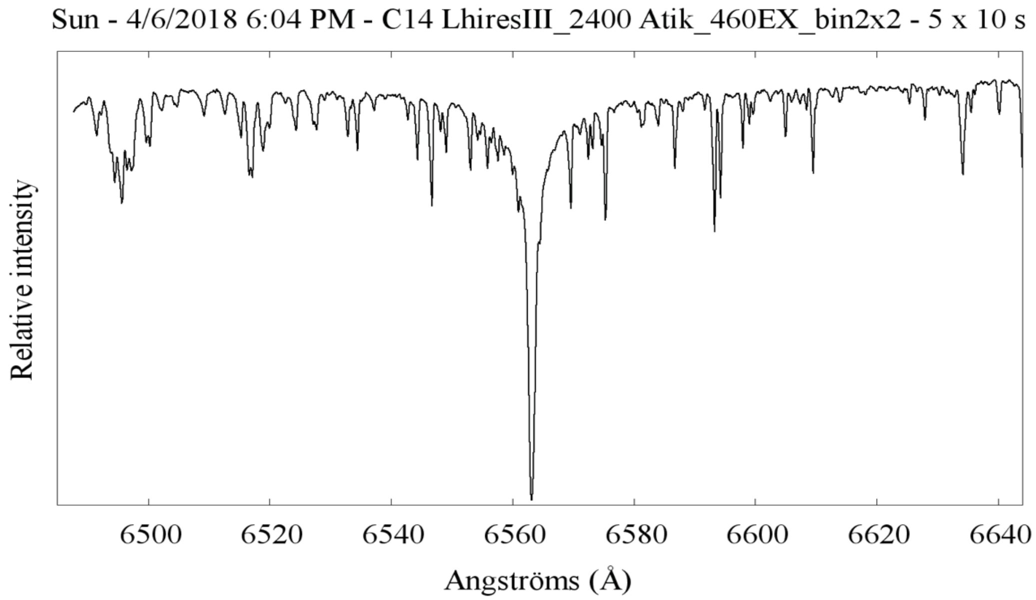

Figure 6- Sample daytime solar sky spectrum, in the Hα region

9. Image Processing

We will now give a sequential list of calibration and processing steps. Those steps already described in Section 8 will simply be listed - steps being introduced here will be described in detail.

Note that it is not advisable to co-add (stack) raw images, even if they were taken one after the other. Produce processed, wavelength calibrated spectra first, then co-add. However, a co-add of the raw spectra can be a useful “first look” to gauge data quality.

9.1. AVSpec Submission Requirements

As mentioned a few times previously, the only strict requirements for submission into AVSpec are that the spectrum has been dark subtracted (assuming that this has also removed the bias), and that it has been wavelength calibrated. Steps such as flat fielding are also strongly recommended but not required although for an end user’s purpose, an instrument response corrected spectrum with flat fielding applied is best.

9.2. Bias Subtraction

Normally performed as part of the dark subtraction process, this process step subtracts the constant bias component of the image prior to dark subtraction. This step is required only when scaling darks to match the exposure time of the target image.

9.3. Dark Subtraction

This process step removes the component of the target image signal attributed to the electronics of the imaging sensor. Dark frames are obtained to measure the amount of signal produced by the sensor for the same or longer exposure time than the target image and, if longer, scaled to match the exposure time of the target image.

9.4. Flat Fielding

Flat fielding accounts for the variations in the registering of photons in the imaging sensor due to the optic of the system, such as vignetting, as well as variation in the sensitivity of the imaging sensor as a function of pixel location. The flat field is produced by a uniform source of white light illuminating the slit and can be obtained from either a built-in flat lamp or by pointing the telescope at a source of diffused white light such as a screen.

9.5. Removing Hot Pixels

IF your processing software provides for it, removing hot pixels provides a cleaner image and reduces the possibility of introducing false spectral features into the final profile.

9.6. Aperture Tracing and Extraction

As was discussed above in the context of flat fielding, a raw spectrum spans at least several pixels in the direction perpendicular to the dispersion. This is called the aperture. These pixels must be defined and then summed into a single one-dimensional spectrum. Defining the pixels to sum over is called aperture tracing, and summation itself is called extraction.

ISIS traces the aperture by having the user select the row closest to the center of the aperture, and then measuring the slant angle between the actual aperture and that row. This can be thought of as a linear trace. The aperture is then extracted more-or-less automatically.

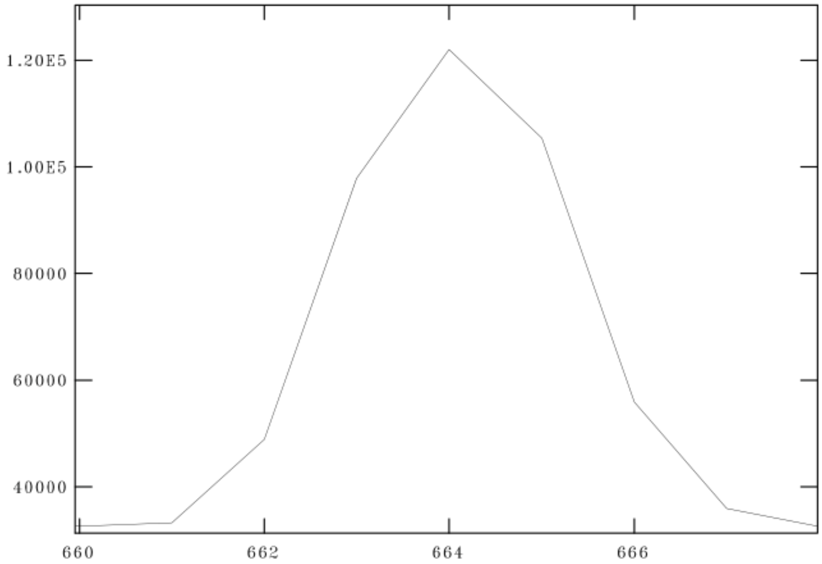

Figure 7- Plot perpendicular to the dispersion direction, showing the spectral aperture that must be summed over.

ISIS traces the aperture by having the user select the row or column closest to the center of the aperture, and then measuring the slant angle between the actual aperture and that row/column. This can be thought of as a linear trace. The aperture is then extracted more-or-less automatically.

In IRAF, aperture tracing is done by the routine appall, which uses polynomial traces (as always, the lowest order that gives a reasonable fit should be used). The routine apsum is then used to extract the spectrum.

9.7. Cosmic Ray Subtraction

Cosmic rays are familiar to anyone who has taken CCD data. They appear as bright dots or streaks in the image. ISIS can remove them as part of the aperture extraction process. There are a number of different routines in IRAF (including external user-written ones) that can be used.

Cosmic ray removal typically involves replacing the affected pixels with the average value from surrounding pixels. An important caveat is that this can leave the profiles of affected spectral lines distorted, which may be an important issue depending on the science that will be done with the spectrum. It might therefore be useful to retain a version of the processed spectrum with the cosmic rays left in, to refer to if you encounter any anomalies during data reduction and analysis.

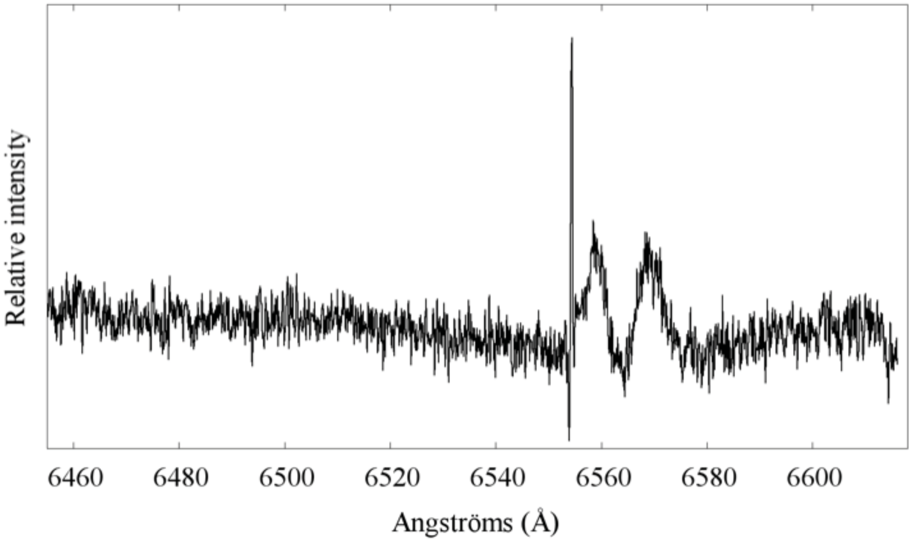

Figure 8- Spectrum showing a cosmic ray spike.

9.8. Wavelength solution (using comparison spectra)

TBS

9.9. Sky subtraction

TBS

9.10. Instrument Response; Continuum Normalization (Fitting or Scaling)

Instrumental response and absolute flux calibration were discussed in Section 8.7. The continuum is the “baseline” level of the spectrum, visible where there are no spectral lines. All of the methods discussed here involve “normalization” or “scaling” of the continuum, in order to produce a spectrum that can be compared to others. Unfortunately, the terms “normalized” and “scaled” are a source of much confusion to some, because they refer to similar but quite distinct concepts, and furthermore are not used in a perfectly consistent way by all spectroscopists. Particular confusion arises from the fact that professionals and amateurs use the terms somewhat differently.

Normalization often means “scaling” to amateurs, but often means “continuum fitting” to professionals.

Continuum fitting, sometimes called rectification (and what “normalization” typically means to professionals), involves fitting a polynomial to the continuum across the entire spectrum and then dividing by the fit to normalize the continuum level to 1 everywhere. One of the primary purposes of continuum fitting is if you want to measure the equivalent width of a spectral line, which is a measure of the total emission or absorption. It is also useful for automated comparisons of spectra. Note that a spectrum that is to be continuum fit does not necessarily require instrumental response correction first, because the instrumental response will be lost (which is convenient in one sense, but also means that information has been lost).

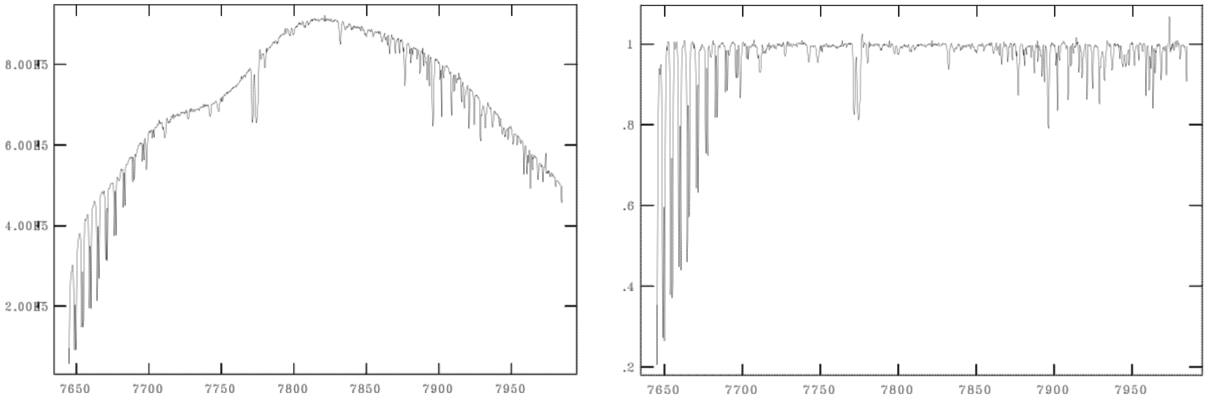

Figure 9- Comparison of a wavelength-calibrated spectrum before and after continuum fitting

Relative flux normalization, also called “scaling,” consists of dividing the entire spectrum by the average continuum value measured in a selected line-free wavelength range. The purpose is simply to reduce the potentially very large ADU values to smaller, more convenient units. In this case, the spectrum will be normalized to 1 (on average) only over the selected wavelength range (with values near 1 over the rest of the continuum).

For convenience, we summarize the various “normalization” terms and their meanings below:

1. Dividing the spectrum everywhere by a constant value = scaling = relative flux normalization = normalization as meant by most amateurs.

2. Fitting a polynominal to the continuum and dividing by it to produce a continuum value of 1 everywhere = continuum fitting = continuum normalization as meant by most professionals.

It is recommended that you adopt the terminology “Profile Scaling” or “Relative Flux Normalization” when referring to No. 1 above, and “Profile Normalization” or “Continuum Normalization” when referring to No. 2 above.

No normalization is necessary for spectra submitted to AVSpec, but observers may choose to scale their spectra. Continuum fitting is not recommended, and end users should be allowed to do this themselves if they desire.

9.11. Heliocentric Doppler Correction

The observed radial velocities of objects depend on the Earth's orbital and rotational motions. Therefore, observed radial velocities vary not only over the course of the year but also over the course of the night, and depend both on the coordinates of the object and the longitude and latitude of the observatory site. If we want to produce a radial velocity curve for an object, then we must correct for this, and place the radial velocity in the Sun's reference frame. But note that the calculation of this correction is non-trivial.

ISIS can automatically calculate the correction if the option is enabled, but a separate routine must be used if you wish to shift the spectrum. However, as matter of principle, if you are not the end user of your data, it is better not to apply this shift to the spectrum, and instead allow the end user to do so. We recommend that AAVSO users do not apply this shift to spectra to be submitted to AVSpec.

A convenient web utility for calculating the heliocentric correction can be found at:

http://as- troutils.astronomy.ohio-state.edu/exofast/barycorr.html

It is important to note that if you intend to co-add spectrum from very different observation times, then you must apply the helio-centric correction first. Also, it is recommended that should be done before any continuum fitting, normalization, or scaling has been applied.

10. Checking Quality and Assessing Problems

10.1. Raw Data Issues

The following issues occur during data acquisition and can usually be identified in real-time.

10.1.1.Saturation (and Non-Linearity)

As with photometry, saturation means irrecoverable loss in data accuracy. Indicators that your spectrum is compromised due to saturation or non-linearity include (but are not limited to):

- Emission lines with flat tops (they should be roughly Gaussian).
- Flattening of the spectral response (in a plot along the dispersion direction); this can usually be checked by comparison to rows away from the center of the aperture.
- Flattening of the aperture profile in the direction perpendicular to the dispersion (this should be roughly Gaussian).
- A perfectly uniform continuum - even a very high signal-to-noise spectrum should show some random variation (though you may have to zoom in to see it).

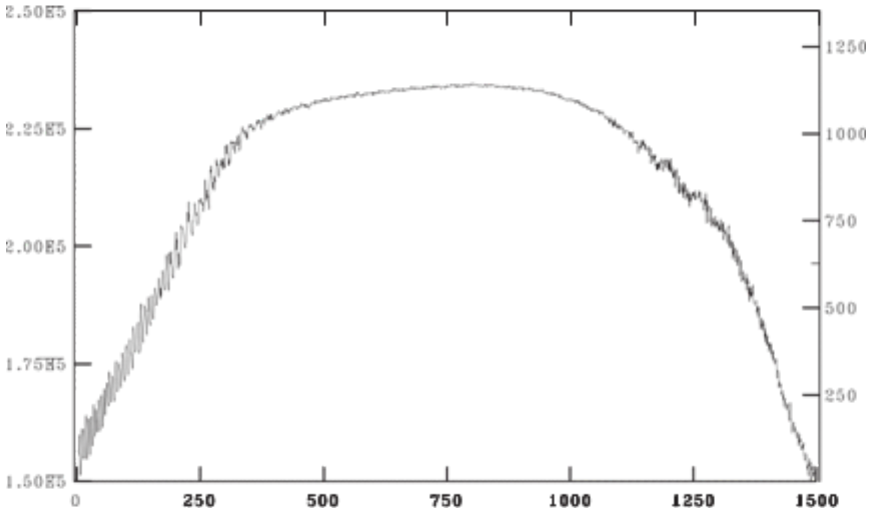

Figure 10- Plot in the dispersion direction for a raw flat field spectrum showing flattening of the spectral response due to saturation.

10.1.2.Under-Sampling

If your spectrum contains no substantial stellar spectral features, then you have probably (a) under-exposed; or (b) not centered, drifted off from, or missed your target.

(a) Under-exposure: at the bare minimum, your target is underexposed if the weakest spectral lines are not statistically distinguishable from the noise. There are rigorous criteria for this (for example, if the equivalent width of the line is less than about 3 times that of a typical noise feature), but practical indicators are that there are no spectral features that are clearly stronger than the largest noise features and/or that there are no spectral features that include the expected number of pixels for a "resolution element" (at least 2 – 4 pixels, as noted in Section 1).

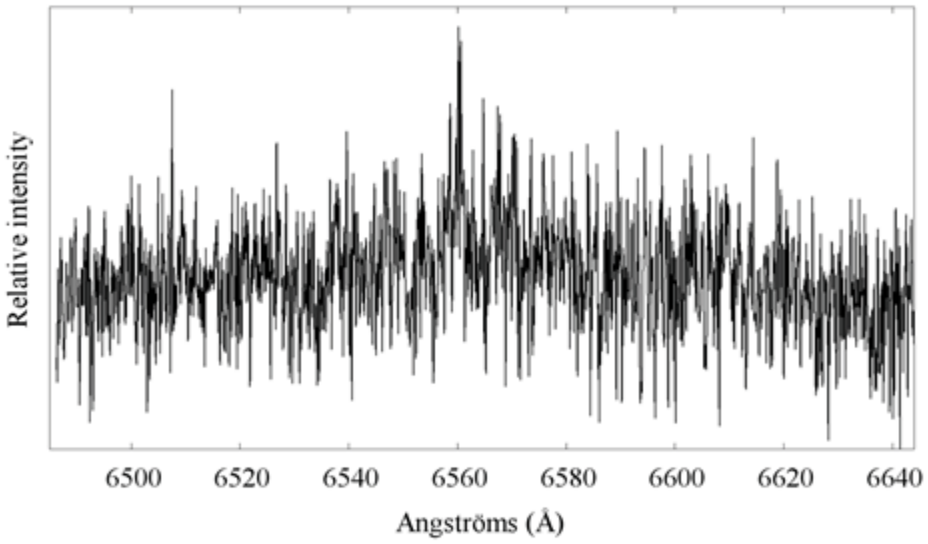

Figure 11- An underexposed spectrum, i.e. low signal-to-noise ratio.

(b) Off-center or Missed Target: This will result in sky emission lines being disproportionately strong compared to the stellar continuum. If telluric absorption lines (due to our atmosphere) are visible in the spectrum, this is an indication that some star/object light has been received (some telluric lines, such as the A and B bands due to O2, are strong enough to be seen even a low continuum exposure).

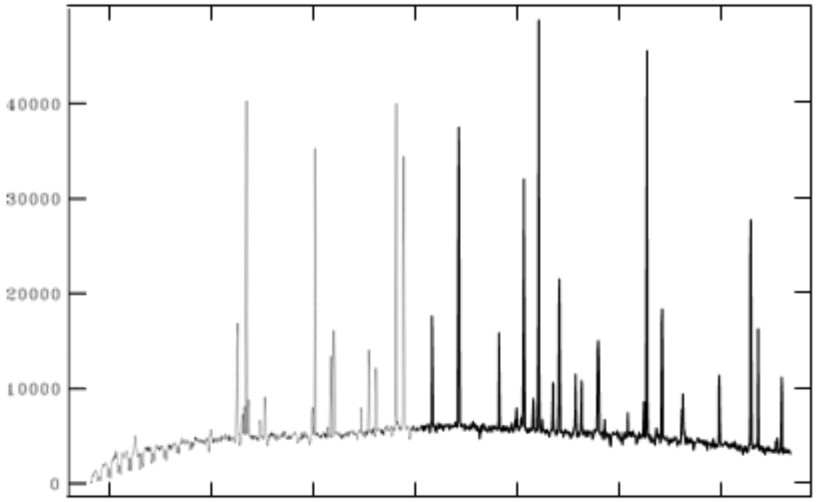

Figure 12- Spectrum in which the stellar continuum disproportionately dominated by sky background, indicating poor centering or a missed target.

10.1.3. Wrong Object

If you have not observed a target before, it may not be readily obvious that you have selected the wrong star. A helpful indicator when centering the star is whether it is as bright as stars of similar magnitude; this same indicator of course applies after you have acquired the spectrum if the continuum counts are much lower than expected (but see the above discussion of under- exposure) for a star of that magnitude. A more precise, but more difficult indicator is whether the star is of the correct spectral type. This can be gauged by comparing the spectrum to an appropriate template; broadly speaking, the absorption line strength of most elements increases with decreasing temperature, i.e., later spectral types.

For stars showing emission lines, such as spectral types Be or WR, the emission lines themselves provide an excellent indicator that you have the correct object. We also call attention to resources such as the BeSS database (for Be stars specifically), where users can easily compare their spectra to others for the same star.

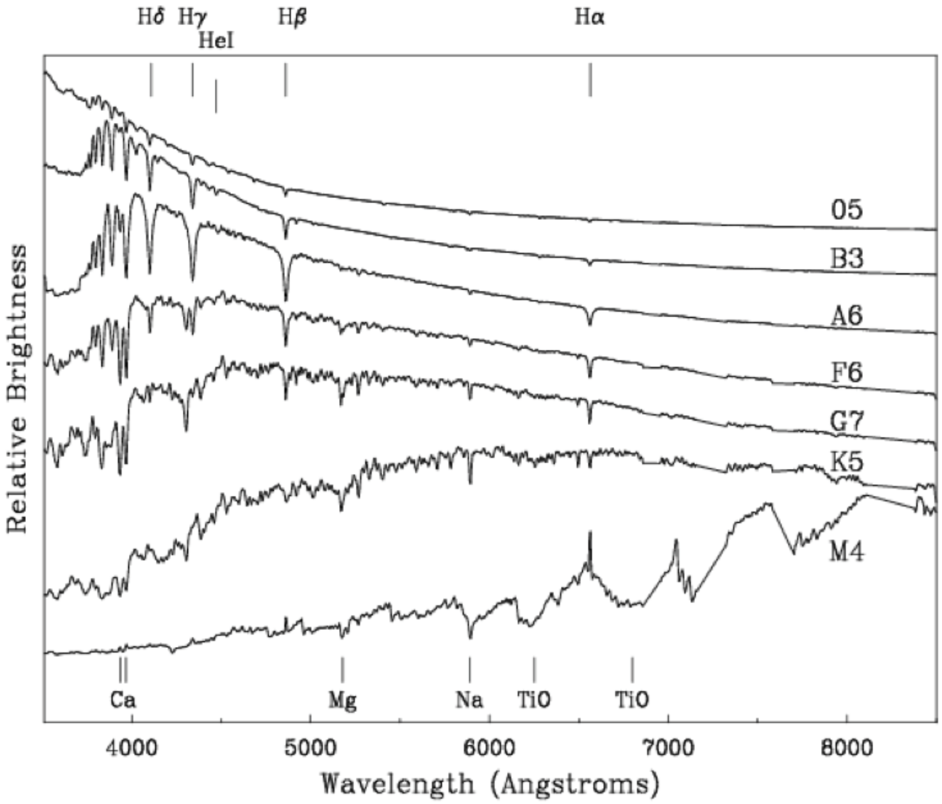

Figure 13- Sample stellar spectra. Note how the number and strength of absorption lines increase from O stars (hottest) to M stars (coolest).

10.2. Data Processing Issues

10.2.1. Poor Continuum Fitting

This occurs when the continuum has not been fit appropriately, and results in substantial variations in the normalized continuum level, which should be 1 everywhere if normalized in the professional understanding of the term. A properly fit continuum should be flat. Another possible manifestation of poor continuum fitting is that if the wings of very strong lines have been over-fit, then part of the line profile will be normalized out, which can be more difficult to recognize. Therefore, we advise the use of a low order polynomial for normalization. If the continuum has only been scaled, then the continuum will still show some variation.

Please note that not all stars should be normalized. Figure 13 showcases that from spectral type K5 and later, the stellar spectrum is dominated by molecular bands and should not be normalized. In this case, no continuum fitting for normalization should be applied.

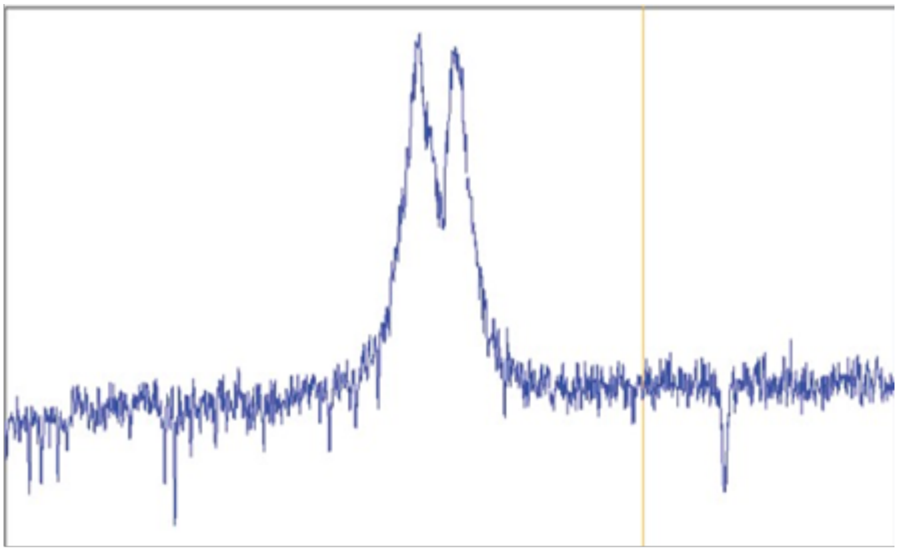

Figure 14- Spectrum showing imperfect continuum fitting. Note that while the continuum on the right (redward) side is relatively flat, the left slopes downward.

10.2.2.Poor Wavelength Solution

This can occur if there are too few comparison lines used, or if an inappropriate fit order is used. The result is a wavelength scale that is skewed or not very uniform over some parts of the spectrum (note that this is likely to affect only parts of the spectrum, portions without many comparison lines being most susceptible). This may not be readily obvious in the finished spectra. Good indicators are that (a) lines in one part of the spectrum give radial velocities that are systematically different from other parts, or (b) the FWHM of the lines being systematically different from other parts of the spectrum (though this would be an extreme case).

#1 and #2 are most likely due to poor normalization between the object and sky spectra, but could also result, for example, if using a fiber-fed spectrograph with a sky fiber that is too close to another star. #3 is simply a wavelength solution issue.

11. Submitting Your Spectra

You can submit your spectra into the AAVSO spectra database, AVSpec where it is available for viewing and download by other amateurs and professionals. To submit your spectra you must first submit a "test" spectrum of one of the stars on a list provided by the AAVSO. You would need to get an AAVSO observer code and register your observing site and equipment. Once you have acquired your spectrum of one of the list stars you reduce it to a 1D wavelength calibrated and scaled spectrum. For the initial "test" submission it is recommended you also normalize your spectrum – but you will not do this for subsequent submissions. This just makes it easier to evaluate your test spectrum.

A moderator will evaluate your test spectrum and notify you of any issues needing correction. Once you have submitted a spectrum that passes evaluation, you will be cleared to begin entering new spectra into the database. A quick guide can be found at:

https://www.aavso.org/sites/default/files/publications_files/aavso_spectra_quickguide-v1.0.pdf

After your initial test spectrum, subsequent spectra submitted into AVSpec will be of variable stars that are in both in VSX and have an AUID. It is also important that the Site Name and Equipment Name in the AVSpec equipment setup match the corresponding names in the FITS header for your observations. This is typically set in the software you are using to acquire your images.

12. Terminology Conventions

Many of the terms used throughout this document as well as in general use in the amateur spectroscopy community may not be consistently used or clearly understood – especially among beginning spectroscopists. Further, some terminology may be inconsistent with that used by professional astronomers. The following is intended to provide clarification and offer a recommended usage to be used throughout the amateur astronomical community.

Term	Definition
Dispersion	The extent to which the light is spread out, that is, by how much wavelengths are separated, and is usually stated in units of nanometers/pixel or angstroms/pixel.
Resolution	Also called Spectral Resolution, it describes the smallest spectral feature that can be clearly distinguished. It is equal to the full width at half maximum (FWHM) of a "thin" spectral line and denoted by $\Delta\lambda$.
Resolving Power	The ratio of wavelength to the resolved difference in wavelength, $\lambda/\Delta\lambda$ where $\Delta\lambda$ is the smallest difference that can be distinguished at a wavelength of λ. Denoted by $R = \lambda/\Delta\lambda$ at λ nm.
Low Resolution	$R < 5000$
Medium Resolution	$5000 < R < 10,000$
High Resolution	$R > 10,000$
Image Calibration	The application of bias, dark and flat field images to the spectral images to correct for optical and sensor characteristics (e.g., vignetting and sensor read noise)
Wavelength Calibration	The assignment of a wavelength scale to a spectral profile. It is obtained from a light source containing known absorption or emission features.
Profile Scaling	Dividing the spectrum everywhere by a constant value to reduce the Y axis values from large values to smaller values. The shape of the profile is preserved.
Profile Normalization	Fitting a low-order polynominal to the continuum and dividing by it to produce a continuum value of 1 everywhere. The profile shape is flattened.
Instrument Response	Correction of the spectrum for instrumental effects, such as QE of the camera and system optics and the Earth's atmosphere. This takes place by dividing the spectrum everywhere by a response curve derived from an observed reference star (e.g., from the Pickles/Miles catalogue).
Flux Calibration	The process of converting the relative flux in your spectral profile into absolute flux units, such as ergs/cm2.

13. Resources and References

AAVSO - https://www.aavso.org

BeSS - http://basebe.obspm.fr/basebe/

Comparison line atlas - http://iraf.noao.edu/specatlas/
IRAF - http://iraf.noao.edu
ISIS - http://www.astrosurf.com/buil/isis/isis_en.htm