

Relative Flux Calibration of Low Resolution Spectra ("Correcting for Instrument Response")

(Latest version at www.threehillsobservatory.co.uk/astro/spectroscopy_21.htm)

A note on terminology

Although commonly used by amateurs, the term "instrument response correction" is used incorrectly where a nearby reference star is used for flux calibration. I have therefore deliberately used the term (relative) flux calibration in place of instrument response correction.

Professionals use the term flux calibration to describe the process of calibrating the raw spectrum in flux units (which can be in absolute, ie in physical units or relative to that at a particular wavelength in the spectrum). As we will see, this includes much more than just the response of the instrument and if a flat is used with a slit spectrograph, the response of the spectrograph and camera play no part at all! I therefore recommend not using the term "instrument response correction" for this process but using the term "(Relative) Flux Calibration".

For information on how to convert spectra from relative to absolute flux using V magnitude photometry see the document "A method of calibrating spectra in absolute flux using V magnitudes" by David Boyd on the BAA spectroscopy resources webpage <https://britastro.org/node/19378>

The Problem

The overall shape of the raw wavelength calibrated spectrum straight from a spectrograph does not match that of the same object seen in databases, text books and publications.

The reason is the text book version is how the spectrum should look if taken with a perfect telescope and spectrograph outside our atmosphere, which is what we are trying to achieve. The light that forms our raw spectrum however has been subjected to a number of unwanted influences which we need to correct for to produce a spectrum calibrated in relative flux (ie the intensities at different wavelengths in the spectrum are correct relative to each other)

The Causes

Atmospheric Extinction

The atmosphere absorbs some of the light dependent on the wavelength (known as atmospheric extinction). More at the blue than the red end of the spectrum but also in specific regions, (the Telluric bands. Water vapour, Oxygen molecules and to a lesser extent Ozone are the main contributors to these.) How much light the atmosphere absorbs can vary from night to night dependent on atmospheric conditions and depends on how high in the sky the target is. Closer to the horizon we are looking through a greater thickness of atmosphere (A higher air mass)

Telescope Optics

The telescope optics (particularly the coatings) do not absorb/reflect all wavelengths equally. In particular most coatings are designed to for best efficiency at visible wavelengths and can significantly reduce the amount of light towards the UV end of the spectrum.

Spectrograph Slit (not applicable to slitless spectrographs)

To optimise resolution the slit width is normally chosen to be equal to the size (full width half maximum) of the star image. Most of the light then passes through the slit but there is some overspill. Ideally the spectrum of the light which is lost should be the same as that passing through the slit but there are two reasons why this might not be the case.

Chromatic aberrations in the telescope optics

If the telescope optics show chromatic aberration, not all wavelengths are in focus at the same point. This means the inner part of the star image will have a different spectrum to that of the outer part (The effect of this is seen visually for example as violet halos around stars or in images as bloated stars from out of focus Infra-Red light). Fully reflecting telescope optics do not have this problem so are preferred for spectroscopy.

Atmospheric dispersion

The atmosphere acts as a prism and refracts the star image into a tiny vertical spectrum relative to the horizon. This is not a problem provided the slit is along the direction of the dispersion (the parallactic angle). If for example in the extreme case the slit is parallel to the horizon though, the slit will selectively sample certain wavelengths, distorting the shape of the spectrum. This effect becomes more severe the nearer the target is to the horizon. (Note the effect of the atmosphere also changes very rapidly due to scintillation (twinkling) so the total exposure time should be long enough to average out this variation.)

The combination of these effects can give significant problems with slit spectrographs, particularly when trying to produce accurately corrected spectra of targets at low altitude.

(Note that chromatism has no effect on the response of slitless spectrographs but can reduce resolution due to the larger, distorted star image and can distort the wavelength calibration, as a proportion of the dispersion due to atmospheric refraction is added to the grating dispersion)

Spectrograph optics

The effects of the spectrograph optics are similar to those seen in the telescope optics and includes all the lenses and mirrors in the spectrograph including the cover glass on the camera and sensor and any coatings. We do not need to worry about any effect on the response due to chromatic aberrations in the optics after the slit, though these will affect the resolution.

The grating

Diffraction gratings do not reflect/transmit all wavelengths equally. This contributes significantly to the overall response of the spectrograph. With gratings that are blazed, this is done deliberately to increase the efficiency in a particular wavelength region.

The camera sensor

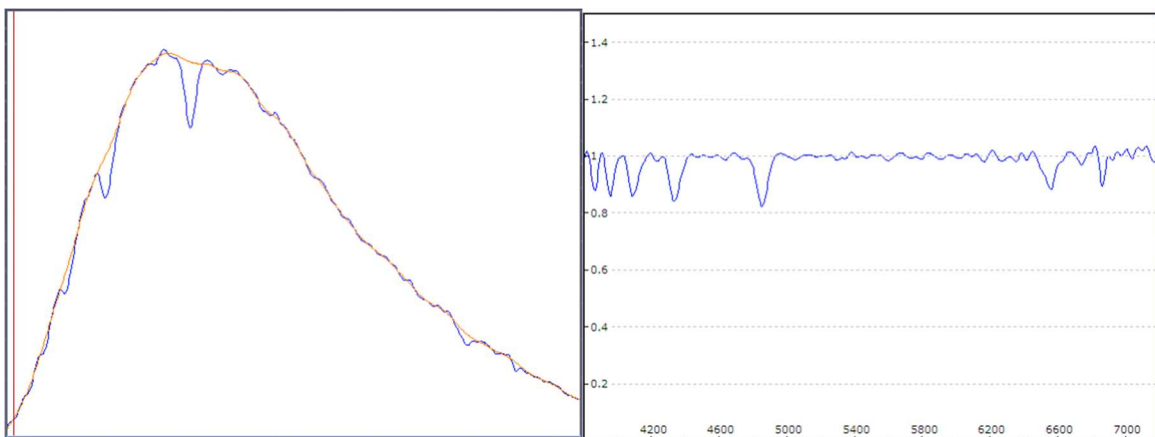
The spectral response of the camera sensor is another major contributor to the spectrograph response. It is unique to each type of sensor and has an overall shape broad shape, often with smaller scale ripples superimposed on it. Colour sensors in particular can have large humps and dips where the response of the colour filters overlap so are best avoided for precision spectroscopy.

Field effects

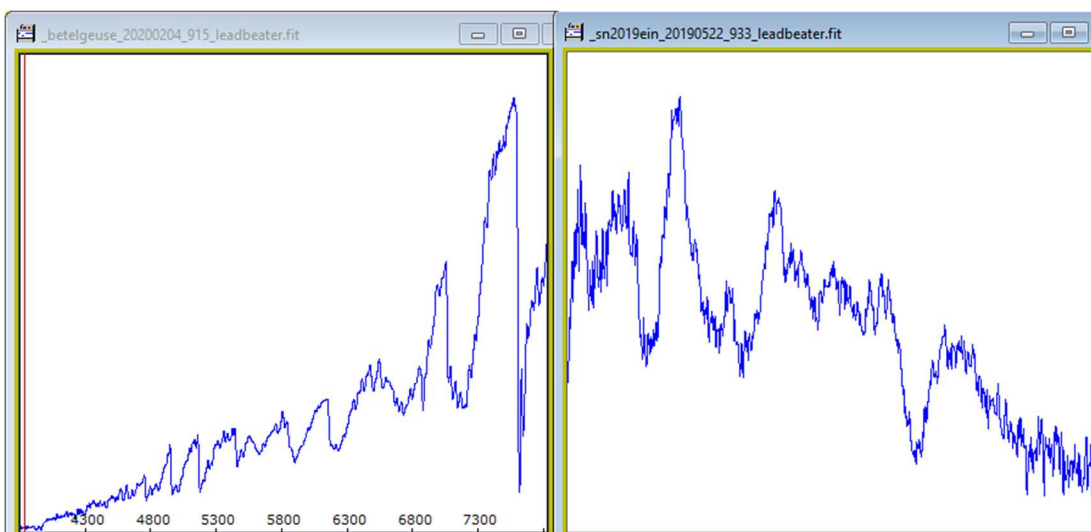
Because the spectrum extends across the camera field, any variations in sensitivity across the field (caused for example by vignetting and dust in the spectrograph optics or pixel to pixel sensitivity variations) will appear in the spectrum. With slit spectrographs these can be removed using a flat field. Conventional flats do not work for slitless systems however so different tactics are need in this case.

Rectification (normalising the continuum)

One option is not to correct for these effects but instead just remove the continuum by dividing the raw spectrum by the continuum (The broad underlying shape of the spectrum without the lines), levelling it so just the absorption and emission lines appear relative to a level datum equal to 1. This has the advantage of simplicity and can be sufficient for some purposes dependent on what the spectrum is going to be used for. It can be impossible to do this reliably where the continuum is not clear, for example due to blending of lines in low resolution spectra. There is also useful information in the continuum and the relative strength of emission lines in particular is lost with this procedure so it is better if possible, to calibrate the spectrum at least in relative flux.



A rectified spectrum can be produced where there is clear continuum as here for a hot star



But not for these spectra where the continuum is not clear (left a cool star, right a supernova)

Flux Calibration - outline

At first glance correcting for all these effects looks a daunting task. Fortunately, professional astronomers have already done the hard work for us by producing reliably calibrated spectra of a number of stars. By measuring one of these stars with exactly the same equipment and under the same conditions as our target and comparing the result with the published version we can correct for all these effects in one measurement. (Photometrists will be familiar with this technique, using nearby comparison stars to measure the magnitudes of other stars.) The outline procedure is therefore:-

Record a spectrum of a star with a reliable known published spectrum (The reference star)

Divide this measured spectrum by the published spectrum for that star to produce the “response” (Note this includes the effect on the spectrum of everything listed above including the atmosphere, not just the spectrograph)

Record the spectrum of the target under the same conditions and divide it by the “response” to produce the corrected spectrum of the target, now calibrated in relative flux

Before going into more detail though, a small diversion to discuss flats.

Flats

Slit spectrographs

Astrophotographers will be familiar with using flats to correct images for defects like dust, vignetting etc. A spectrographic flat performs the same functions but it also contains a wavelength dependent component. (A flat image taken using a lamp before the spectrograph slit is effectively like taking the spectrum of the flat lamp.) This is actually an advantage as the flat correction then compensates for the spectral response of all of the components after the lamp, including the grating and the camera sensor (and the telescope optics if the flat lamp is placed in front of the telescope), replacing them in the response with the flat lamp spectrum. For a halogen lamp this is a smooth curve which is easier to deal with compared with the smaller scale variations in camera response for example.

Slitless spectrographs

Unfortunately, this does not work for slitless systems as each point in the flat produces its own spectrum so the flat image is a mix of spectral and positional effects which are very difficult to disentangle. For this reason, flat correction is not used for slitless spectra. The best we can do to avoid problems with flat defects is to keep the optics clean and place the spectrum of both the reference and target stars away from any obvious defects and in the same location in the camera field so that any flat field defects cancel after correcting for response. See this document for further information on avoiding flat field problems with slitless systems like the Star Analyser

http://www.threehillsobservatory.co.uk/astro/SA_flat_field_notes.pdf

The flux calibration procedure

Choice of reference star

The reference star should be a hot star (A or B) as they have few lines in the continuum and preferably main sequence (luminosity class v) as they tend to be non-variable. It should preferably

have a known reliable published spectrum. Alternatively it can be a star with a known reliable spectral classification and low interstellar extinction (caused by interstellar dust between us and the target which tends to redden the spectrum) ie $E(B-V)$ should be ~ 0 . In this case a typical spectrum of that spectral class, such as one from the Pickles library is used as the reference spectrum. For best accuracy and certainly if the target is low in the sky, the reference star should be chosen so it can be measured close to the same altitude as the target, preferably in the same part of the sky and close in time so the atmospheric extinction is the same.

A good tool for finding suitable reference stars is Francois Teyssier's "Reference Star Finder" spreadsheet, downloadable here

<http://www.astronomie-amateur.fr/ProjetsSpectro0.html>

Entering the observatory location, time and target coordinates produces a list of potential reference stars of either known spectral type and low interstellar extinction or with professionally measured spectra available from the MILES library of measured stars.

The MILES library of stars is a good source of stars with measured spectra for low resolution spectroscopy. These can be found in a spreadsheet from Paolo Berardi (use the non-de-reddened version of the spectra as this is as the star appears to us including any interstellar extinction)

<http://www.spectro-aras.com/forum/viewtopic.php?f=8&t=941&start=10>

Acquisition

The spectrograph should be aligned so the spectrum is as close as horizontal in the camera field as possible. (For slit spectrographs, the calibration lamp lines should then be approximately vertical.)

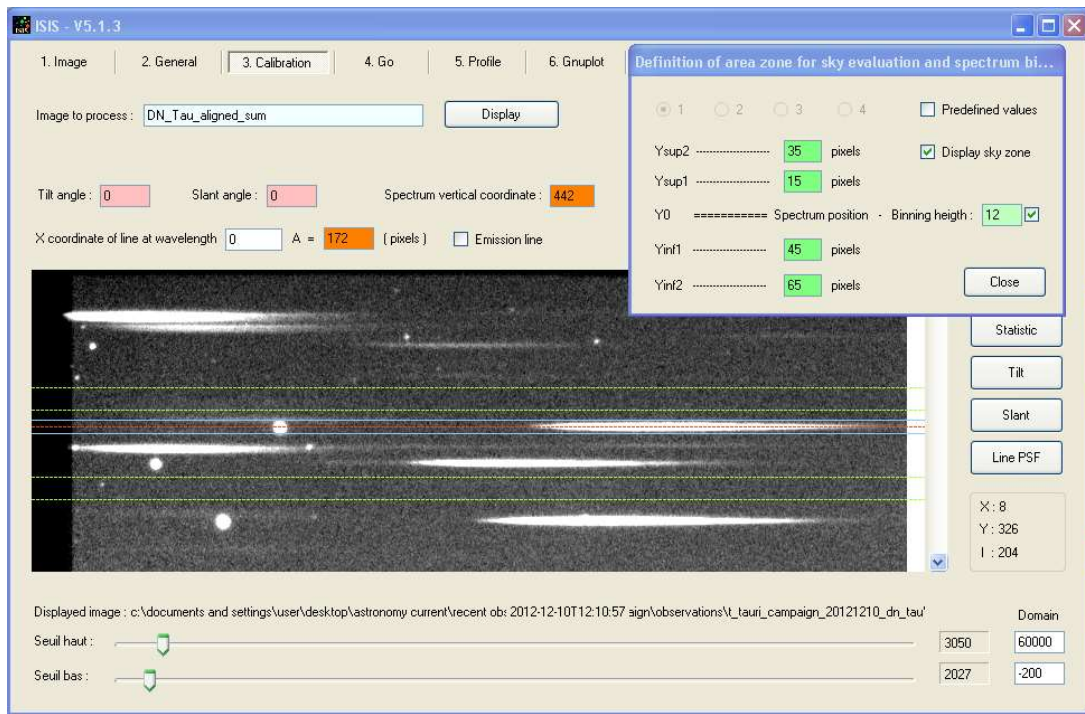
Take spectra for both target and reference stars making sure that nothing changes between the two observations (Particularly focus if using a slit spectrograph with refractive telescope optics including focal reducers, to minimise the effects of chromatism. Allow everything to cool before starting an observing run). If you think conditions may have changed, take a repeat reference spectrum. Place the spectrum at the same position for both reference and target (particularly for slitless systems to avoid flat field errors.) Check that there are no saturated pixels in the spectrum (with slitless systems, saturation in the zero order does not matter.) Total exposure time should be at least 10 seconds and preferably >30 seconds to avoid problems with scintillation. Sum several exposures if necessary. Take matching darks and for slit spectrographs, calibration lamp and flat images. (If the spectrograph shows any flexure, lamp and preferably also flat images should be taken while the telescope is pointing at the star being measured). Flats should be well exposed but not saturated and a sum of at least 20 exposures, preferably 30 to ensure enough signal at the blue end where the halogen lamp output is low.

Pre processing

Spectrum Images should be dark, hot/cold pixel (and for slit spectrographs, flat) corrected and if necessary, tilt (and for slit spectrographs, slant/smile) corrected

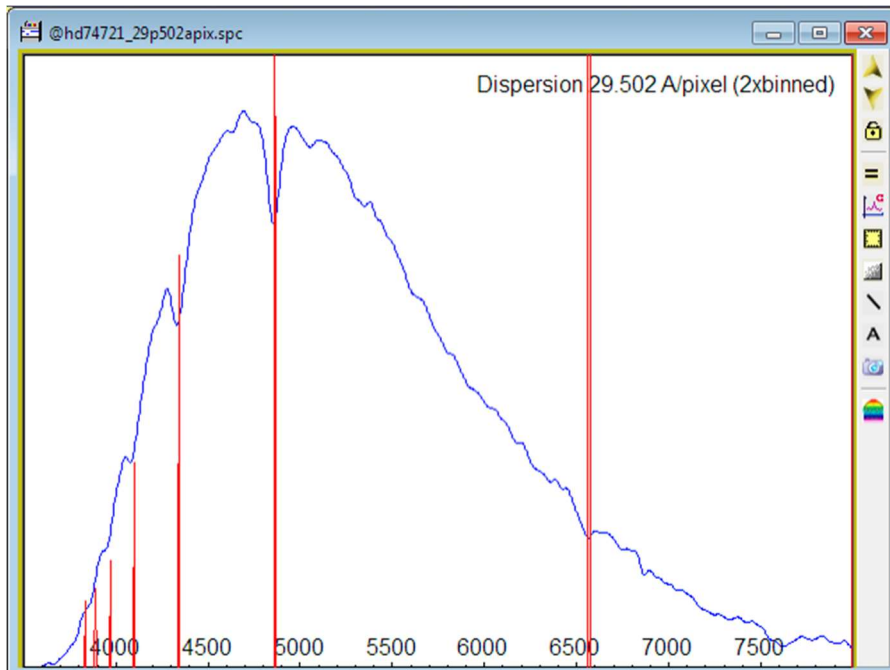
Removing the sky background and binning

The binning and sky background zones should be set up ensuring that the binning zone includes all the spectrum and the sky background zones above and below the binning zone include none of the spectrum (and for slitless spectrographs no background spectra or zero order stars). Stretch the image contrast to see this more clearly.



Example binning and background subtraction zones (Star Analyser slitless spectrograph ISIS software)

Produce a raw binned spectrum profile and wavelength calibrate.



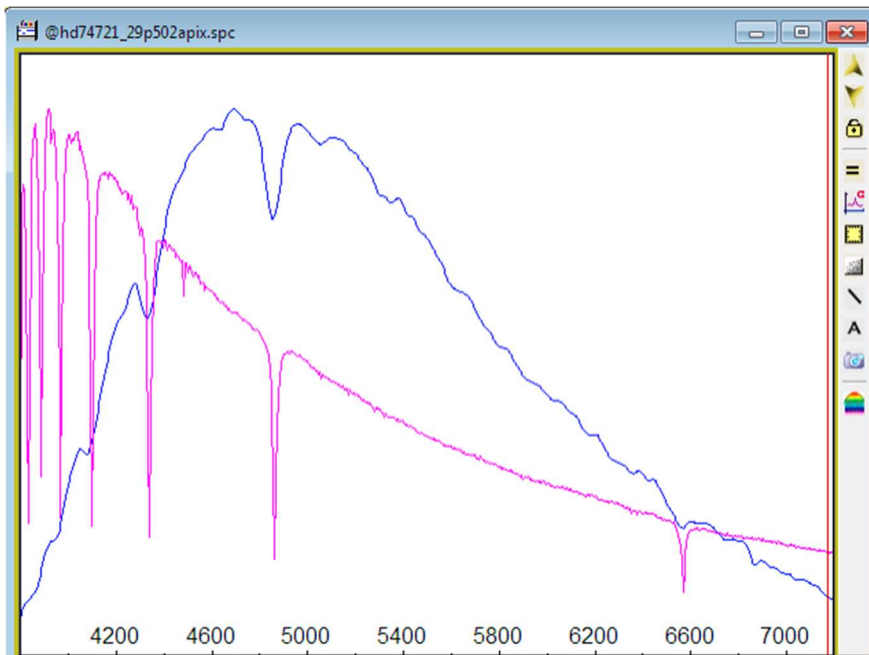
Wavelength calibrated raw spectrum profile (Star Analyser spectrograph Visual Spec software)

Producing the response from the reference star spectrum

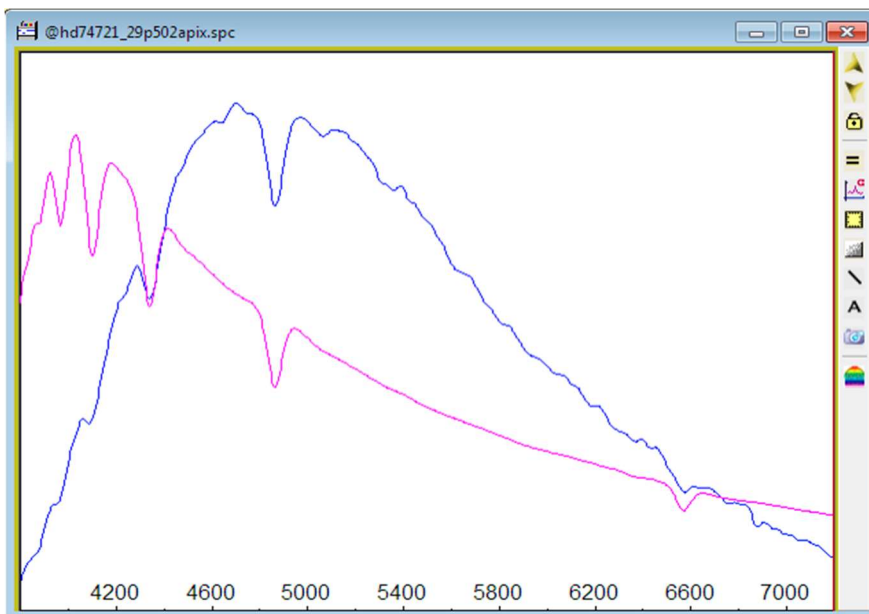
Crop the spectrum of the measured reference to the wavelength range where there is reliable data (eg from 3700 Angstrom, the limit of the system sensitivity to 7500 Angstrom, the limit to avoid

contamination from the second order spectrum) and rescale it to roughly 1 on average to avoid having to work with large ADU numbers

Overlay the published spectrum of the reference star

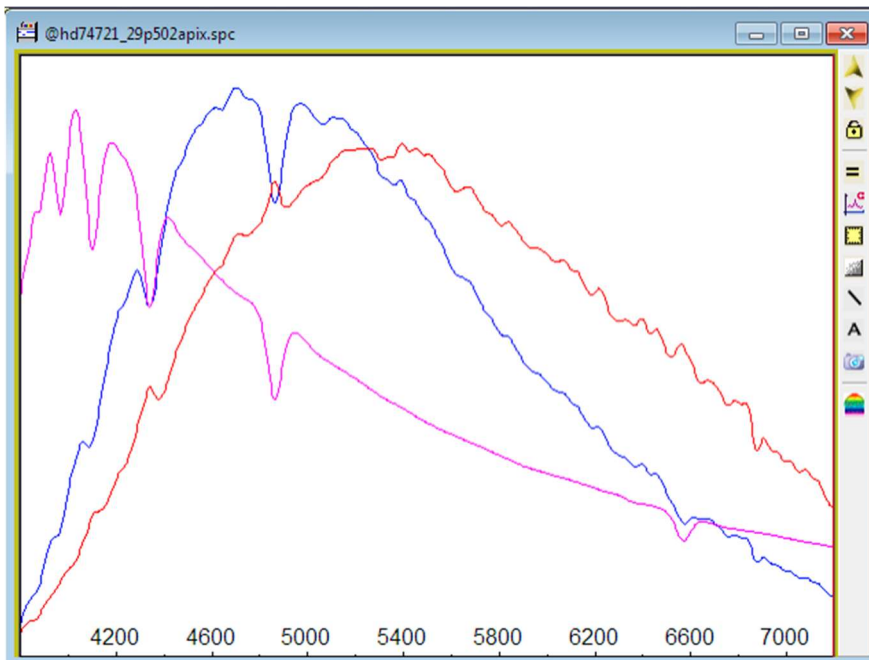


Published spectrum of the reference star overlaid on the raw measured spectrum and filter it to approximately match the resolution of the measured spectrum.



Published spectrum filtered to approximately match resolution of the measured spectrum

Divide the measured spectrum by the published version. The result is the raw response.

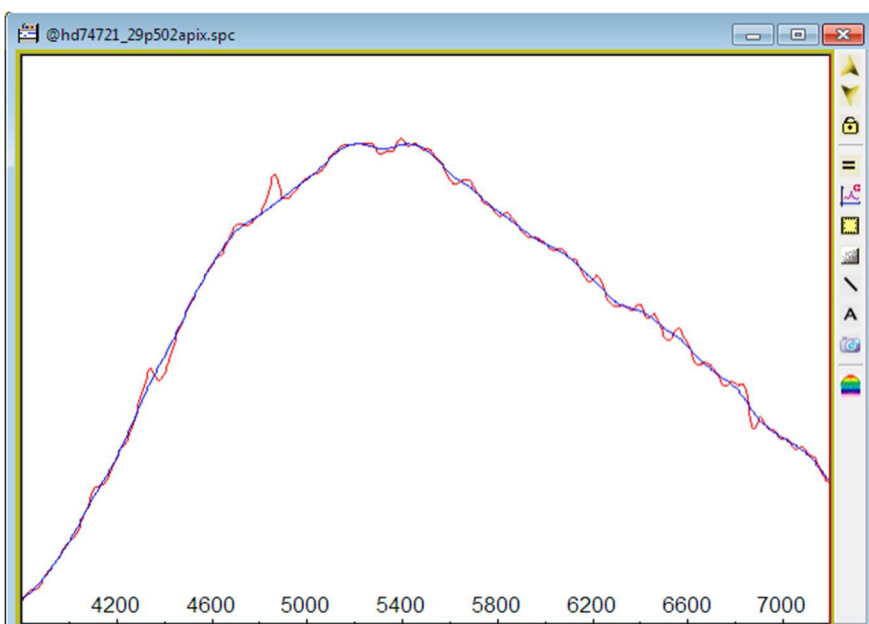


The raw response (red)

Tidying up the response

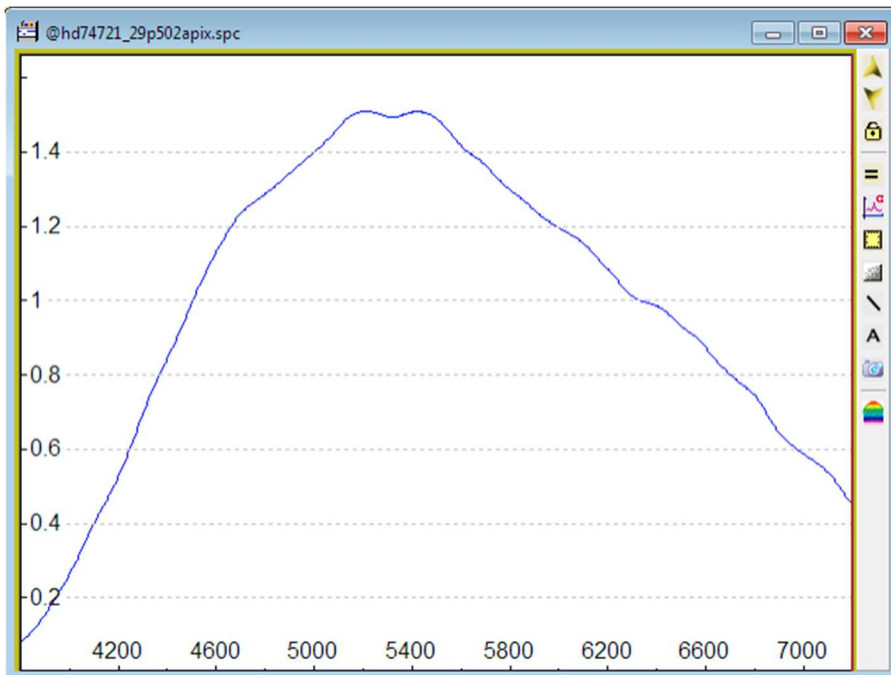
Crop again if there are any artifacts at the ends and crop out any remaining artifacts where the Balmer lines have not exactly divided out. Crop out the telluric bands at the red end (which will appear in the measured spectrum but not in the published version)

Apply a spline filter to smooth the response. Do minimum smoothing just to remove remaining artifacts and noise. There may be ripples in the camera response that you will want to include and it is also important that the smoothed curve fits well at the blue end where the spectrograph sensitivity is low.



Tidying up the raw response to produce the final result (blue)

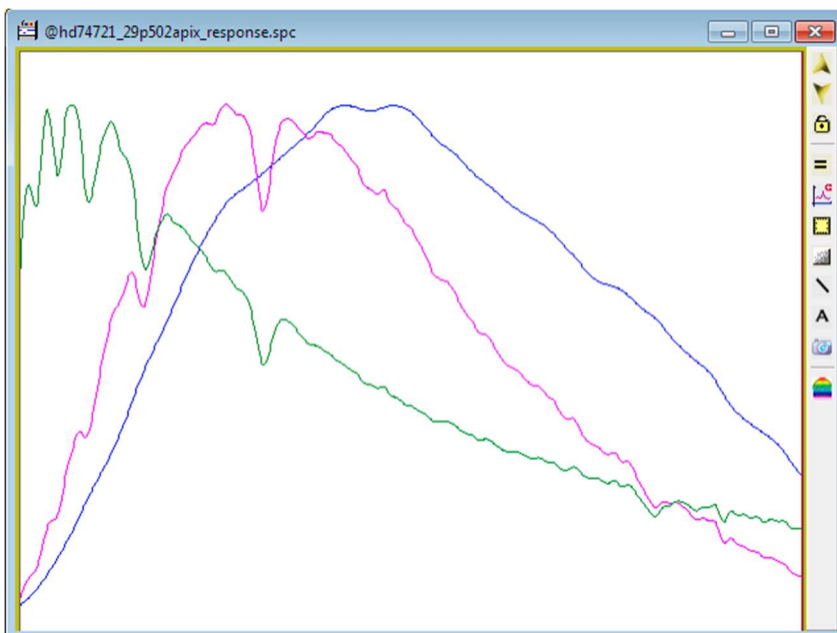
Rescale the response to approximately 1 on average and save it.



The final result. (the effect on the spectrum of the instrument plus atmosphere)

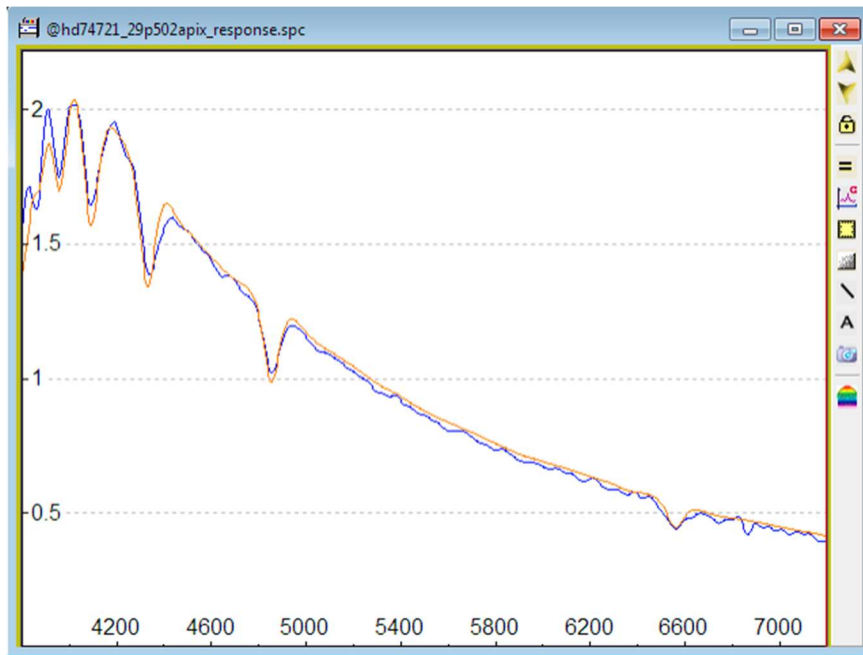
Testing the response

Check the response by dividing the raw spectrum by it.



Flux calibrated spectrum (green) = raw spectrum(pink) / response

The result should closely match the published version (apart from any difference in resolution). If it does not, investigate the reason

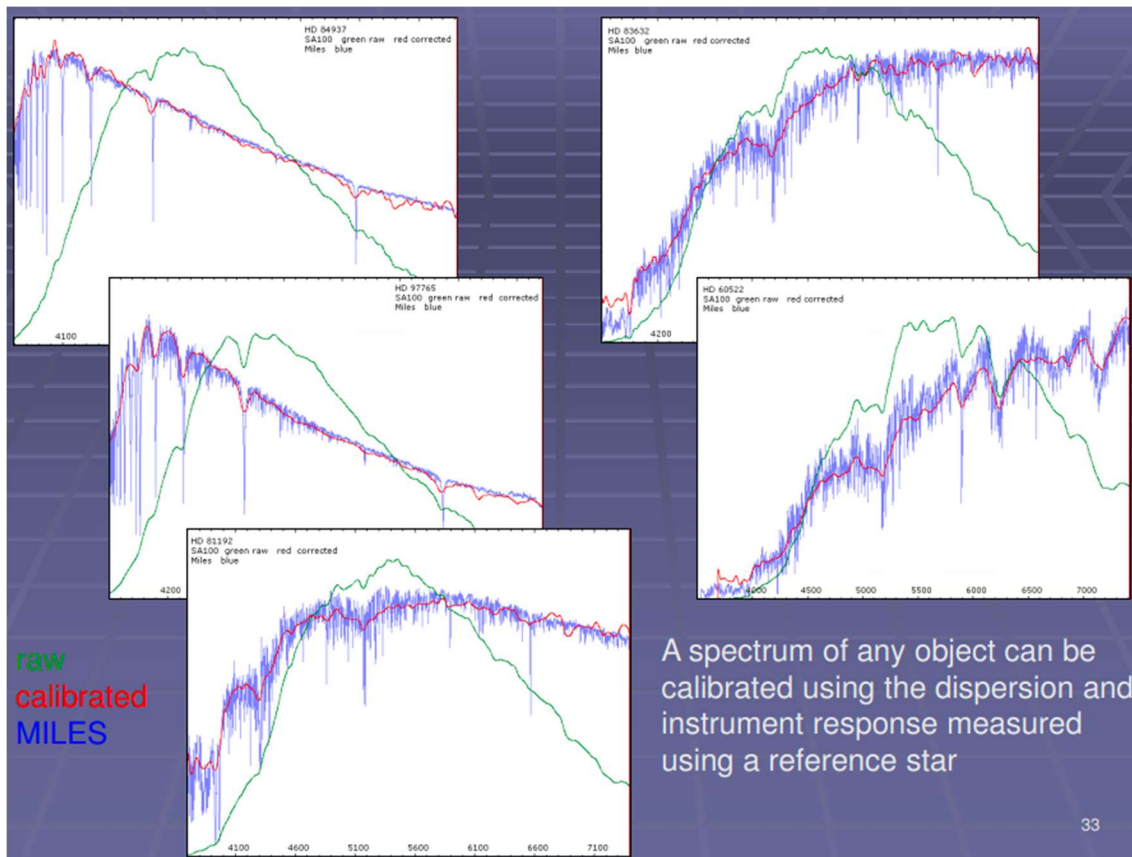


The flux calibrated measured spectrum (blue) compared with the filtered published version (orange)

Note that any telluric bands will still appear in the spectrum. It is normal practise to leave these in for spectra which are included in a database for general use. The user can then remove them if necessary.

Using the response.

Process the spectrum of the target star in an identical way (up to the point of producing a raw wavelength calibrated spectrum, cropped to the useful wavelength range and scaled to approximately 1). Divide the resulting raw wavelength calibrated spectrum by the response. Rescale the result to 1 at some chosen reference wavelength (eg 5500A) and save the final result, which is the spectrum of the target calibrated in relative flux.



Spectra of stars with different spectral classes flux calibrated using the response (raw spectrum green, flux calibrated spectrum red, published spectrum. Star Analyser slitless spectrograph)

Note the reference and all the targets were at similar altitude ie with similar atmospheric extinction so the same response produced using the A type reference star was used for all the targets

Practise, practise

Practice by producing some flux calibrated spectra of various stars with known spectra eg from the MILES catalogue using responses derived from nearby hot reference stars. Compare the results with the published versions. This will give you confidence that the results you produce on other stars will be reliable and can be submitted to public databases and Pro-Am campaigns.

Examples of these exercises can be found on my website for both slitless (Star Analyser) and slit (ALPY 600) spectrographs

http://www.threehillsobservatory.co.uk/astro/spectroscopy_21.htm

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