

Spectral Data Reduction for Amateur Astronomers

Task-oriented Tutorial
with Freeware Programs

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1 Introduction

It exists a large variety of programs for the data reduction of recorded spectra, as well as for the generation, calibration and analysis of spectral profiles. In [1] an overview is provided to what is presently available in the professional and amateur sector.

The main goal here is to provide a task-oriented guide, optimized for the most important spectroscopic applications and involving several programs. Thus this description is to be understood just as a supplement to the program-specific manuals and should further be comprehensible particularly for amateurs.

The stepwise processing of spectroscopic data reduction, as well as the generation and calibration of an intensity profile, are demonstrated here with IRIS and Visual Spec. Further for some auxiliary functions, ISIS and Fitswork are used. The described processes are restricted to those which the author applies himself but never claiming to be the most optimal options within these extensive and very well-documented programs. This document also reflects the specific experiences gained by the numerous recordings for the spectral atlas [2] and is also intended as a practical supplement to the books:

- M.F.M. Trypsteen, R. Walker: *Spectroscopy for Amateur Astronomers, Recording, Processing, Analysis and Interpretation* [1]
- R. Walker: *Spectral Atlas for Amateur Astronomers, A Guide to the Spectra of Astronomical Objects and Terrestrial Light Sources* [2].

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Special thanks to Valérie Desnoux and Christian Built, but also to Jens Dierks, the author of Fitswork, for writing these fine programs and providing them as a freeware. A real door opener to the world of spectroscopy for a fast growing number of interested amateur astronomers around the globe!

Changes in version 2.0:

- IRIS Chap. 3.2: Due to specific algorithms, applied in IRIS, the highest value for the intensity (I) within the recorded spectral stripe may be at most 1/2 of the full saturation, and not 2/3 – this in order to avoid artifacts. Many thanks to Martin Dubs for the hint!
- Vspec Chap. 7.2: With version 4.2.6, the division of the intensity profile by the currently displayed fit already appears while correcting the continuum fit. The description has been adjusted accordingly

Changes in version 3.0 (09/2018):

- IRIS Chap. 3.2: Necessary measures for very large files, recorded with high-resolution camera chips.
- Adjustment of this tutorial to Vspec version 4.4.0

Experiences and consequences with the installation of the program

Changes in version 4.0 (07/2019):

- IRIS Chap. 3.5: Method for recordings with high noise levels – e.g.. from High-z Quasars
- Vspec Chap. 8.7: Filter algorithms for smoothing artifacts

Changes in Version 5.0 (12/2020):

- Vspec Chap. 15: Measurement of filter curves
- Vspec Chap. 16: Transfer of a measurement curve into a Visual Spec (spc) file

Changes in version 6.0 (08/2021):

Removal of telluric H₂O lines in the H α region with the programs *SpectroTool* or *Visual Spec*.

2 Preliminary Remarks and Applied Programs

2.1 Recording and Processing of Spectral Pictures

The Freeware *IRIS* Version 5.59 [10] is applied here for the processing of the spectral image and *Vspec* Version 4.3.2 [11] for the subsequent generation and evaluation of the spectral profile. The displayed spectra were obtained with the DADOS slit spectrograph from Baader Planetarium, the SQUES echelle spectrograph and a 200L transmission grating. The recording was made with the camera Atik 314L+. The processing of "Flats" was generally omitted [1].

2.2 Applied Programs


Both, *IRIS* and *Vspec*, are running under all versions up to Windows 10 in the languages French or English (2017). With both programs, different ways are often leading to comparable results. For the described spectroscopic applications, only a small fraction of the entire *IRIS* and *Vspec* functions are needed. Therefore, it is strongly recommended to consult also the authors' manuals and tutorials [10], [11]. *IRIS* for example, provides abbreviated methods enabling for a whole series of spectral recordings the simultaneous extraction of the sky background in a single step. The author however prefers to perform a stepwise reduction of the individual recordings and to combine this way a quality inspection and selection of the images to be evaluated.

Furthermore, provided by the *ISIS* software, the databases of the standard stars for the relative, spectrometric flux calibration are used here. In addition, *Fitswork* is applied to convert the RAW files generated by DSLR color cameras into the black and white Fits format.

2.3 IRIS

The freeware *IRIS* was developed by Christian Buil as a quite extensive, astronomical image processing program. Here just a small part of the special division for spectra-processing is applied [10].

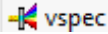
<http://www.astrosurf.com/buil/us/iris/iris.htm>

Some steps for processing the spectral recordings must be entered as so called "commands", via a "console" with correct syntax. Anyway, in more recent *IRIS* versions, many functions, here still described as "Commands", are now implemented as menu items. This "console" can be activated with the icon . Each command line must start with > and finally be confirmed by "Enter". Since *IRIS*, in the current version 5.59, knows neither a close nor a clear command, it has been proven to restart the program with *exit* before loading a new image.

It is absolutely mandatory to define a *default path* for the *working directory* in *Program Files/Settings/Working path*. Otherwise, without any error messages, various *IRIS* commands will not be executed! For download of *IRIS* see [10].

2.4 Visual Spec (Vspec)

The freeware *Vspec* (Visual Spec) [11] was developed by Valérie Desnoux mainly for the generation and analysis of spectral profiles, which are based here on spectral stripes, processed by *IRIS*. The procedures described here can all be accessed by conventional menu items in the title bar. Anyway, as *IRIS*, also *Vspec* provides a console mode. The installation of the program must be carried out exactly according to the instructions of the homepage and the download address by Valérie Desnoux. Tests on various computers with Windows 7, 8.1 and 10 have shown that only the two-step installation procedure, proposed just for "problem solving", has properly worked. This requires installing first the old version 3.8.8,

followed by deleting the application file  vspec in the root directory (program folder) and finally replacing it by the downloaded, updated version [11].

This tutorial is based on the version 4.3.2. Tests have shown that the program must first be installed as a system administrator and subsequently also always opened this way, to avoid DLL and other error messages. The analysis tools, implemented in Vspec, e.g. lists with ions and elements, apply Angstroms [Å] as wavelength unit. If these tools are not applied, the spectra may also be calibrated in any other units such as [nm] or [eV].

It is further advisable to define the same working directory for Visual Spec (*File/Options/Preferences*) as for IRIS.

2.5 ISIS

ISIS Version 5.8.0 [10] by Christian Buil, is a kind of "synthesis" of the spectroscopic functions of IRIS and Visual Spec, including many of the features described here. However, the author prefers the separate processing with IRIS and Vspec, because he considers this path to be more flexible with regard to the parameters to be set and the possible processing options. The procedures described below use here in just one case a data base, which can be found in the root directory of ISIS, containing numerous standard stars for the flux calibration.

Especially for owners of Shelyak spectrographs and those who prefer a widely automated processing, it is worth considering ISIS for the general data reduction [10].

2.6 Fitswork

Fitswork by Jens Dierks (here Version 447) is a well-known freeware for the processing of astronomical images. For the processing of RAW files described later (e.g. taken with Canon color cameras), the Zip folder dcrawfw1477.zip, must be copied in to the program folder of Fitswork and finally unzipped.

Already at the beginning Fitswork has to be downloaded in the desired language. A subsequent language change seems not to be possible [18].

2.7 Further Programs for Data Reduction

In chap. 15, but also in [1], other programs can be found which are successfully applied in the amateur- and the professional field.

3 Processing of Spectral Images with IRIS

3.1 Preliminary Remarks

- The recorded spectral images must first be processed with IRIS, so Visual spec can later generate an intensity profile.
- If the wavelength is calibrated with a light source, the recordings, both of the calibration and the object spectrum, must be processed with exactly the same steps and parameters. This applies first of all to the Y-values of the spectral strip position (exact position and width of the marking frame)!
- The following descriptions assume that the raw images have been taken with a Monochrome camera in Fits format and have already been edited with any Darks and possibly Flats. In chap. 3.5 a possible way is presented how to convert Fitswork RAW files, taken with color cameras, for processing with IRIS.
- The mounting angle of the camera should be chosen so that the recorded spectral strip runs already horizontal and a subsequent, software-based correction of the angle is unnecessary.

3.2 1D Spectrum Generated from a Single Spectral Recording

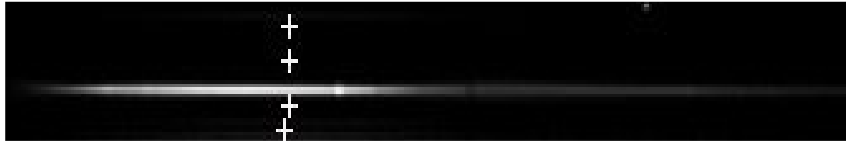
If just a single spectral image of a bright object was taken, the following steps apply:

1. Copy the Fits file of the image to be processed into the predefined working directory of IRIS and load it with "*file/load*".

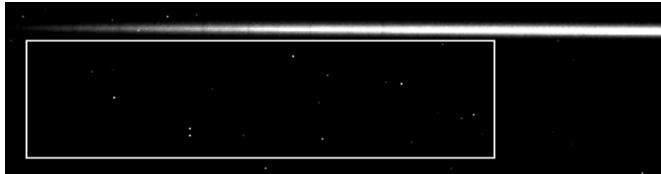


Notes:

- For most astronomical cameras it is the *fit* format. Sometimes, however, other formats are used. If necessary, this can be determined by tests. It may be necessary to change the FITS file type from (*.fit, *.fits) to (*.fts)!
 - If recorded with a high-resolution camera chip the file may become too large and IRIS shows on the screen only a limited section of the spectral strip. In this case, the file must be reduced with "*Geometry/Resample*" so that the entire length of the stripe fits on the screen. The corresponding reduction factor for the X- and Y-axes must be determined by experiments, e.g. 0.3. If the binning mode is available, it is preferable to reduce the file size already during recording (for example by 2x2 or even 3x3 mode).
 - If the loaded image is exposed to short, the brightness can be increased with the upper threshold slider in the popup menu. This has no influence on the final result of data reduction.
 - The highest value for the intensity (I) within the recorded stripe must not exceed 1/2 of the full saturation range. Otherwise, artifacts can occur. In the lower right corner of the screen, in addition to the coordinates (X, Y), the pixel intensity (I) of the cursor position is displayed
2. Subtract the sky background with the command `>I_sky3`.
 3. In the output window follows now the request "*select 4 points*". To mark the reference zones, click each two points, slightly above and below the spectral stripe. With the final click on the fourth point, the subtraction instantly takes place.



4. Remaining hot pixels or cospics within the strip area, can be framed with the cursor and removed with the command `>max X`. *X* is the estimated maximum number of concerned pixels.



Note: Hot pixels *within* the spectral strip must be marked very closely by framing with the cursor and individually removed with `>max 1`

5. Mark the "cleaned" spectral stripe by framing:



Notes:

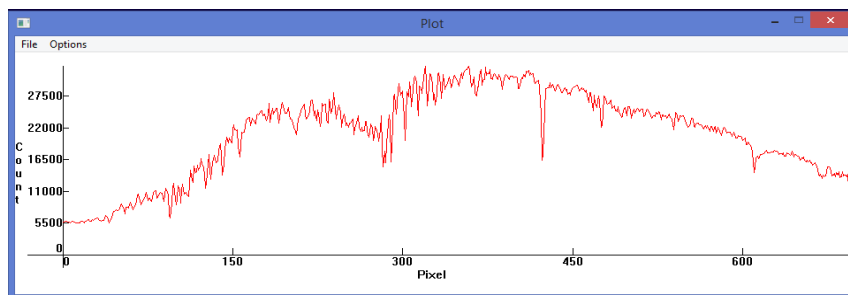
- If subsequently a spectrum of the calibration light source has to be processed, the Y-values of the upper and lower frame edges should be noted here for later reapply. The coordinates of the current cursor position are displayed in the lower right corner of the screen.
 - The frame does not need to be stretched over the entire length of the strip
6. Generate a 1D spectrum with *Spectro/2D -> 1D optimal addition*:



Note: To generate the resulting 1D spectrum, IRIS applies an algorithm to smooth the different brightness values in the Y-direction and increases finally the height of the resulting strip to 20 pixels.

7. Save this 1D spectrum with *file/save*, at best with a descriptive name, such as *Sirius 1D*. This file will later be used to generate the intensity profile in Visual Spec.

Note: The command `>l_plot` can now be applied to generate a first provisional spectral profile for a first control, which however cannot be saved and is further not suitable for further processing.



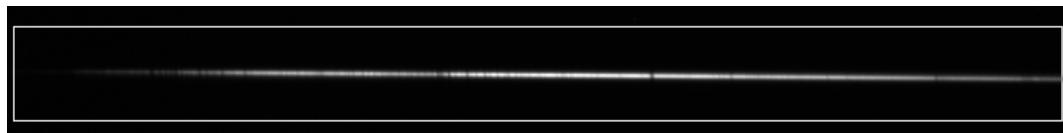
3.3 1D Spectrum Generated from Several Stacked Spectral Recordings

Similar to astrophotography a series of spectral recordings is stacked here. Thereby the signal-to-noise ratio SNR can significantly be improved.

1. Copy the spectral stripes for further processing in the working directory of IRIS

Note: Each individual file must first be processed according to chap. 3.2, steps 1 – 5.

2. Rename these files and number them consecutively, from 1 to n, e.g. *castor1*, *castor2*, *castor3*. The numbering must necessarily start with 1 and no missing intermediate numbers are allowed!
3. Load the *first record* of the series (eg *castor1*) with "*file / load*" into the IRIS program.
4. Mark this stripe by framing with the cursor, comprising also the positions of the other files to be stacked.



5. Start the stacking process with "*Composite of a sequence of spectra 2D -> 1D*".
6. Enter in the window "Composite" for "*Input Sequence*" the filename without a number (e.g. *castor*). For "*Output Sequence*" enter a different, arbitrary name or a letter like "*b*" (these generated files are later no longer needed). Enter for "*Number*" the number of recordings to be stacked (e.g. 3).

7. By clicking *OK* the Stacking of all generated 1D files is triggered

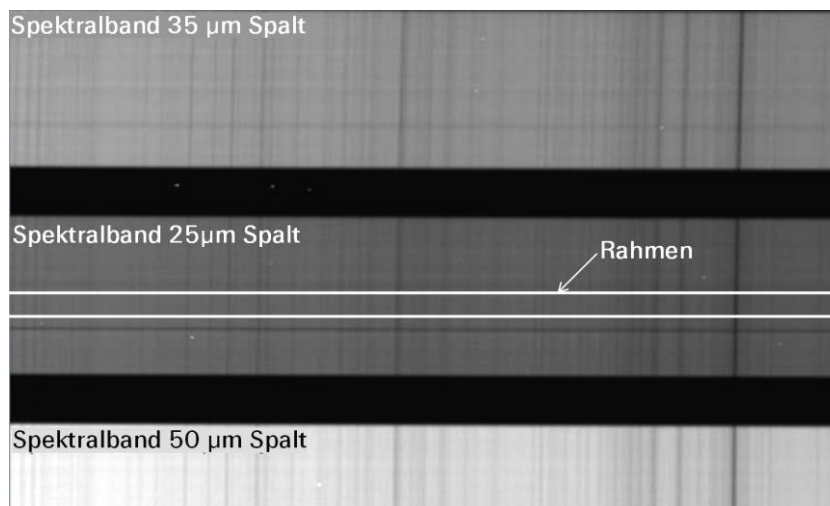


8. Save the stacked 1D Spectra with *file/save*, e.g. as *Castor1Dsum*. This file will later be used to generate the intensity profile in Visual Spec.
9. Delete in the working directory the generated but no longer needed files of the *Output sequence* (here *b*).

3.4 1D Spectrum Generated from 2D Appearing Objects

With the exceptions noted below, the processing runs according to sections 3.2 and 3.3. The spectra of 2D appearing light sources (daylight, sun, emission nebulae, etc.), recorded by a slit spectrograph appear here as "spectral bands" with a maximum height corresponding to the length of the slit. In such cases, a thin, "clean" strip within the desired band must be marked with a frame – for DADOS generated by the three slits 25, 35, or 50 μm .

Important: Use exactly the same marking range (Y-values) for the subsequent calibration of the object- and calibration spectra.



Subtraction of the sky background:

If the recorded object extends over the entire length of the slit, there is no reference left for the subtraction of the sky background with the command `> I_sky3`. In this case, immediately and next to the object - and with the same exposure time - the sky background must be recorded separately and directly subtracted from the object image. However, this complicated step is required only with long exposure times, but at the latest when the emission lines of light pollution become noticeable [1]. The subtraction can be done with IRIS (*Processing / subtract to a sequence*), but also with Fitswork [18].

3.5 1D Spectrum for very Noisy Images

Note: The following procedure can be attempted with very faint objects, e.g. high-*z* quasars, if only a very noisy image can be obtained and the standard procedure according to chapter 3.2 fails.

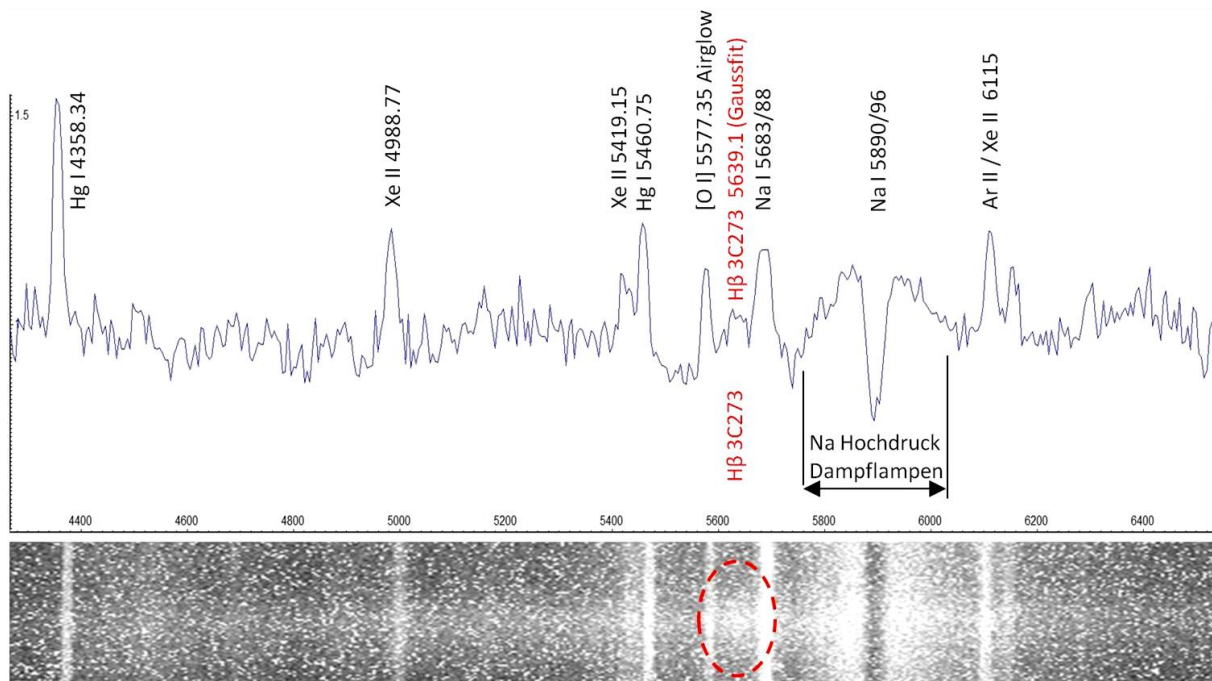
It is exclusively limited to the estimation of the wavelength of very distinctive emission lines, especially of the H-Balmer and -Lyman series, e.g. for the determination of the *z*-value. Otherwise, the contrast enhancements applied here make the evaluation of the other spectral parameters scientifically worthless. In the normal procedure according to chapter 3.2, the position of the "Threshold" controls therefore reasonably remains ineffective for the further processing steps. For this special case, this "lock" can be bypassed by temporarily saving the "adjusted" image as a BMP file and, for further processing, reloading it as

such in the IRIS program. In principle, the procedure according to chapter 3.2, steps 2 - 5 must be adapted as follows:

1. Adjust the strongly underexposed image to optimal brightness and contrast with the two Threshold controls
2. This setting is now saved as an image with file/save in BMP format and NOT in Fits format.
3. Load the saved BMP file back into IRIS, set "File type" to "Graphics".
4. Continue as described in chapter 3.2, Step 5 with the exception that the framing must be limited here to the weakly recognizable stripe of the astronomical object and the generated 1D file must finally be saved as BMP.
5. Load the obtained 1D file in Visual Spec (set file type to bmp) and process according to chapter 4.

Note: The known lines of light pollution can also be used to calibrate the wavelength (see Spectral Atlas).

The following example shows H β as the only evaluable emission line of 3C273 that is otherwise only recognizable as a fuzzy white stripe within this noisy stripe. The easily recognizable light pollution lines all appear along the entire slit height.

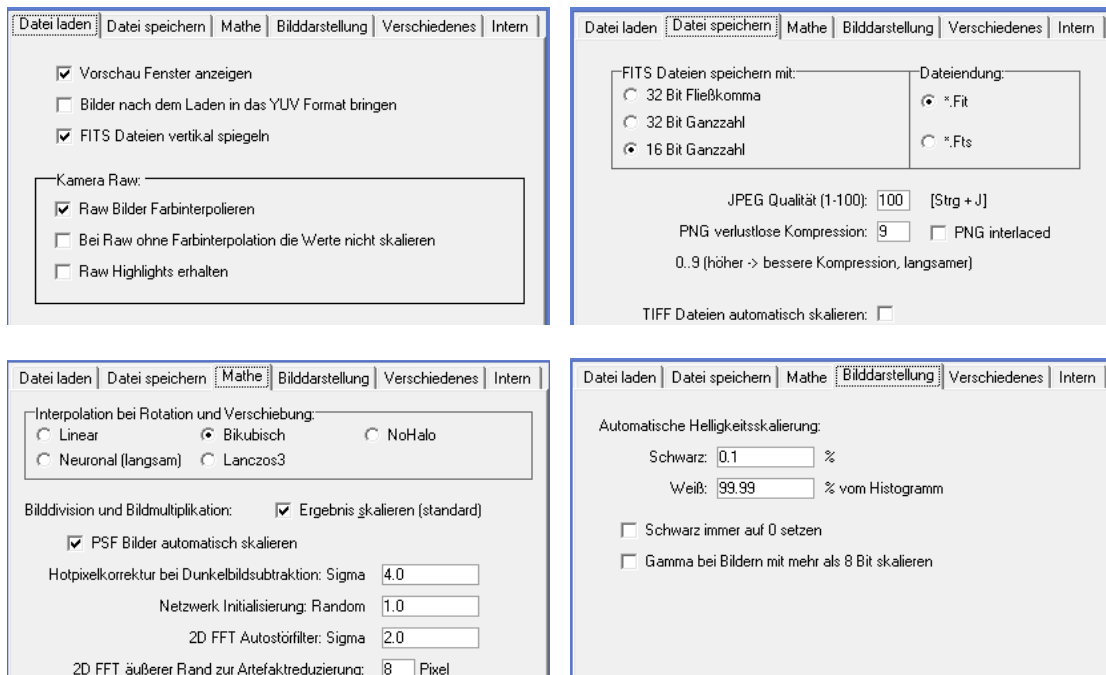


3.6 Preparing of Color Images in CR2 RAW Format with Fitswork

Here just the way is shown how a single spectrum, taken with a DSLR camera in color RAW format (Canon CR2), can be converted into an IRIS-compatible fits file. The very descriptive DADOS tutorial by Bernd Koch [5] also shows how Fitswork can be used to directly stack several recordings in RAW format. Recorded with an unmodified DSLR camera, due to the filters, only a part of the spectrum of about 4000 – 7000 Å can be evaluated.

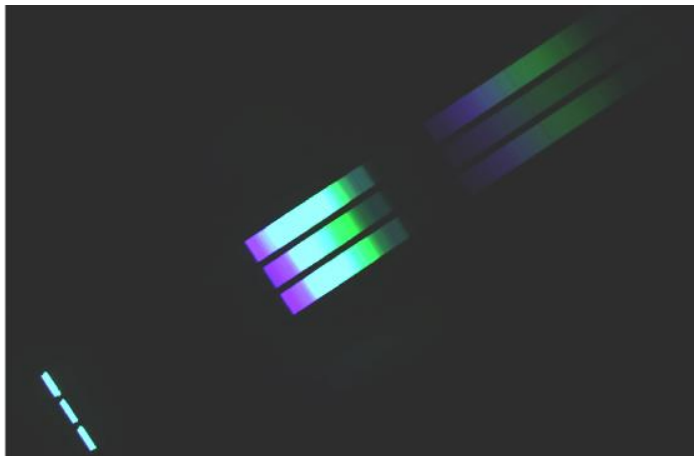
Note: This procedure also works with BMP and JPEG formats.

1. For this task the settings in Fitswork must be adjusted as follows:



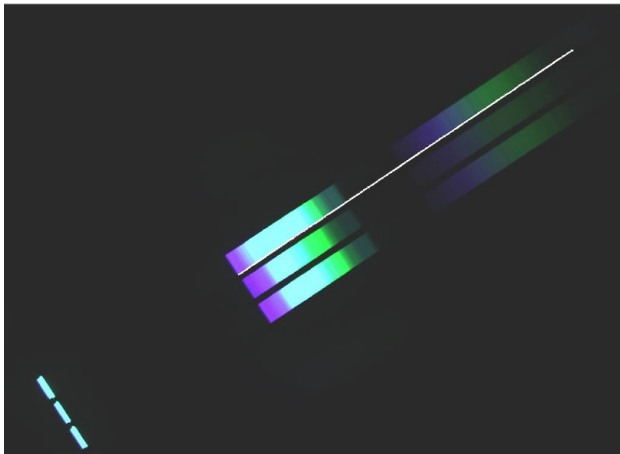
2. Load the RAW CR2 image with *File/open* in to the program

Note: Displayed in this image are the three DADOS strips of the daylight spectrum in the orders 0, 1 (overexposed) and 2 (faint), appearing inclined at about 33° to the horizontal

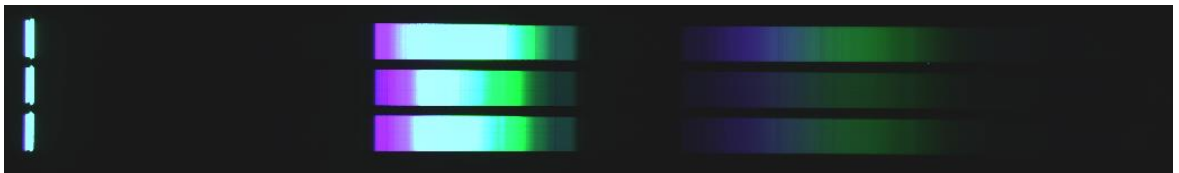
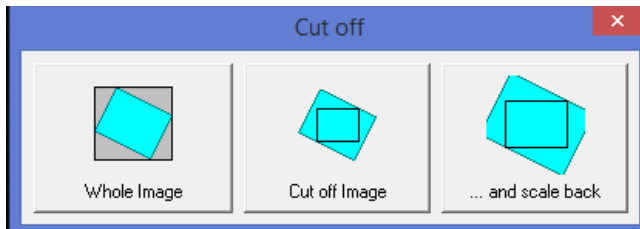


3. Rotate the spectral strips into the horizontal with *Processing/Image geometry/Rotate Image with Subsidiary Line*

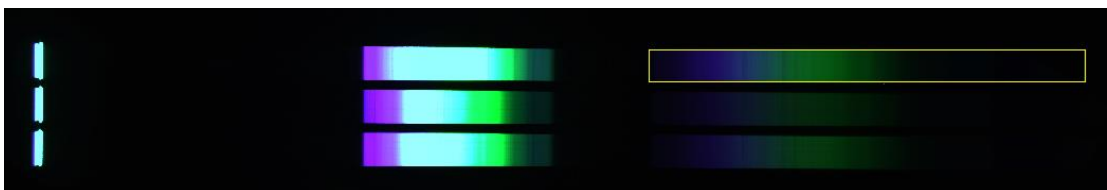
4. Draw a subsidiary line with the cursor along the spectral strip




5. Confirm with Ok
6. Click the button "*Whole image*" and the spectral strips appear horizontally



7. If several orders are shown, use the cursor to span a frame around the desired strip or the entire order (in this case upper strip of order 2).



8. By click on the icon  cut out the marked strip
9. Save the resulting strip with *File/Save as* e.g. *Daylight color 16 bit*



10. Convert the color strip in to b/w with *Processing/Color Image to B/W (Luminance)*

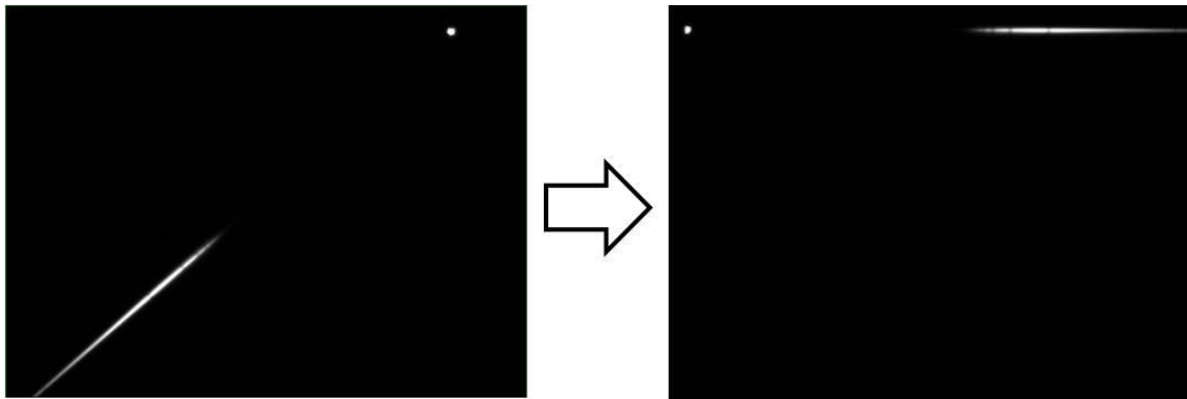
11. Save the resulting strip with *File/Save as* e.g. *Daylight mono 16 bit*



12. Further processing of the strip or the entire order in IRIS according to chap. 3.2 and ff.

3.7 Slitless Recordings with Transmission Gratings

Recordings of such spectra can be processed by IRIS, analogously to chapters 3.2 and 3.5. The best resolution is mostly achieved when the spectral strip is recorded as stretched as possible. For this purpose, for the recording the image diagonal should be exploited. Finally, for the evaluation with IRIS, the strip can be moved, rotated, scaled and mirrored with the tools *Geometry/Shift -/Rotate -/Perspective adjustment -/Flip*. If a calibration is to be performed with a reference star, the orders 0 and 1 must be imaged together. For the calibration of such spectra see chap. 6.




4 Generating Intensity Profiles with Visual Spec

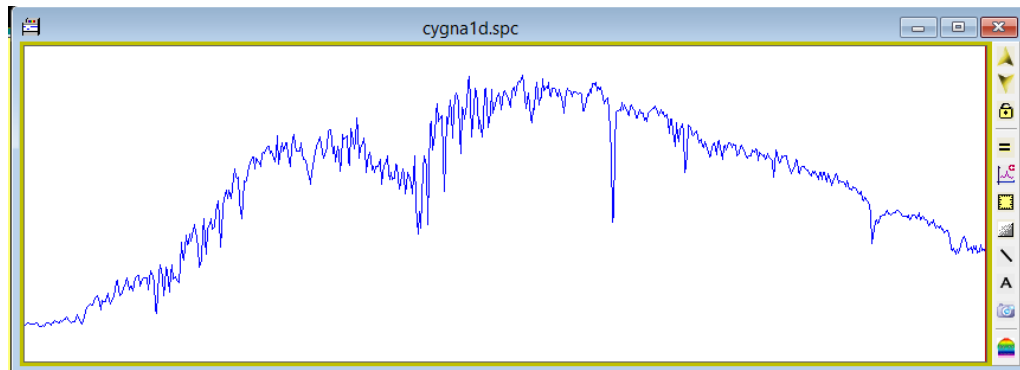
4.1 Preliminary Remarks

With Visual Spec an intensity profile (I) is generated, plotted over the wavelength axis ($I = f(\lambda)$) and based on a 1D spectral strip, previously processed with IRIS.

- Under *Options/Preferences*, define the same working directory as in the IRIS program.
- Under *Options/Preferences/Working Directory* set the Format of Image files to *fits* and for "Profil" to *.spc*
- For heliocentric corrections, under *Options/Preferences/Position* the corresponding parameters of the observation location must be entered (coordinates in decimal degrees)
- Define further preferences as needed, e.g. *Language*.
- If in "Open Profile" existing *.spc* files remain invisible, set the *file format* from "*.spc*" to "*all*".

4.2 Generating an Intensity Profile with Visual spec

1. Load with "Open Image" the previously IRIS processed 1D spectral strip in to the Vspec program.
2. Generate the Raw Profile with the Icon "Object Binning"  .



3. Save the raw profile with "save as" e.g. *castor.spc*.

Note: If the calibration is done with a light source, then this intensity profile has to be generated *only* for the object spectrum. The calibration process, according to chap. 5.3, applies directly the *Fits File* of the 1D calibration spectrum.

5 Wavelength Calibration with Slit Spectrographs

5.1 Preliminary Remarks

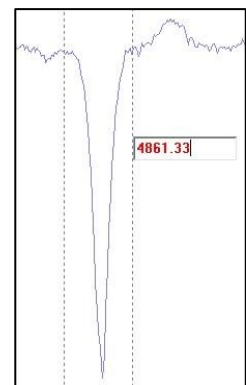
- The wavelength scale of a raw spectrum, recorded with a prism, runs strongly non-linear. But even taken with modern reflection or transmission gratings, the scale remains, albeit just slightly, nonlinear. For low requirements, Vspec allows linear calibration with only two lines. Here, however, just the only recommended, *non-linear calibration*, with at least 3 lines is described.
- If in the spectrum several well distributed lines can be undoubtedly identified, the intensity profile can be calibrated with the known rest wavelengths λ_0 (e.g., the hydrogen Balmer series). This is also the only option if the spectrum was recorded without a slit by a transmission grating or an objective prism (chap. 6). This method is also required if, based on λ_0 , unknown lines should be identified in an unshifted profile.
- Measuring redshifts in the spectrum, e.g. for determination of the radial velocity, requires the absolute calibration with the wavelengths of a light source. This is also indicated if the spectrum contains just a few known lines, e.g. with the late types of the spectral class M, or with novae and supernovae.

5.2 Non linear Calibration with at least Three Known Wavelengths

1. Load the raw profile with "*Open Profile*" into the Vspec program. (if necessary set the file format of ".spc" to "all")
2. Start the process with *Spectrometry/Calibration multiple lines*.

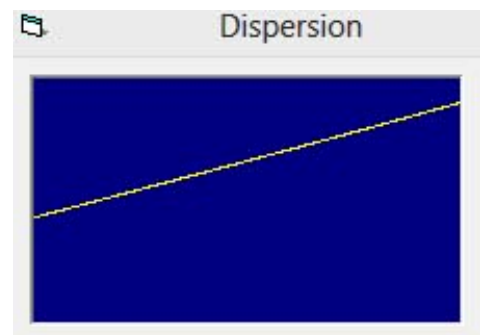
Note: In the pop-up window "*Non linear calibration*", the degree of the calibration polynomial "*Degré*" can be left at the default value of 3.

3. Mark with click and drag the line profiles and type the known rest wavelengths λ_0 into the popup field. These can be found in the spectral atlas [2].
4. By confirming with *Enter* the wavelength is copied in to the window "*Non linear calibration*".
5. Repeat steps 3. and 4. with at least two further well-distributed lines.
6. Click the "*Calcul*" button in the window "*Non linear calibration*". This starts immediately the calculation of the calibration polynomial and simultaneously calibrates the spectrum non-linearly.




Notes:


- In addition, a graphic shows now the course of the calibration polynomial (picture on the right). Here no curved but a *straight line* must appear, otherwise calibration error has happened. Invalid inputs are announced with "*Value is not consistent*" or "*Inflection*". In such cases Vspec marks the affected calibration point, which can then be corrected in the table.
- The coefficients of the polynomial are displayed under "*Interpolation*". With *Save* the corresponding equation can now

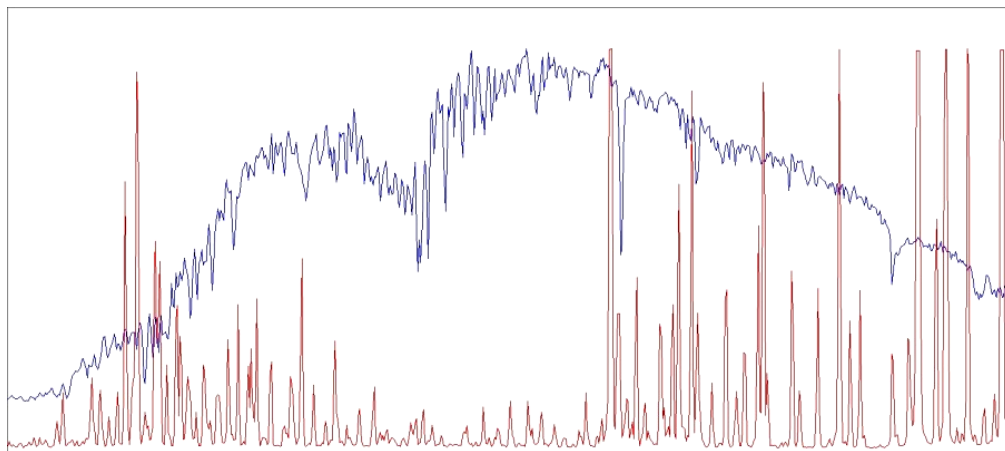


be saved as *.txt* file for reapply. With *Load* and *Apply* the calibration can be transferred to another profile recorded with identical device setup. For higher standards, this method is too inaccurate, but proposed in Chap. 6 for the calibration of slitless recorded profiles.

- The wavelengths of the lines can also be copied from a pdf document, or other formats, with *ctrl C* and transferred in to the box with shift insert, e.g. from an atlas of calibration lines [4]. This avoids annoying transmission errors. The function *ctrl V* does not work here.
7. Close the window with "*close*".
 8. Check the calibration of the profile with known lines.
 9. Save the calibrated profile with *file/save* e.g. as *Siriuscalib*.
 10. Clicking the yellow square  on the right edge of the box will display the scaled X- and Y- axes. Formatting of the graphic see chap. 8.

5.3 Non linear Calibration with Light Source

1. Load the raw profile with "*Open Profile*" into the Vspec program. (if necessary set the file format of *.spc* to *"all"*)
2. Load with "*Open Image*" the processed 1D strip of the calibration light source
3. Start the process with clicking the Icon *Reference Binning* . The generated intensity profile of the lamp spectrum appears now superimposed to the spectral profile.




4. Perform non-linear calibration with "*Spectrometry/calibration multiple lines*" analogously to Section 5.2, Steps 3 – 6. and applying well-distributed spectral lines of the calibration lamp.

Notes:

- The calibration generated this way, is immediately transferred to the spectral profile (*Intensity*).
- In the lamp spectrum no overexposed (saturated) lines must be evaluated, i.e. those with flattened peaks
- During the calibration process, the superposition of the profiles appears remaining. For better distinction it is recommendable to change the color of the calibration spectrum (in the left section of the title bar)

5. Save the calibrated spectral profile (*Intensity*) of the object e.g. as *Siriuscalib*.

Note: The still visible lamp spectrum (Ref 1) will thereby *not be saved* and must not be deleted.

6. Click on the yellow square  on the right edge of the frame. The scaled X and Y axes appear. Formatting see chap. 8.

6 Wavelength Calibration with Slitless Recordings

6.1 Preliminary Remarks

In the case of profiles recorded slitless with transmission gratings or objective prisms, the main focus is here on the calibration according to chapter 5.2, which is based on the rest wavelengths of identified lines. A direct, absolute calibration of such spectra with light sources, according chap. 5.3, is not possible. Thus, a precise determination of the radial velocity is excluded.

However, thanks to the displayed order 0, for transmission gratings exist two alternatives of how to calibrate such a profile with external references. However, this requires that the orders 0 and 1 of the object spectrum must be displayed on the same picture. Further this enforces a compromise in respect of the achievable resolution, because it does not allow spreading the whole strip of just order 1 across the entire width or even in the diagonal of the image.

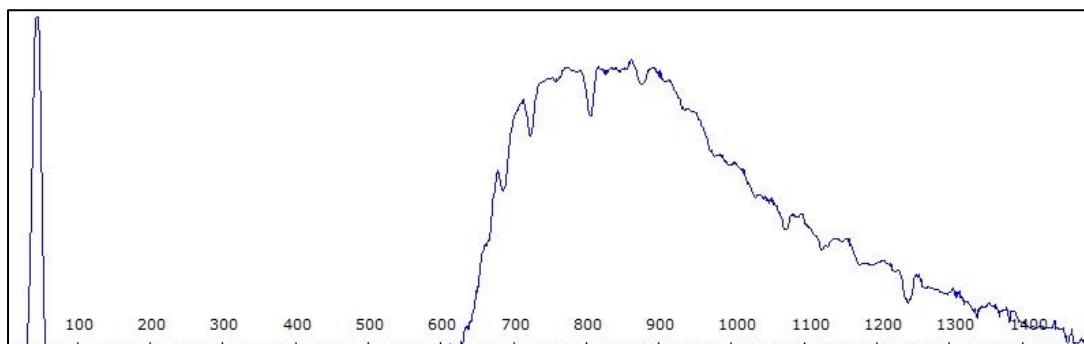


6.2 Calibration with the Dispersion and Reference to the 0th Order

This very simple, but also very inaccurate option is described in the Vspec manual, requiring the dispersion of the spectrum. This can be determined by the spectral sampling [$\text{\AA}/\text{Pixel}$] of a calibrated reference spectrum (chap. 5.2 and 9.3) which was recorded with identical device setup. For this, e.g. a bright A-class star with a striking Balmer series can be recorded.

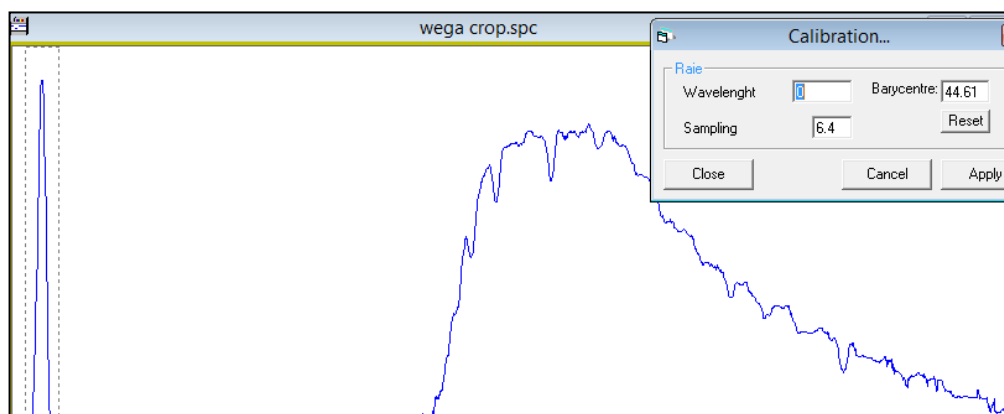
Starting from the common reference point *order 0*, by this very rudimentary method the calibration of the reference spectrum is just linearly transferred to the object spectrum. A typical application is the rough estimation of the redshift (*z*-value) of a quasar, e.g. 3C273. The following steps require a spectral 1D strip, processed according chap. 3.2.

1. Determine the dispersion of the spectrograph by the sampling of a wavelength-calibrated bright "reference" star. For the following example it yields $6.4 \text{ \AA}/\text{pixel}$.
2. Generate the intensity profile of the object spectrum running over the orders 0 and 1

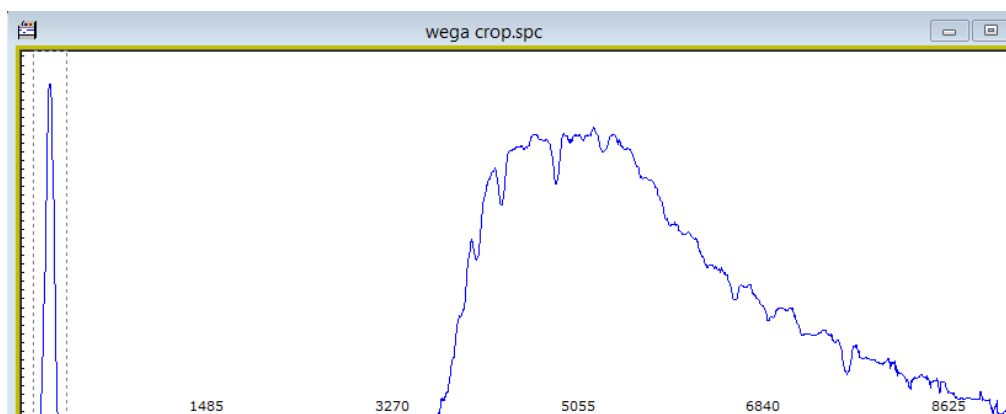


3. Mark order 0 with click and drag
4. Start the calibration process with *Spectrometry/Calibration 1 Line*
5. In the *Calibration Window* enter 0 for the *Wavelength*
-> Dispersion starts at Order 0.

6. For *Sampling* enter the determined value for the dispersion (here 6.4 Å/Pixel)



7. Start the calibration process with click on "*Apply*". Thereby the dispersion of the bright "reference" star is now linearly transferred to the object spectrum



8. Save and format the calibrated profile. Such a calibration is highly inaccurate and just applicable for very rough investigations.

Note: Such a calibration is very inaccurate and useful only for rough estimates

6.3 Calibration with a Polynomial and Reference to the 0th Order

Calibration polynomials are usually applied for the non-linear calibration of profiles, generated by slit spectrographs (Chap. 5.2). Here an option is presented how this method, with reference to the 0th order, can be adapted to slitless applied transmission gratings. Unfortunately, the possibility to define the 0 point of the polynomial by marking the 0-th order (as in Chap. 6.2) is missing. Therefore appropriate "artifices" are necessary here. The accuracy of this method is significantly higher compared to the rough procedure according to Chap. 6.2. The following steps require a spectral 1D strip, processed according chap. 3.2.

Calibration principle

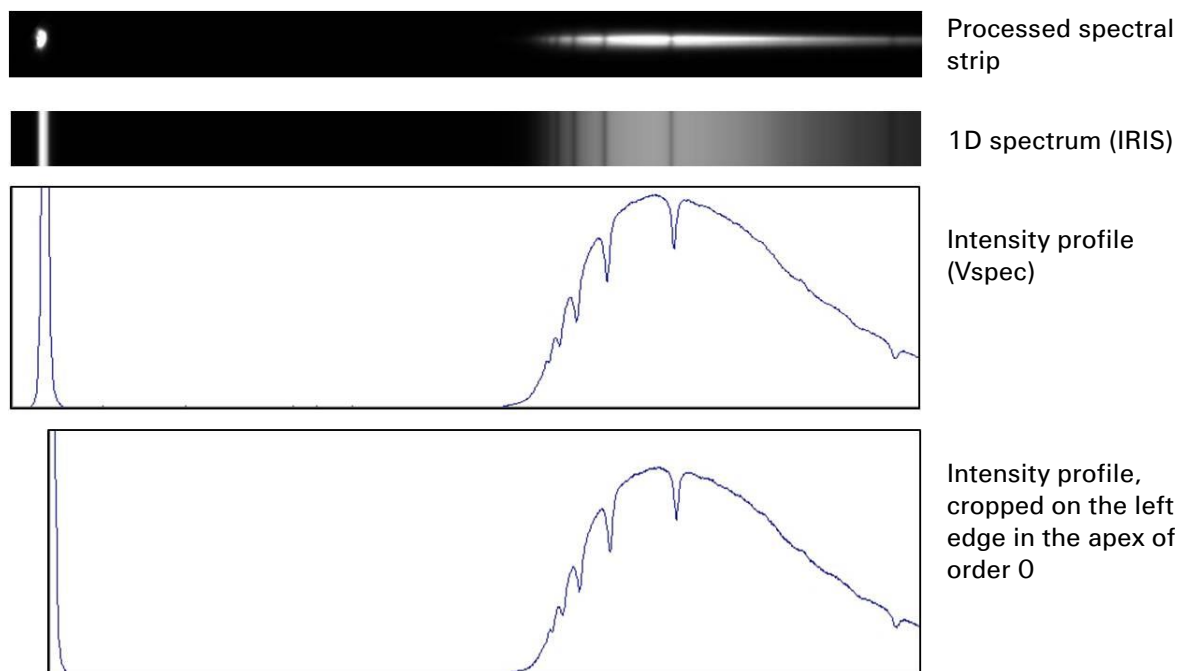
The order 0 corresponds always to the wavelength $\lambda = 0$ and forms here the only common reference point for uncalibrated spectra. For this reason, the raw profiles of the "reference" star and of the object spectrum are both cropped on the left edge so they both start exactly in the apex of order 0. The object profile contains on the right side the part to be analyzed of order 1. At the right edge, the profile of the object spectrum may be maximal equal to or shorter than that of the "reference" star. With the relative simply determinable vertex of

order 0, a common starting point of the polynomial for the calibration- and the object spectrum is forced. The following steps require a processed 1D spectral strip, according chap. 3.2.

Generation of the calibration polynomial

1. Record as a reference a qualitatively good spectrum of a bright star of spectral class A (striking H-lines) with identical device setup, and create a raw profile.
2. Crop the raw profile on the left edge in the vertex of the 0th order.

Note: The following figure shows for Vega the way from the processed spectral strip to the raw profile, finally precisely cropped in the apex of the 0th order. The spectrum was recorded with the setup C8/transmission grating (200 L/mm)/Atik314L+.



3. Calibrate the cropped raw profile nonlinearly with approx. 4 Balmer lines (chap. 5.2) including the H α - and a short-wave (H ϵ or H8) absorption. The combination H α : 6563Å, H β : 4861Å, H γ : 4340Å, H8: 3888Å (possibly H δ : 4102) has proven to be successful.
4. Start the calibration with *Calcul*
5. Check if the graph of the dispersion forms a straight line and by the cursor position if the wavelength λ at order 0 is positive.
6. If λ is negative, iteratively change the wavelength of the short-wave- and possibly also of other lines in the table by small amounts, here 3888 \rightarrow 3889Å, this yielded here the new wavelength $\lambda = +96\text{Å}$ at Order 0.

Non linear calibration				
Liste de raies				
lambda	raie	pixel	d_lambda	
3889	1	769.929	0.	Calcul RMS: 0 <input type="checkbox"/> Delta Lambda Degre <input checked="" type="radio"/> Degre 1 <input type="radio"/> Degre 2
4340	2	858.5017	0.	
4861	3	960.8387	0.	
6563	4	1298.327	0.	
Load				
Save				

7. If the wavelength λ at order 0 is positive by a small amount, save the calibration polynomial with *Save*.
8. Function control of the polynomial, e.g. on an accordingly cropped raw profile

Notes: The exclusive concentration of the calibration lines in the right-hand part of such spectra causes the relatively large deviations of the wavelength at order 0. This process therefore often requires several trials. If the wavelength λ at the order 0 is negative, the spectrum can be calibrated, but the polynomial can no longer be applied to other profiles (error message).

Calibrate the spectrum with a polynomial

The still limited accuracy of this calibration procedure allows here to reapply a proven calibration polynomial also for later sessions, if the same device setup is applied. This way the calibration of a new accordingly cropped profile gets very simple:

1. Load the accordingly cropped raw profile with *"Open Profile"* into the program. (if necessary set the file format from *.spc* to *all*)
2. Start the process with *Spectrometry/Calibration multiple lines*
3. Load in the lower part of the window *"Equation"* the previously stored calibration polynomial with *Load*:
4. Start the calibration with *Apply Eq*

Equation

Load **Lambda** = x⁴ 0.E+0 + x 1.4717E+1 + x³ 6.4034E-6 + -835.14 + x² -9.9272E-3 Apply Eq

Save

Reset

C:\Program Files (x86)\Visual Spec\test3.exc ✓

7 Calibration and Normalization of the Intensity

7.1 Preliminary Remarks

The calibration of the spectral flux density, hereafter called intensity "I" or flux calibration is much more complex compared to the wavelength λ . In addition, there are several, different options, which must be correctly chosen according to the task. For an appropriate decision support see [1].

The intensity profile of the recorded raw profile (pseudo-continuum) appears to be strongly deformed, mainly due to instrumental influences, but also caused by scattering effects in interstellar space and in the earth's atmosphere. This continuum course is therefore unusable and must, together with the embedded spectral lines, be proportionally scaled to a new level. For the theoretical background see [1].


7.2 Rectification of the Continuum Intensity

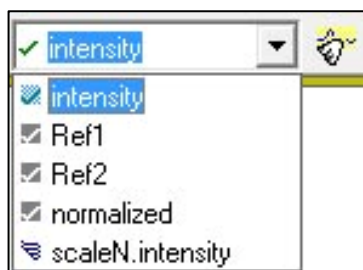
Here the intensity profile is removed from the spectral profile, and its course gets rectified. This is done by dividing the calibrated raw profile by the fit of its own continuum course. This results in a rectified, horizontally running profile. Even in the professional field this simple calibration is adequate for most applications. If the recorded raw profile shows a reasonably steady course, the easier variant "*Radiometry/Automatic Continuum*" can be tried. Otherwise, the more work-intensive, manual option "*Radiometry/Compute Continuum*" must be applied [1].

I Automatic generation of the continuum fit

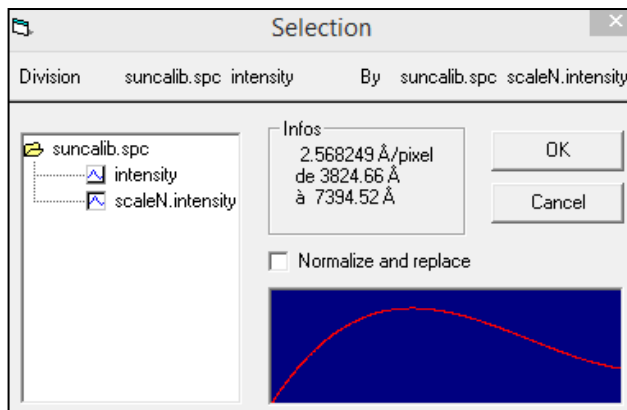
1. Load the wavelength-calibrated raw profile with "*File/Open profile*" into the Vspec program (if necessary set the file format from ".spc" to "all").
2. Create continuum fit with "*Radiometry / Automatic Continuum*". This automatically generated continuum fit is now called "*scaleN.Intensity*". If the result is insufficient, the continuum fit must be created manually (see below).

Note: With the following steps 3 – 7 the spectral profile "*Intensity*" is divided by the continuum fit:

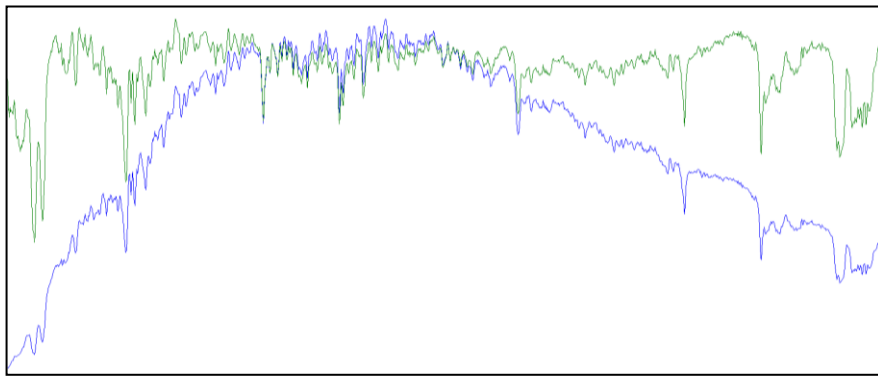
3. Delete all profiles in the window with the icon "*Erase*" 
4. Select "*Intensity*" profile (window on the left edge of the header)



5. Select *Operations/Divide Profile*
6. In the popup window "*Selection*" activate "*scaleN.Intensity*" as divisor



7. Confirm with OK. The rectified, continuum-adjusted profile, appears now superposed and in green color with the name "*Division*".






8. Click the "*Replace*" Icon 

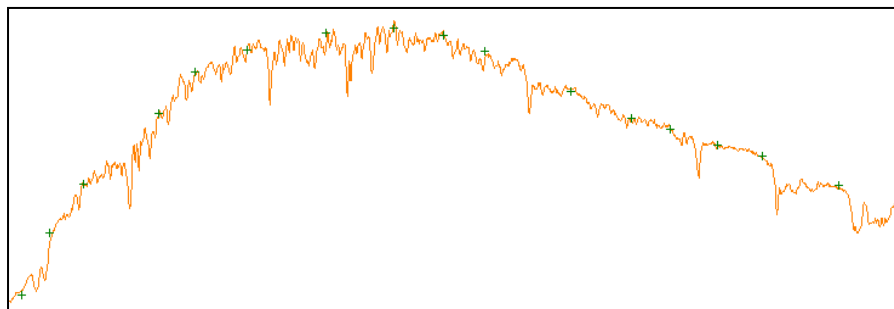
9. Mark "Intensité"


10. Confirm with OK

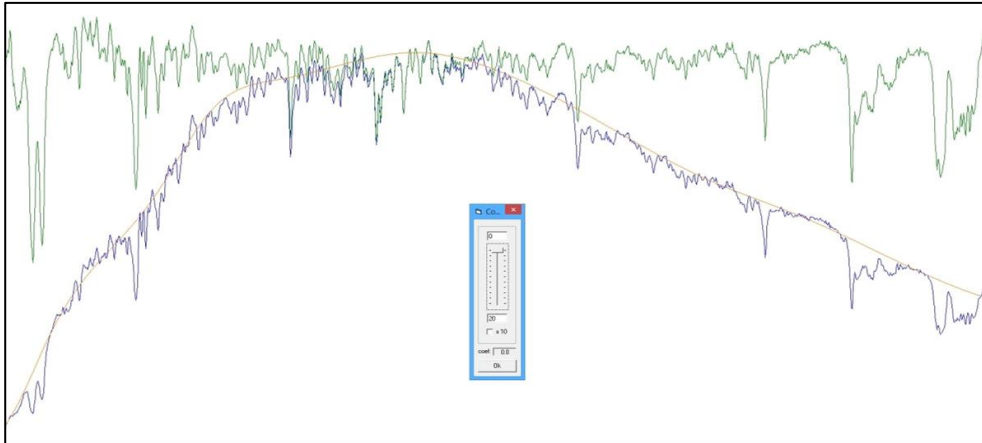
11. The adjusted profile appears now with the name "Intensity" and can be saved under a changed name.

II Manual generation of the continuum-fit

1. After loading of the profile start process with "*Radiometry/Compute Continuum*".
2. On the new appearing toolbar, press the icon  for point editing
3. Mark on the curve with the cursor several points, representing the run of the continuum, whereby spectral lines must be skipped! A cross can only be set if the hand symbol  of the cursor changes to the arrow display .




4. Generate the fit to the continuum by clicking on the Execute icon . This manually generated continuum fit is now called "*Fit Intensity*".
5. With a click on the pop-up slider, additionally the straightened, continuum-adjusted profile appears. This shows, as a preview the result if the calibrated raw profile would now be divided by the currently displayed continuum fit.



6. If the curve looks similar to the example on the image above, press the OK button on the popup slider. If the smoothed polynomial fit (now appearing "orange") runs still too "jumpy", it must be further smoothed with the pop-up slider. In order to achieve a visible effect (depending on the course of the curve) a two- up to a maximal five digits figure (for example 20,000) must be entered in the lower window and possibly even the x10 field must be ticked. In stubborn cases, possibly the entire procedure needs to be repeated with a changed point distribution.
7. Select the "*Division*" profile (window on the left edge of the header)

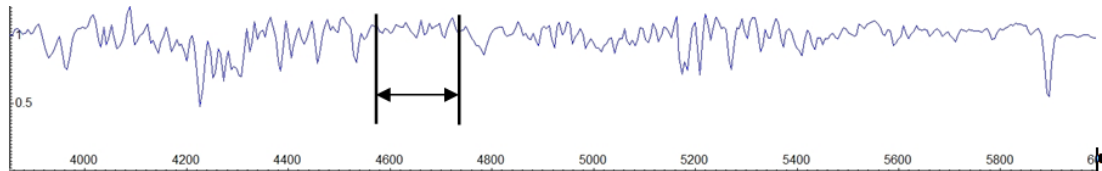



8. Click the "*Replace*" Icon 
9. Mark "*Intensité*"
10. Confirm with *OK*
11. The adjusted profile appears now with the name "Intensity" and can be saved under a changed name.

7.3 Normalize the Intensity to a Continuum Section

After rectifying the profile according to 7.2, the intensity axis appears scaled with up to 6-digit numbers, which were derived by Vspec from the ADU (Analog Digital Units) of the raw profile. This scaling is mostly unusable and the rectified new continuum level is therefore set to $I_c = 1$, i.e. "normalized to unity".

1. Mark with the cursor a representative appearing section with very few spectral lines



2. Normalize this section with the icon  to 1. The continuum level has now the intensity $I_c = 1$. This step is e.g. necessary to determine the equivalent value EW of a spectral line.

7.4 Normalize the Intensity to the Continuum Peak

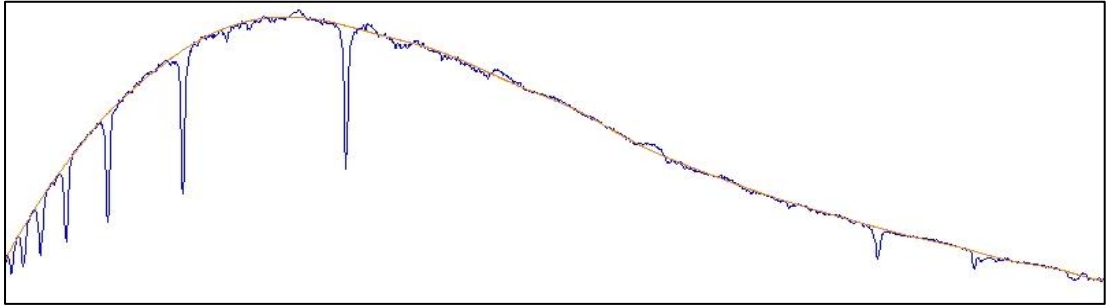
In special cases it may make sense to define the maximum peak intensity of the continuum course I_{max} exactly as 1:

1. Load the wavelength-calibrated raw profile with "*File/Open Profile*" into the Vspec program (if necessary set the file format from ".spc" to "all").
2. Use the cursor to move to the point of highest intensity I_{max} in the profile and read off and note the intensity value I in the yellow window of the toolbar
3. Click "*Operations/Operations with values*"
4. Click *Division* in the Popup menu and enter the maximum intensity value I_{max} in the parameter field.
5. Click *Apply* and then *close*. All y-values of the curve are now divided by the maximum peak intensity, i.e. the intensity curve moves now between 0 and a maximum of 1.

7.5 Relative Flux Calibration by a Synthetic Continuum

The goal of this simplistic method is a very rough approximation of the recorded pseudo continuum to the *original*, and therefore *unreddened* continuum course of a recorded star whose spectral class however must be known. The intensities of the recorded spectral lines are scaled directly to the synthetically generated continuum course of an interstellar *unreddened star model*, as far as possible of the same spectral class. For theoretical aspects of this type of calibration, see [1].

1. Load the wavelength-calibrated raw profile with "*File/Open Profile*" into the Vspec program (if necessary set the file format from ".spc" to "all").
2. Create a continuum fit to the Intensity profile, analogously to chap. 7.2, steps 2 – 6. This new curve is named "*Fit.Intensity*".




3. If still unknown, determine first the spectral type of the recorded star, e.g. with planetary programs like Winstars, Redshift, or stellar databases like, SIMBAD [6].

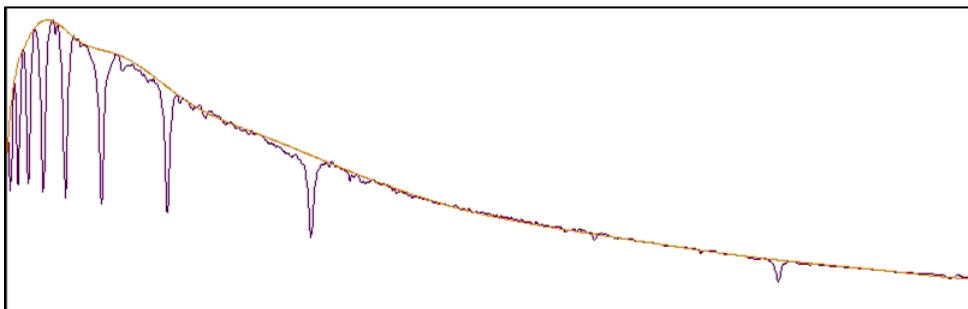
Note:

For brighter stars also the Vspec function (*Tools/Spectraltype*) can be applied. This feature requires the enabling of macro execution by Excel defined under *Excel Options/Trust Center*, which however reduces the security level. Alternatively you can directly open the Excel file *brscat2* (Bright Stars Catalog) in the root directory of the Vspec program. For this Vspec function, the required input format is the abbreviated "Bayer Number" e.g. for Rigel *betori* (Beta Orionis), for Betelgeuse *alpori* (Alpha Orionis) or alternatively with the "Flamsteed Number" e.g. *58ori*.

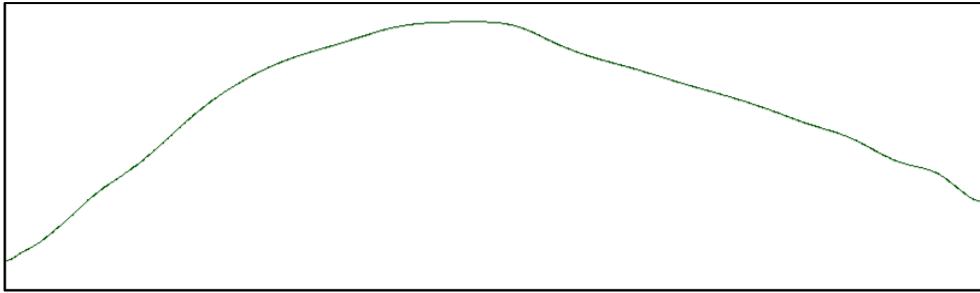
4. Load under *Assistant/Library* the synthetic profile of the star model, with a spectral- and luminosity class as close as possible to that of the investigated star. Move the appropriate *.dat*-file from the upper part of the window with click and drag into the profile window. The profile of the star model immediately appears superimposed in the window, named after the spectral type, e.g. 2b9iii.dat (B9III).



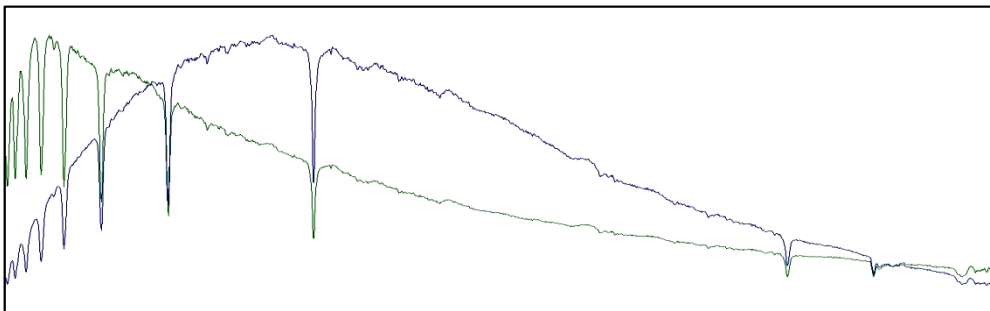
5. Delete all profiles from the window with the icon "Erase" .
6. Load the synthetically generated profile of the star model (e.g., 2b9iii.dat) in the window on the left edge.
7. Create continuum fit of the profile, analogously to chap. 7.2, steps 2 – 6. This new profile is titled "*Fit.[Spectral class].dat*" (e.g., *Fit.2B9iii.dat*)



8. Divide "*Fit.Intensity*" by the smoothed model profile "*Fit. [Spectral class] .dat*", as described in chap. 7.2, steps 7 – 11. This correction curve is named "*Division*" and corresponds to the so-called "*Instrumental Response*".



9. By dividing the "*Intensity*" raw profile by the Instrumental Response "*Division*", the spectral lines of the recorded pseudo-continuum are finally scaled directly to the fitted continuum course of the star model. The procedure runs analogously to chap. 7.2, steps 7 – 11.

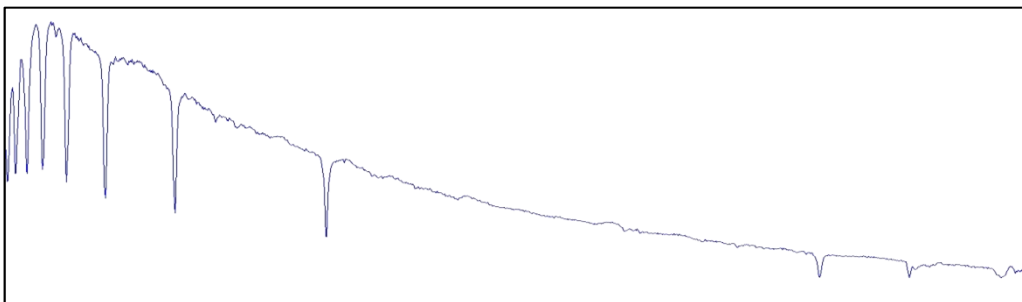


10. Click the "*Replace*" Icon



11. Mark "*Intensité*"

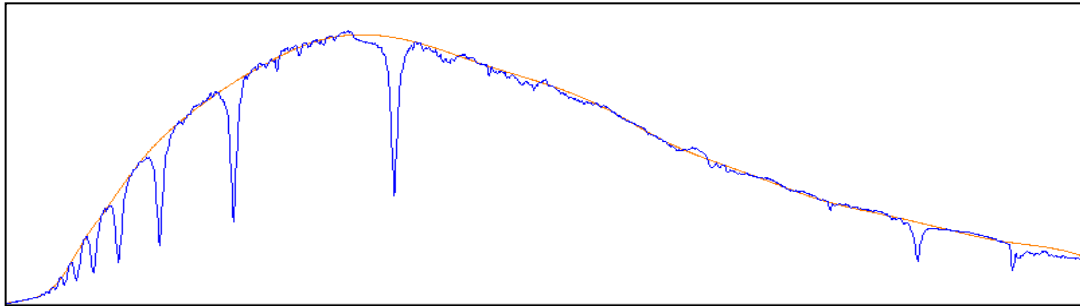
12. Confirm with OK. As a final result, the radiometrically corrected profile now appears in blue under the name "*Intensity*" and can now be saved under a different name.



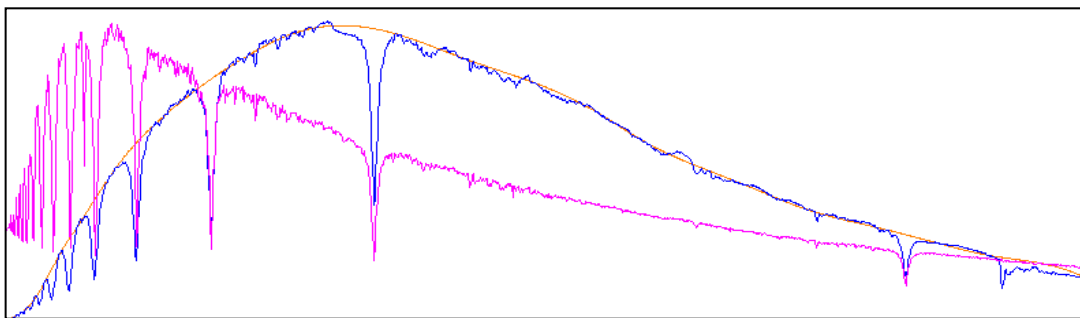
7.6 Relative Flux Calibration by a Standard Star

The principle of this method is described in [1] and works analogously to that in chap. 7.5. The generation of the correction curve "instrumental response", however, takes place here with a separately recorded standard star which must be as close as possible to the examined object. Here it is strongly recommended to first generate and save the response curve in a separate process. Steps 3 – 8 in chap. 7.5 can be skipped and, instead of step 8, this stored response curve is loaded into the diagram. In this section, only the generation of the response curve, generated with the recorded standard star, is demonstrated:

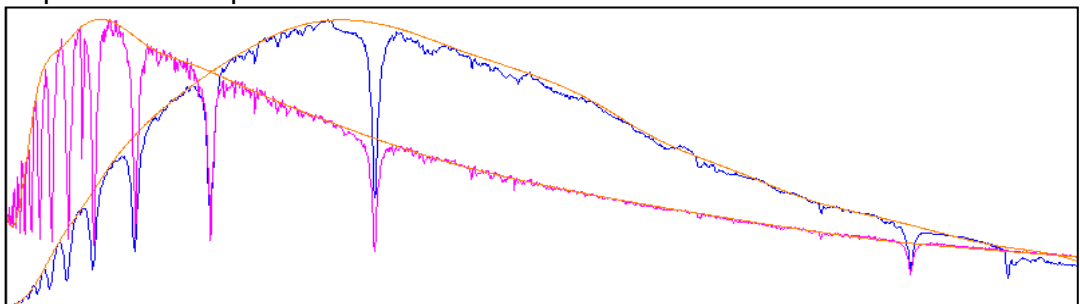
1. Load the wavelength-calibrated raw profile of the recorded standard star with "*File/Open Profile*" into the Vspec program (if necessary set the file format from ".*spc*" to ".*all*").
2. Generate a fit to the profile of the standard star, analogous to chap. 7.2, steps 2 – 6. This profile is named *Fit.intensity*.




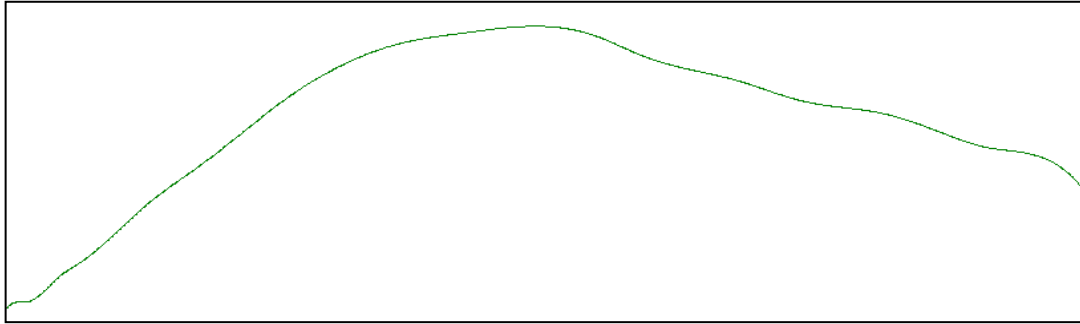
3. Load the profile of the identical star from the catalog (same HD number), e.g. from the *ISIS_Standardstar Database_v7*. Open the profile with *File/open profile*. The file format must be set under "*filtre*", depending on the catalog, to *.dat* or *.fit*. The catalog-profile opens in a separate window and must first be copied into the main diagram with Copy Paste. Here it appears superimposed in red and is named *serieX*.



4. Generate a fit to the catalog profile *serieX*, analogously to chap. 7.2, steps 2 – 6. This profile is titled *Fit.serieX*



5. Delete all profiles from the window with the icon "*Erase*" 
6. Divide the fit of the standard star "*Fit.intensity*" by the smoothed catalog profile "*Fit.serieX*", analogously to chap. 7.2, steps 7 – 11. This correction curve is named "*Division*" and corresponds to the so-called "Instrumental Response". This can now be saved under a new name, e.g. *instrep*.



7.7 Search for the Appropriate Standard Star

ISIS [10] contains several catalogs with standard stars. They can be found in the root directory under the folder *isis_database_v7*, most of them stored with the HD numbers in the notation *m_HDxxxxxx*. To process such profiles they can be loaded in Vspec with "*File/Open Profile*". Depending on the catalog, the format in the "*filtre*" field must be set to *.dat* or *.fit*. It is worth copying this ISIS Folder with this database into the designated working directory of Vspec.

The HD number of a star increases in principle with increasing right ascension. Therefore, to find a suitable standard star, first determine the approximate range of HD numbering in the vicinity of the examined object. With this information you can search for standard stars with similar coordinates in the various catalogs of the ISIS software. Helpful here would of course be a corresponding list, which is sorted by coordinates!

In the ISIS program, these databases appear under the folder "*5. Profiles*" and the button "*Database*". With "*Display*" (for example, Miles), the data of the standard stars such as the spectral class, coordinates and profiles can be viewed.


The Miles Library (IAC) is probably the most suitable for broadband spectra. For practical reasons (generation of the continuum fit), the spectral class should be restricted to late B-, A- and possibly early F classes (with the button on the right). It is important that the elevation angles above the horizon are as similar as possible for both objects. This can best be determined with a planetarium program (e.g., Winstars).

A table sorted by right ascension can also be found on the Miles homepage. Here, the interstellar reddening $E(B - V)$ can also be viewed for every standard star.

<http://www.iac.es/proyecto/miles/pages/stellar-libraries/the-catalogue.php>

8 Formatting and Exporting a Spectrum with Vspec

8.1 Formatting the X- and Y-Axis

1. Click on the yellow square  on the right edge of the frame. The scaled X- and Y- axes appear.
2. Double-click on diagram area – the pop-up window "Graphic" appears.
Note: In most cases the default values displayed in "Graphic", generate an unusable formatting and must be adapted accordingly:
3. **Axis X:**
 Remove the tick in the box "Auto" and put e.g. *Nb ticks* on 10 and *tick* on 10. If the labeling appears too dense, the combination 10 and 20 can also be tried. Possibly set the range to be displayed on the X axis with X min and X max. However, this can also be done by marking the desired diagram area with the cursor and cropping with Crop.
4. **Axis Y:**
 Set the desired vertical display range of the curve with *Hi threshold* and *Lo threshold*. If more than one profile is open and you want to apply this customization to all series, mark "Apply to all Windows". Remove check mark on "Auto" and adjust values. If a horizontal profile has been normalized to 1, e.g. set *Nb ticks* to 20 and *tick* to 0.01. For raw profiles, e.g. the combination 5 and 5000 can be tried. The display of the Y axis can also be suppressed by removing the mark in the box "Y-axis display".

8.2 Customize Colors and Fonts

1. Click on the spectral curve ("*Intensity*") (or select in the window) and select the curve color with the menu in the header (e.g. *Blue*)
2. Use *Format/background color* poss. to adjust the background color of the diagram
3. Under *Format/Line* the line width can be set to 1 or 2 and the font size and type can be adjusted with *Format/Font*.

8.3 Presentation of Several Superimposed Curves

To compare the intensity of multiple profiles – even with non-rectified profiles – they can be displayed superimposed in one single diagram:

1. Previously normalize all profiles, to be overlaid according to chap. 7.3, to the same continuum section to unity ($I_c = 1$).
2. To display superimposed, copy these normalized spectra with *copy/paste* into one diagram.
Note: Under *Options/Preferences/Continuum* you can enter the start- and end wavelength to ensure an uniform reference section.
3. In the box "Axis Y", the position with respect to the Y-axis and the desired amplitude of the selected curve can be set with "*Hi threshold*" and "*Lo threshold*". The curve to be formatted can be selected by mouse click or in the window on the left edge of the header. If the amplitudes have to be adjusted, this must be done proportionally equal for all curves, to grant a valid intensity comparison.

8.4 Export of the Formatted Graphic

With *file/export*, a screenshot of the current display on the screen can now be created in various formats (for example, jpg, bmp).

Note: In the Vspec program, "*save as*" only saves the calibration and normalization. The graphic formatting, but also the superposition of several profiles, are getting lost!

8.5 Create a Synthetic Spectral Image

Derived from the intensity profile, a synthetically generated, colored spectral image can be generated. This has no scientific value but may e.g. be used for later commenting of the spectrum or as a graphical complement to the spectral profile. The brightness and contrast of this synthetic spectral image is sensitive to the formatting and position of the profile with respect to the Y-axis. Therefore, often a further editing in Photoshop is necessary.

1. Select *Tools/Synthesis* (spectral strip appears in black and white)
2. Color display: right click on the spectral strip and click "*colorer*"
3. Export under the desired file format and name with "*exporter*".

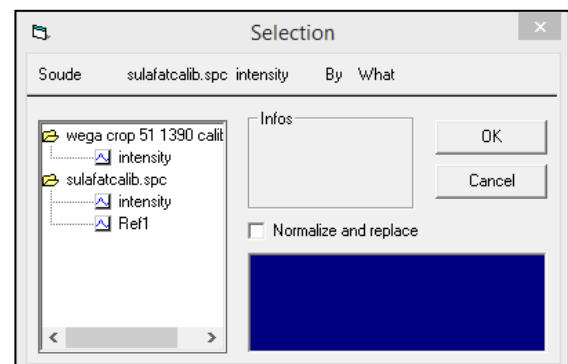
Note: Mostly, the image must be to be reworked somewhat with the *levels* correction in the Photoshop program.



8.6 Assembly of Overlapping Spectral Profiles

Preliminary remark: With this method, two calibrated spectral profiles can be assembled, which slightly overlap at the interface. This function is best performed on profiles with a rectified continuum (chap. 7.2). A practical example is displayed in chap. 14 by assembling of two echelle orders.

1. Open the two calibrated profiles (.spc) in Vspec.
2. If not already done, rectify both profiles by removing the continuum course according to chap. 7.2.
3. Under "*Operations*" select the command "*Join*". The window "*Selection*" appears with a File Explorer and a blue display
4. Double-click on the both folders so that the "intensity" files are displayed.
5. Click both boxes with "*intensity*" files. The according profiles are displayed in the blue window.
6. Confirm with *Ok*. A new window with the composite profile (green) appears under the name "*NewSpc-0*" and can thus be saved.



This procedure is relatively delicate. If the message appears "*The two series do not superpose*", the composition can be retried by cropping a modified overlap area.

9 Quantitative Information in the Spectral Profile

9.1 Preliminary Remark:

Here the practical extraction of quantitative information from the calibrated and normalized spectral profile is described. Theoretical basics see [1].

9.2 Info Based on Marked Single Lines or Profile Sections

1. Mark the desired line by *click and drag*
2. Right-click to call Popup Menu. Alternatively, it can also be called up by *Spectrometry/Computation Preferences*.
3. Click *Computation*
4. Tick the desired values in the popup field
5. Confirm with *OK*
6. The results are displayed in the blue display window (delete with reset):

SNR: Signal Noise Ratio in the spectral profile - the bigger the better. This value is not determined at a single line but within a larger, marked section. The choice of a reasonable reference area is tricky.

FWHM: Full Width at Half Maximum Height of a spectral line [Å]

EW: Equivalent Width of a spectral line [Å]

Barycenter: Centroid of the line profile [Pixel]

Line Center: Wavelength of the spectral line i.e. of the barycenter [Å]


Area: Area of the line profile

Std deviation: Standard deviation of the curve in the area of the line profile

Notes

- FWHM and EW (LEQ) should, with few exceptions, always be measured by a Gauss fit of the original profile, as is common in the professional field today. This curve is generated by *Spectrometry/Gaussian Fit*. In this case FWHM is calculated and displayed directly. However, EW (LEQ) must be determined at the Gaussfit according to the above displayed steps 1 – 6 with several, possibly averaged measurements, since the result reacts sensitively to the marked area.
- The selection of the marked area can also be done more reproducibly with an autoselect function under *Options/Preferences/References*. First enter in the box "*Auto Selection line width*" the estimated width of the entire spectral line in [Å]. With pressed *ctrl* key then just click the line and the selection takes place automatically.
- The EW value can only be determined after a normalization of the profile to unity (Section 7.3). Thereby the selected section for normalization has no noticeable influence on the result!

9.3 The Determination of Spectral Sampling

In the upper menu bar , as a measure for the dispersion, the "Spectral Sampling" of the profile, obtained with the specific pixel grid of the applied camera, can be read in [Å/pixel].

9.4 The Determination of the Photosphere Temperature

The inclination of the continuum $dI/d\lambda$ allows the estimation of the photosphere temperature, in Vspec called "*Temperature de Planck*". The principle is described in [1] and in the Vspec Manual [11]. This requires a relative flux calibration of the profile with standard star according chap. 7.6. Based on the slope of this profile, finally, the "*Température de Planck*" can be read:

1. Select *Radiometry/Planck*
2. Enter the estimated photosphere temperature of the star in the pop-up temperature window
3. Change the value iteratively until the displayed curve (for example P_3200) runs as parallel as possible to the radiometrically corrected continuum.

10 The Line Identification

The principle and the strategies of the line identification are described in [1]. Here follow some hints for according tools in Vspec. Under *Assistant/Elements* you will find element and ion lists for several object classes (3000 – 10'000 Å). The prerequisite for the analysis is a high-resolution spectrum which is calibrated according to rest wavelengths and thus is neither red nor blue shifted. Clicking on a specific position on the loaded profile immediately marks in the list the entry with the nearest wavelength. The box *Elements* allows for ions or elements to be specifically selected and transferred to the calibrated profile for display by *Sort* and *Export*.

lineident

This list is used for identifying unknown elements or ions in stellar spectra.

element

This list has proven to be useful when evaluating laboratory spectra, e.g. for determining the gas composition in a discharge lamp or calibration light source.

sun

Contains solar absorptions between 6000 und 6800 Å

nebplan



Contains emission lines typical appearing in emission nebulae

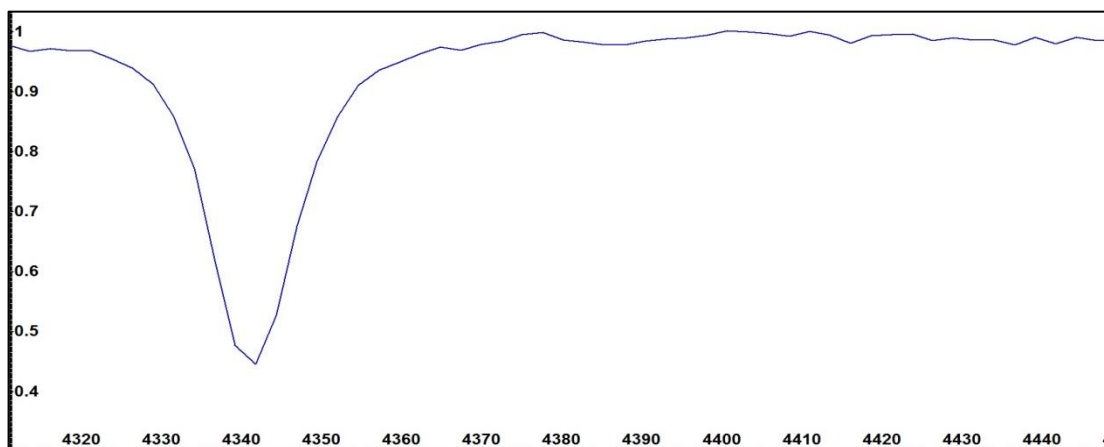
atmos

Contains the atmospheric H₂O lines around the H α line.

11 Scaling the X-axis in Doppler Velocity

For the display e.g. of star rotations and velocity variations in binary star systems, it makes sense to scale the wavelength axis in the range of the investigated line profile, instead of the wavelength [Å], converted into Doppler velocity [km/s].

1. Open in Vspec the profile, wavelength calibrated, rectified and normalized to unity, with "*file/open profile*" (if necessary set the file format from *.spc* to *all*).
2. Click on the yellow square  on the right edge of the frame. The scaled X- and Y-axes appear.
3. Mark with *Click and drag* the desired zoom range around the line to be measured and activate it with the magnifying glass icon .
4. Double-click on the diagram area – to activate the pop-up window "Graphic".
5. Deactivate "*Auto*" in the "Axis Y" section and, for example, set *Nb ticks* to 50 and *tick* to 0.002 to achieve a reasonable scaling of the Y axis.
6. Restrict the displayed area of the Y-axis in such a way that the intensity curve of the line fills a large part of the diagram height. In the "Axis Y" section, adjust the "*Hi threshold*" and "*Low threshold*" values accordingly and confirm with *Apply*.
7. Move the part of the curve to be examined by the section "Axis X" with appropriate values for x_{\min} and x_{\max} to the left near the intensity axis.

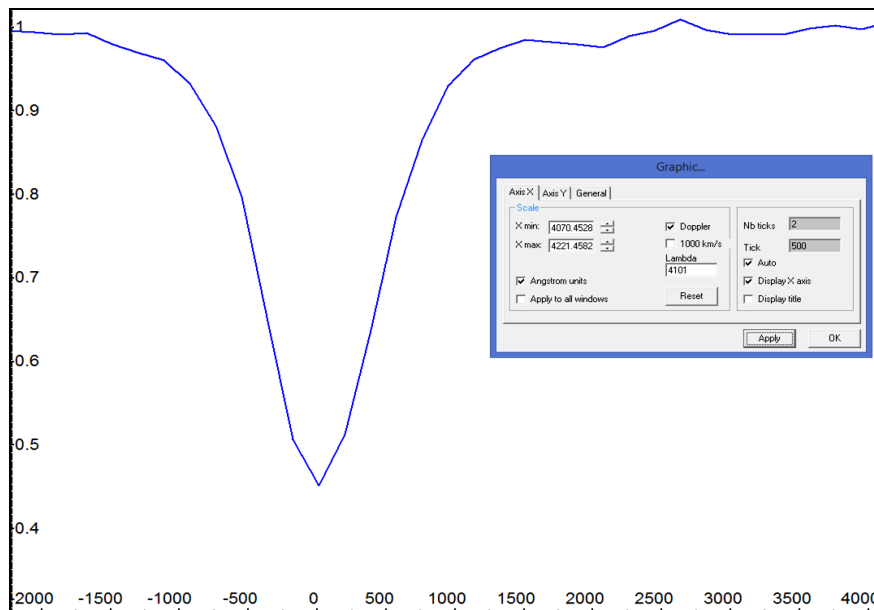


8. Adjust the font under *Format/Font*
9. In the section "Axis X", mark the Doppler box. Disable the "*Auto*" box and set *Nb ticks* to 10 and *tick* to 1 typically. Furthermore, the central wavelength λ_{r0} of the line must be entered in the "*lambda*" field.

Notes:

This value will now define the 0 point on the wavelength axis from which the Doppler velocities are plotted in the red direction (positive values) and in the blue direction (negative values). In many cases, λ_{r0} corresponds to the measured wavelength of the profile. Often, however, also Doppler shifts are displayed this way (for example in the case of spectroscopic binaries). This then requires a corresponding adaptation of λ_{r0} . If the box *1000km/s* is marked, Vspec automatically scales the displayed area of the X axis from -1000 km/s to +1000 km/s.

10. Finally confirm with *Apply*
11. The X-axis appears now scaled in Doppler speed



12. In some cases the correct display of the scale may still require an adjustment of the tick values in the section "Axis X". If the zero point should now be wrongly labeled e.g. with -2 km/s instead of 0 km/s, the *Nb Tick* value is usually too low. Sometimes changing the zoom range will also help.
13. The resulting diagram can now be saved with "File/Export bmp".

12 Heliocentric Corrections

12.1 Heliocentric Correction of the Radial Velocity

Here, a topocentrically measured radial velocity $v_{r_{measured}}$ evaluated by Vspec is reduced to the generally applied heliocentric viewpoint $v_{r_{Hel}}$. For this purpose, the average orbital velocity of the earth around the sun (about 30 km / s) and further the influence of the earth's rotation on the measured radial velocity of an object, must be compensated:

1. Under "*Preferences/Position*" enter the coordinates, altitude and time zone of the observation site (Western longitude and southern latitude negative -).
2. In the Vspec program activate "*Spectrometry/Heliocentric correction*". Under "*Site coordinates*" you can see the location coordinates of the observation site, entered in step 1.
Note This function can only be activated if any profile is loaded!
3. Under "*Object coordinates*" in the line "*Alpha*", enter the right ascension and in the line "*Delta*" the declination of the observation object with the correct sign.
4. Under "*Date*" the date is entered, whereby the observation time is expressed as a decimal value, proportional to the day length of 24h. 3.75 means e.g. the 3rd day of the month, 18'00.
5. By default, the λ_0 value of the H α line appears under "*Lambda ref*".
6. The calculation is triggered by clicking on "Compute".

Heliocentric

Site coordinates

Latitude (deg.) 47.2400016784

Longitude (deg.) 8.5 + E, - W

Object coordinates

Alpha 19 hh 15 mm 33 ss

Delta 77 ° 4 mm 15 ss

Date

Day, month, year

17.75 11 2017

Lambda

Lambda ref: 6562.85 angstroms

Compute

Close

Infos...

Reset Header Save

Julian Day: 2458075.25

Corr. Lambda (Å): 0.031

Speed (km/s): 1.41

Corr. JD (days): 0.00114

Azimuth (deg.): 163.5

Height (deg.): 55.08

Air mass: 1.219

12.2 Evaluation of the Calculated Data

- Julian Day: Julian date of the entered observation date/time
- Corr. Lambda: Amount in [Å] by which a recorded profile appears displaced due to heliocentric earth movement
- Speed: Heliocentric correction speed $v_{r_{korr}}$ in [km / s] by which the measured radial velocity of the object $v_{r_{measured}}$ must be corrected.

$$v_{r_{Hel}} = v_{r_{gemessen}} + v_{r_{korr}}$$

Corr. JD: Correction value [days] to heliocentrically correct the time of an observed event. Example: $0.00114 \times 24 \times 60 = +1.64$ minutes

Additionally indicated are here azimuth and elevation, as well as the "Airmass", i.e. the light path of the object through the Earth's atmosphere, relative to the minimum distance in the direction of the zenith.

Notes:

- The signs of the determined values must be algebraically correctly applied in the formula.
- The calculated $v_{r_{Hel}}$ can be checked for Milky Way objects in CDS SIMBAD [6] and for extragalactic objects in the NED (NASA Extragalactic Database) [7].
- Comparing measurements of many objects with known radial velocities (e.g., sun) allows for the detection of any systematic bias that may be corrected in future measurements.

12.3 Correction of the Doppler Shift in the Spectral Profile

After performing steps 1 – 6 in chap. 12.1, the wavelength calibration of the loaded profile by the value Corr. Lambda can be corrected to the rest wavelength λ_0 .

1. Start the correction process with *Spectrometry/Heliocentric* speed correction. In the pop-up field, the heliocentric correction velocity appears $v_{r_{korrr}}$. appears as the deviation to the rest wavelength λ_0 . This number can also be overwritten with another value.



2. Start the adaption of the calibration of the loaded profile by clicking "Appliquer".
3. The adjusted "Intensity" profile can be saved under a new name

Note: If the profile contains known spectral lines, it can of course also be recalibrated based on rest wavelengths λ_0 .

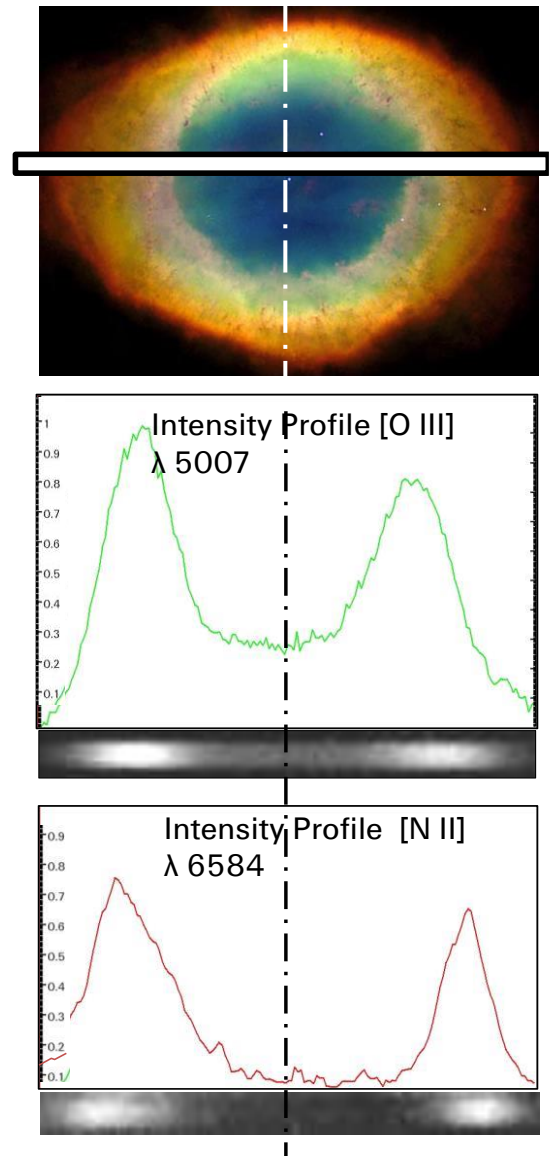
13 Intensity Distribution of Ions within an Emission Nebula

Spectrographs with a long slit allow 2D- appearing objects such as emission nebulae, to map the intensity profile of a given spectral line along the entire length of the slit. This allows rough conclusions about the distribution of the emission strength the corresponding ion produces at a specific wavelength.

This example from the spectral atlas [2] shows the planetary nebula M57, supplemented with a drawn 50 μ m slit. At 2000mm focal length, the slit length exceeds ideally just barely the diameter of the nebula projected in the slit plane. Here, the different intensity courses of the two strongest appearing emission lines, O III at 5007 \AA and N II at 6584 \AA , have been evaluated.

Since DADOS aligns all three slits in a line, this array can be evaluated as a "long slit" with two short gaps. The different slit widths hardly play a role here, since only the intensity profile is evaluated. As an example, see the cross sections through M42 in the Spectral Atlas [2].

Prerequisite for this procedure is an accurate tracking, possibly even supplemented with autoguiding, which ensures that the slit position with respect to the object shows no significant shift. In order that a serious, subsequent analysis is possible, the exact slit position with respect to the nebula must be documented, e.g. by a screenshot.



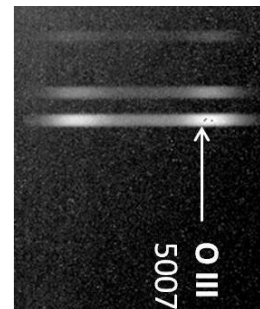
Note:

IRIS and Vspec have no designated function to accomplish this special task. However in the following it will be shown, how such an intensity profile can be generated, applying these programs combined with some "artifices".

1. Load in IRIS with "*file/load*" an image processed according chap. 3.4



2. Rotate the image by 90 ° with *Geometry/Rotate* according to chap. 14.1. The individual spectral lines should now run horizontally, otherwise adjust the angle of rotation. This and the following steps are only demonstrated on the O III line.

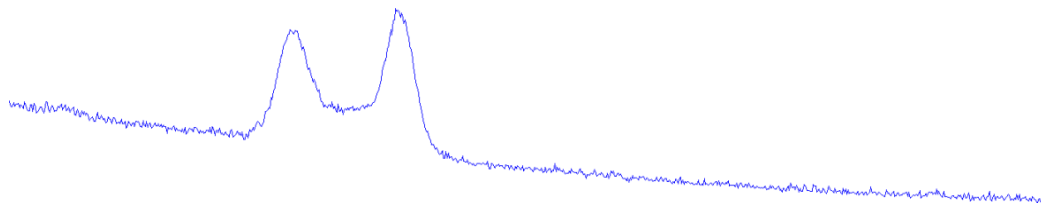


3. Generate a 1D intensity course along the slit length: Frame the line with the cursor and apply *Spectro/2D -> optimal addition* (according chap. 3.2, steps 7 – 8).



1D

4. Save the 1D intensity course for further processing with Vspec
5. Load the 1D intensity course in Vspec and generate an intensity profile according chap. 4.2, steps 1 – 3.



Note: With Vspec, the continuum can *only* be rectified at a wavelength-calibrated profile, why a *purely fictitious* and *arbitrary* "*pseudo-calibration*" must be performed here. Following the easiest way:

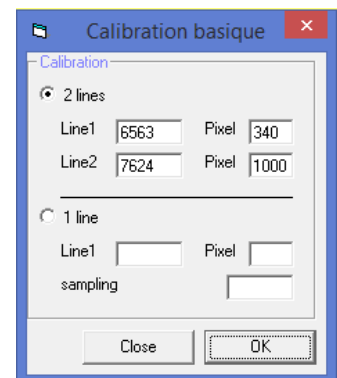
6. Select *Spectrometry/basic calibration*

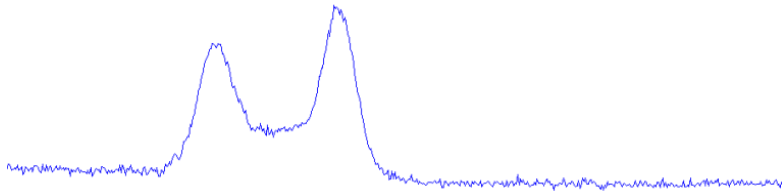
e.g. input for

Line 1: 6563 to Pixel No. 340 and

Line 2: 7600 to Pixel No. 1200

7. After confirming with OK the profile appears with the arbitrary pseudo-calibration, just to enable the further steps.
8. Rectify the course of the continuum analogously to chap. 7.2, steps 1 – 15. Exception: Only points on the left and right side of the intensity profile should be marked.





9. Crop the profile to the area of the intensity profile and export it as Bmp or Jpeg. When formatting the intensity scale, it may make sense to select the highest point as 1 and the base of the profile as 0 (see graphic above from M57).



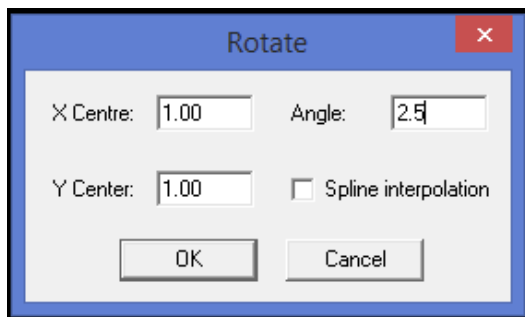
10. The graphic may now be imported e.g. into PowerPoint for further formatting and labeling.

14 The Processing of Echelle Spectra

14.1 The Evaluation of Individual Orders

In most cases Echelle spectra are obtained for the high-resolution investigation of specific lines. Here, the much simpler evaluation of individual orders is often sufficient. However, the prerequisite is that they are only slightly curved and the spectral lines are reasonably perpendicular to the wavelength axis. Therefore, also profiles, generated by Baches- and SQUES spectrographs, can be conventionally processed, calibrated and formatted as with ordinary grating spectrographs.

Due to a mostly present, if only slight curvature of the strip, it's leveling requires some care. This adjustment should be performed *before* the recording by the mounting angle of the camera and recording the daylight or calibration light source. It is the aim to strive for a reasonable compromise through trial and error. By software, the rotation of a spectral image in IRIS can be done via "Geometry / Rotate":



The X- and Y- values define here the pixel coordinates about which the rotation (angle) of the strip is to take place. Of course, this procedure must be repeated identically for the calibration spectrum.

14.2 Overview of the Processing Steps

The following graphic first provides a rough overview of the individual steps of data reduction. Order 43 from the Arcturus spectrum contains the striking magnesium triplet (Fraunhofer b) in the range of approximately 5160 – 5190 Å. This area should be shown here as a section.

Horizontally leveled raw recording of order 43, Arcturus α Boo

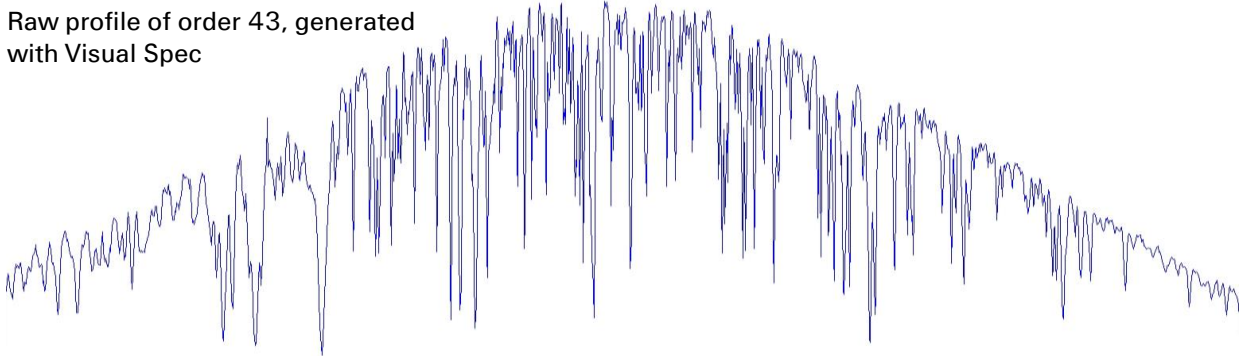
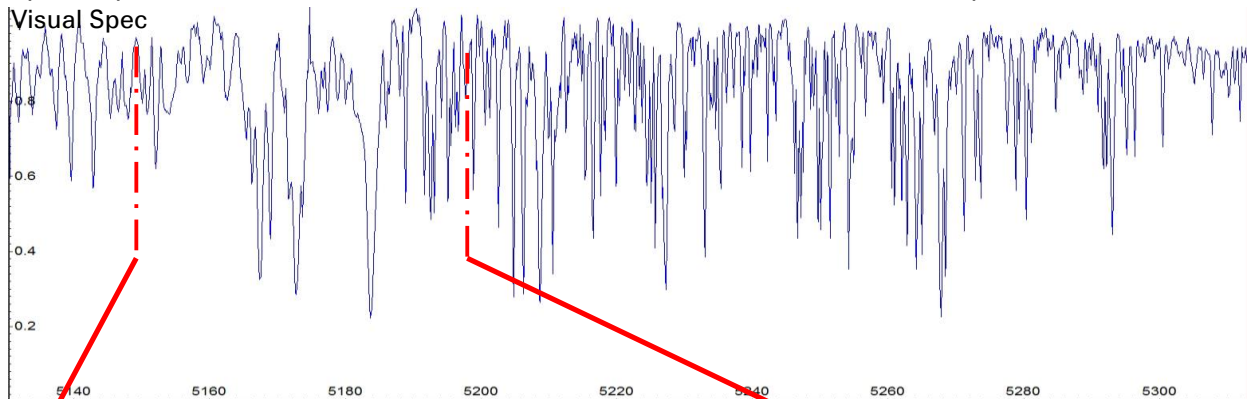
1D Spectrum of order 43 after processing with IRIS



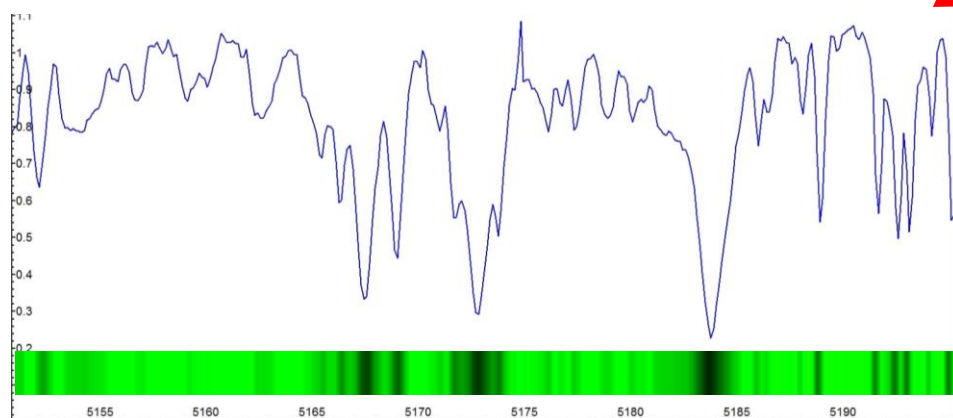
1D RELCO calibration spectrum of order 43 after processing with IRIS



Raw profile of order 43, generated with Visual Spec

Spectral profile of Arcturus, Order 43, calibrated rectified, and normalised to unity $I_c = 1$ with Visual Spec

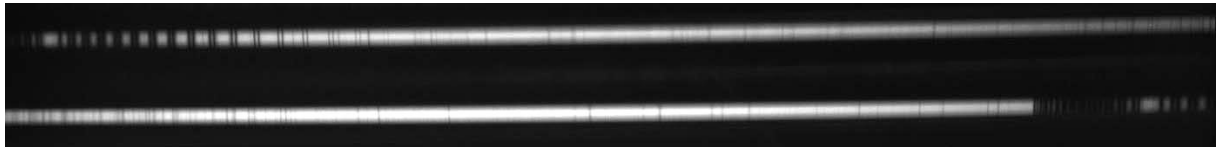
Cut out of the Magnesium Triplet Arcturus, Order 43 with Visual Spec



14.3 Assembly of Individual Orders – Detailed Presentation of the Process

The entire process is demonstrated here using the example of the impressive and finely structured Fraunhofer A line. The following section of a SQUES-Echelle spectrum of the day-light shows this absorption, distributed among orders 29 (top) and 30 (bottom).

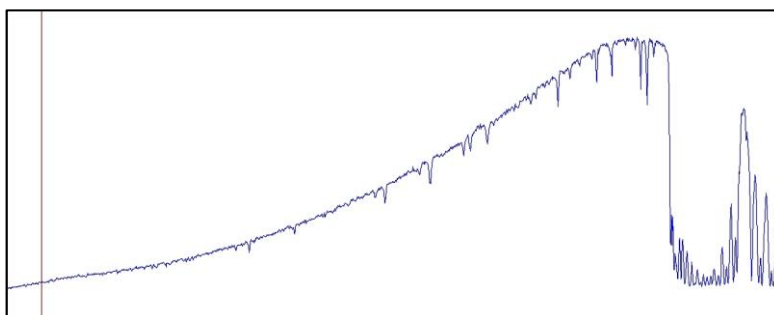
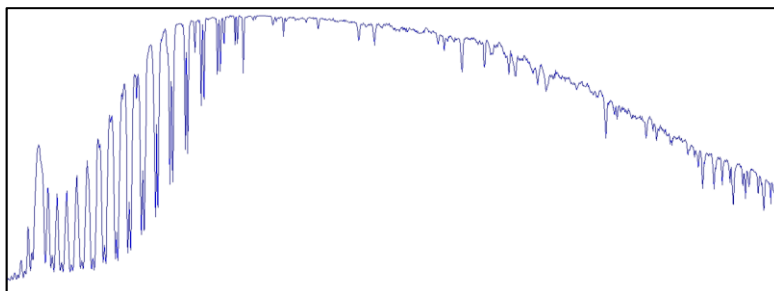
Because this broad spectral feature extends over two orders, both must be evaluated separately and then, according to chap. 8.6, be assembled.




1. The data reduction takes place, with one exception, according to steps 1 – 9 in chap. 3.2. Step 5 is omitted here, because with Echelle spectra, due to low slit height, the sky background can only be subtracted as a separate recording.
2. After step 9, the processed orders 29 and 30 are displayed here as 1D strips. They are shown slightly widened.

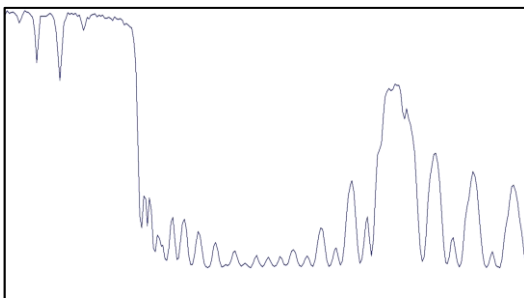
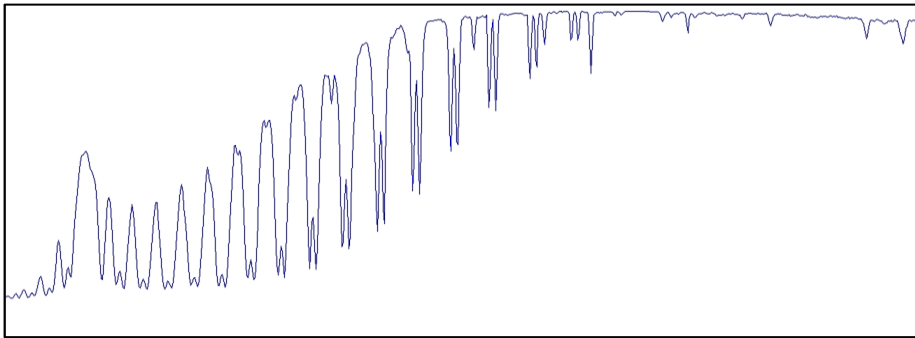


3. The calibration spectrum must be processed analogously to the object spectrum (not shown here).
4. Generate the raw profiles for the orders 29 and 30 according to chap. 4.2.



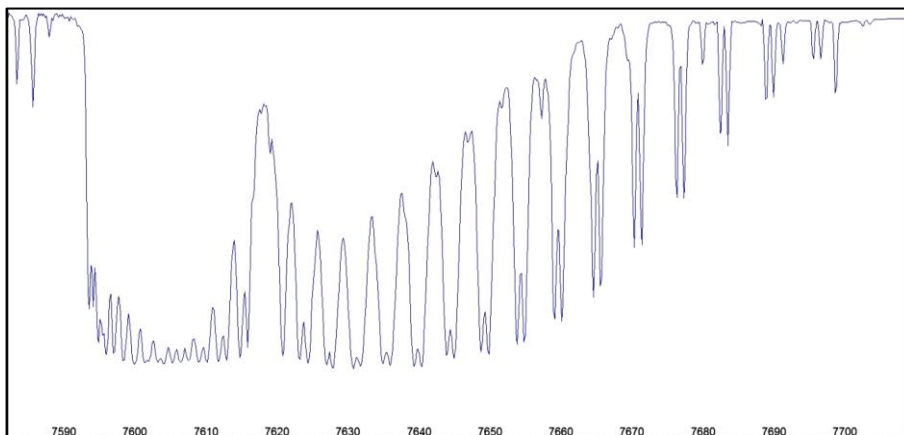
5. Now both orders have to be *not linearly* calibrated with the corresponding calibration spectra according to chap. 5.3, or calibrated on the basis of known lines (chap. 5.2). These steps are not demonstrated here.

6. In these calibrated profiles, the area of the Fraunhofer A line is now marked with the cursor and cropped with the icon .



7. Rectify the continuum course according chap. 7.2 (here poss. already after step 5)
8. Finally assemble both profiles in Vspec with *Operations/Join* according to chap. 7.6.
9. Further editing and formatting as with a normal spectral profile

Here is the final result after rectifying the continuum course according to chap. 7.2.



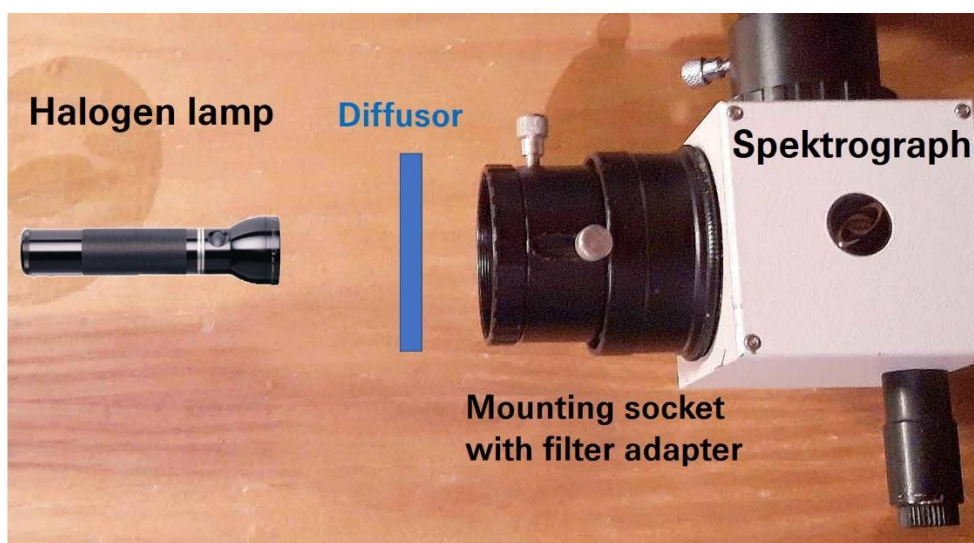
15 The Measurements of Filter Curves

15.1 Objectives

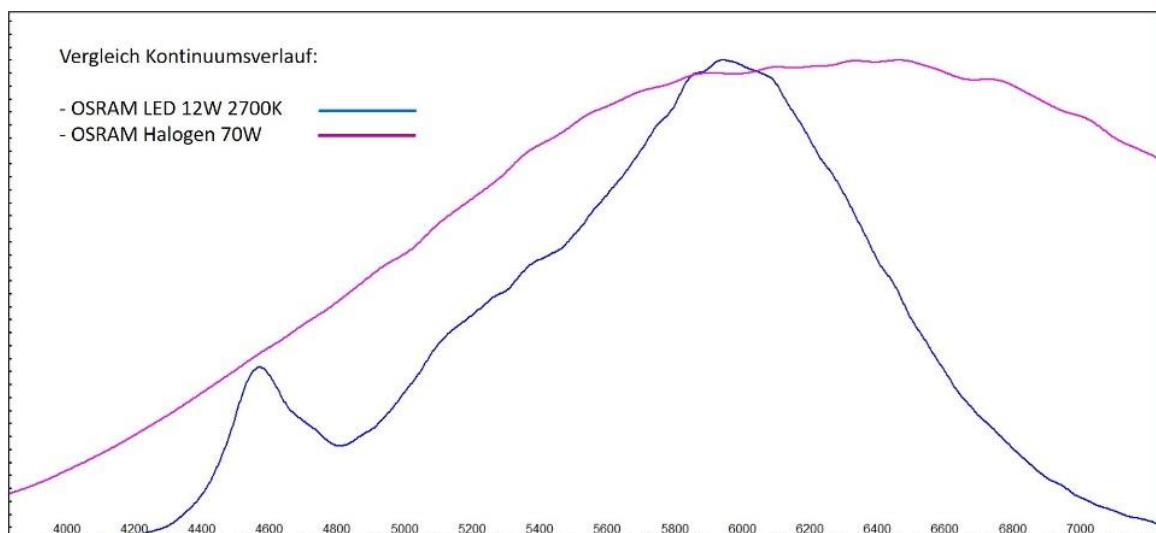
With the following, rudimentary method, a transmission spectrum is applied to generate a transmission curve for a filter.

15.2 Generating a Transmission Spectrum

For this purpose, the filter to be measured is screwed by an adapter into the mounting socket in front of the spectrograph. This prevents the filter from being tilted relative to the optical axis. In front of the spectrograph an incandescent halogen bulb is positioned, which should create an uniform continuum over the whole wavelength range to be measured. Between lamp and filter there should be a diffusor or a diffusing disc (e.g. a thin sheet of white paper).



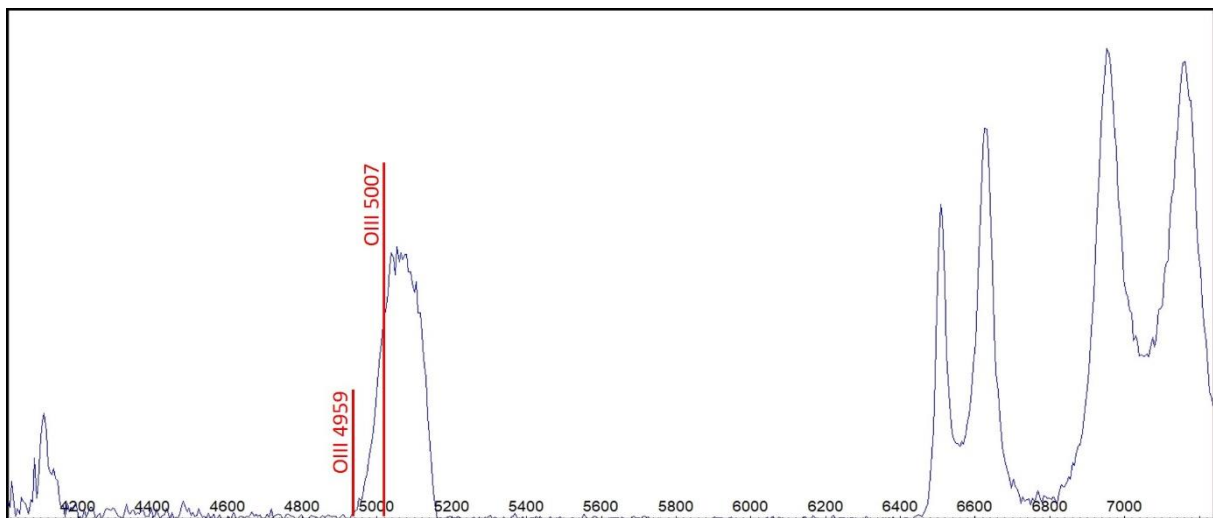
LED lamps are unsuitable here because they usually cover a wavelength range which is too short and furthermore create a continuum with a jumpy shape which is difficult to fit with Visual Spec. The following diagram shows the curve of a halogen bulb compared to a LED light.



15.3 Recording and Procession of the Spectrum

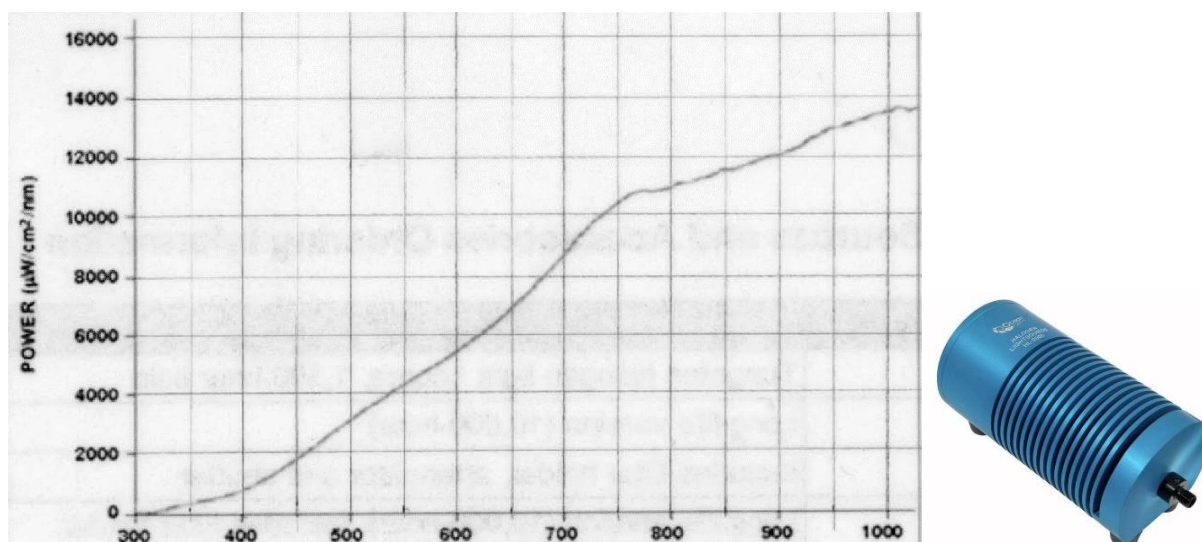
1. Record the spectrum of the halogen bulb and calibrate the wavelength axis
2. Smooth the spectrum, e.g. with a Gaussian filter. Alternatively (or additionally) a fit to this raw profile can be generated.
3. Record transmission spectrum of the filter and calibrate the wavelength axis
4. Divide the transmission spectrum by the shape (or fit) of the halogen lamp profile. This roughly neutralizes the "response" of the camera and the spectrograph as well as the radiation characteristic of the lamp.

The following figure shows the transmission spectrum of an older Lumicon O III filter. Here it becomes obvious that the filter range has shifted and the short wavelength O III line is now outside the passband.



16 Transfer of a Measurement Curve into a Visual Spec File

The measurement curve of a calibration light source, which is used e.g, for radiometric correction, should be transferred to a Visual Spec profile for further processing. However, there exists here no data file of the measuring curve, but just a diagram. This task requires a lot of effort and various "tricks". The following diagram with the title "Spectral Output" shows the course of the spectral flux density [$\mu\text{W cm}^{-2} \text{ nm}^{-1}$] between 300 and 1000 nm, corresponding to 3000 - 10'000 Å, for the halogen lamp HL-2000 from Ocean Optics.





1. Measure the pairs of values for the wavelength and the corresponding spectral flux density (intensity) in the diagram of the measurement curve, in any wavelength interval.
2. Load any existing spectral profile in Visual Spec, which must cover the intended wavelength range, and save it as dat file
3. In this dat file overwrite the values, using the Windows Editor (or Notepad), with the measured value pairs. As an alternative the separation of the value pairs by a simple tab distance worked in the test. In the following example the wavelengths are in the left column and the corresponding intensity values in the right column. The wavelength raster (here $\Delta\lambda = 250 \text{ Å}$) can be chosen arbitrarily, however must remain constant and without any gaps in the table.

3000	00
3250	150
3500	250
3750	500
4000	850

.....

4. Save the modified *dat* file under any name. If the modified file is provided in *txt* format, the extension "*txt*" can be overwritten with "*dat*".
5. For a test, load this *dat* file into Visual Spec. The measurement curve should now become visible. In all our tests the curve sections in the first and also in the last

wavelength interval were not displayed graphically, despite existing values, so that further processing steps were necessary (steps 8 - 11).

6. Using the cursor along the curve, check that the pairs of values match the measured values in the *dat* table.
7. Show now the axis labels  (chapter 8.1). In our tests, the labeling values for the wavelengths deviated from the correct cursor values at the long-wave end, because further processing steps were necessary (steps 8 - 11). The intensity values, however, were displayed correctly.
8. In the Visual Spec load in two separate windows the existing spc file according to point 2, and the new generated *dat* curve according to point 4.
9. Use copy paste to copy the newly generated curve in dat format into the window with the spc file.
10. Check if the formatting of the *dat* curve is now completely identical to that of the *spc* diagram and if the curve has been smoothed to an acceptable degree by Visual Spec by this copy process.
11. Finally convert this curve with the "Replace" icon  as "Intensity Profile" and save it under any name.
12. Subsequent use: If the recorded raw profile of the calibration lamp is divided by the measurement profile generated in steps 1 – 11, a correction curve ("Instrumental Response") results, valid for the instrument setup used for recording. This can now be applied for relative intensity correction of other measured lamps by dividing their profiles by this correction curve.

17 Removal of Telluric H₂O Lines in the H α Domain

In high-resolution spectra ($R > \text{ca. } 10'000$) numerous telluric-earth-atmospheric generated water vapor lines superimpose, especially the section around the frequently analyzed H α line. Here, two possibilities for their removal ("drying") are presented.

With SpectroTools... (recommended option!)

<https://spektroskopie.vdsastro.de/software-24.html>
<http://www.peterschlatter.ch/SpectroTools/>

This multi-functional program by Peter Schlatter also allows to solve this task. He has written a detailed step by step description. Here just follows a shortened version for the authors own use:

1. load the file with *File open*
=> The file appears in a separate window *File List*. Double click on this file
2. Open the list of model parameters with *i-Tools/Remove Atm. Water*
3. In Switzerland (approx. 47th latitude) as a first try click
H2O_Summer_Lat47_Hgt0600_Z60
=> popup field with sliders appears
4. Execute the process either manually (*Autoclean inactive*) with the three sliders, or automatically (*Autoclean Method 1 or 2*). The automatic option is started after marking a section containing no stellar lines (mark with mouse pointer and left button).
5. Now transfer the "dried" profile to the File List (still invisible) with the button "*Store Dried Profile button*". In most cases the following offered option of the displacement correction is not necessary.
6. Close diagram window (cross at the top right)
=> The "File List" appears, now additionally with the "dried" profile (...noH₂O)
7. Double click on this file
=> The diagram with the "dried" profile appears
8. Save with *File/Save as Fits* or *File/Save as Dat.*

With Visual Spec

Visual Spec also offers a somewhat simpler, but also manually or automatically working option for removing these lines:

1. Load the calibrated profile with "Open Profile" in the Visual Spec program (possibly set the file format from "spc" to "all")
2. Start the manual option under *Radiometry/H2O correction*
=> Popup panel appears with two sliders for optimizing the "drying process"
3. Alternatively, start the automatic option under *Radiometry/Auto H2O correction*
4. Save the result with *File/Save as*

18 Bibliography and Internet

Literature:

[1] M.F.M. Trypsteen, R. Walker: *Spectroscopy for Amateur Astronomers - Recording, Processing, Analysis and Interpretation*, ISBN: 9781107166189

[2] R. Walker: *Spectral Atlas for Amateur Astronomers - A Guide to the Spectra of Astronomical Objects and Terrestrial Light Sources*, ISBN: 9781107165908

Internet Links:

Author:

Various publications on the topic spectroscopy can be downloaded at this link:

[3] <http://www.ursusmajor.ch/astrospektroskopie/richard-walkers-page/index.html>

[4] *Glow Starter RELCO SC480 Atlas of Emission Lines – Recorded by the Spectrographs SQUES Echelle and DADOS*

<http://www.ursusmajor.ch/downloads/sques-relco-sc480-calibration-lines-5.0.pdf>

Tutorials:

[5] DADOS Tutorial by Bernd Koch

<http://www.baader-planetarium.de/dados/download/tutorial-dados-d.pdf>

Databases

[6] CDS Strassbourg: *SIMBAD Astronomical Database* with the most important data about astro objects like stars, galaxies, star clusters etc. <http://simbad.u-strasbg.fr/simbad/>

[7] *NASA Extragalactic Database (NED)* with the most important data, spectra, images etc. on galaxies and quasars <http://nedwww.ipac.caltech.edu/>

[8] *The SAO/NASA Astrophysics Data System*, Database of astrophysical publications <http://adsabs.harvard.edu/index.html>

[9] *NIST Atomic Spectra Database*:

http://physics.nist.gov/PhysRefData/ASD/lines_form.html

Spectrographic Software for Data Reduction

[10] *IRIS* and *ISIS*: Webpage of Christian Buil

<http://www.astrosurf.com/buil/>

[11] *Vspec*: Webpage of Valerie Désnoux

<http://astrosurf.com/vdesnoux/>

[12] *RSPEC*: Webpage of Tom Field

<http://www.rspect-astro.com/>

[13] *SpectroTools*: Freeware programm by Peter Schlatter for extraction of H₂O lines

<http://www.peterschlatter.ch/SpectroTools/>

[14] *MIDAS*, ESO

<http://www.eso.org/sci/software/esomidas/>

[15] IRAF, NOAO, <http://iraf.noao.edu>

[16] *SimSpec V4, Spectrograph Exposure Time Calculators (ETC)*: Excel based program

<http://www.astrosurf.com/buil/us/compute/compute.htm>

[17] BASS, Basic Astronomical Spectroscopy Software, Restricted Yahoo Group

<https://uk.groups.yahoo.com/neo/groups/astrobodger/info>

[18] *Fitswork*, Image processing for Astro photographers

<http://www.fitswork.de/software/>