Processing meteor spectra

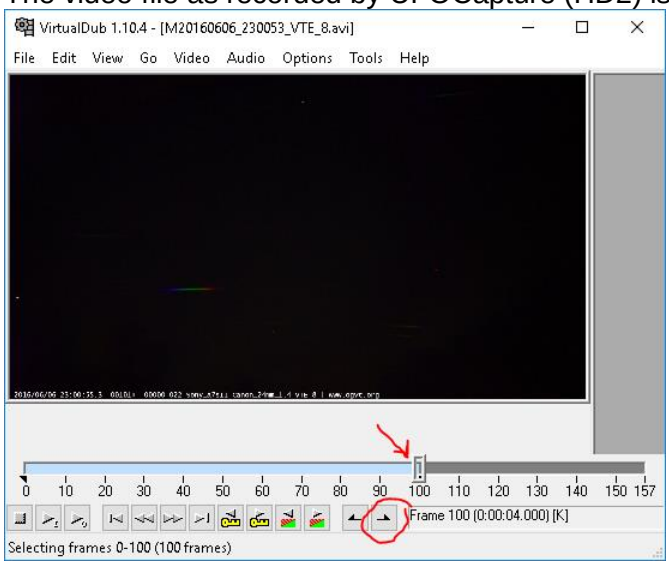
Introduction

This manual describes the processing of meteor spectra obtained with video cameras. Slightly different methods are used for colour cameras such as Sony alpha 7S or Canon EOS6D and b/w analogue video cameras such as the Watec 902 Ultimate H2, which are used as examples. The manual applies for other cameras as well, some settings may be different.
For the pre-processing IRIS has been used (http://www.astrosurf.com/buil/us/iris/iris.htm) for most processing steps. Although a little bit outdated, it has the advantage that most operations required for the spectra processing can be done and it has a simple script language which allows describing the sequence of commands in a simple way. A list of the available commands is given here with descriptions:
http://www.astrosurf.com/buil/iris/nav_pane/CommandsFrame.html
It even allows combining commands in simple programs which simplify the processing.
Of course, other image processing software can be used as well, as long as they contain the same or equivalent functions.
The method used for the calibration of meteor spectra is based on an image transformation to an orthographic projection, which is described here:
http://www.meteorastronomie.ch/images/20160605_MeteorSpectroscopy_Dubs_IMC2016.pdf
and here:
http://www.meteorastronomie.ch/images/20160605_Calibration_of_Meteor_Spectra_Dubs_IMC2016.pdf
It was presented at the International meteor conference in Egmond, June 2 -5, 2016 http://imc2016.amsmeteors.org/, where other interesting papers on current activities in meteor observation may be found.

Pre-processing

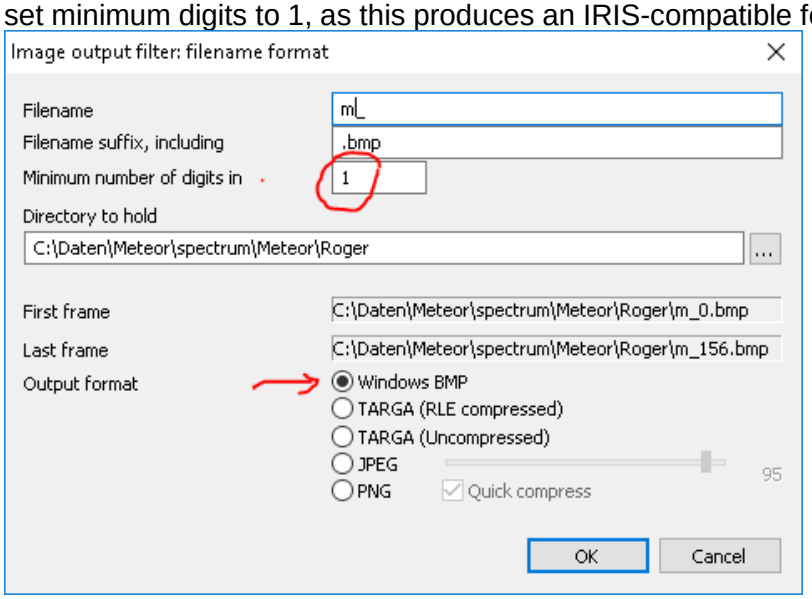
Extraction of single images from video with VirtualDub

IRIS has the function File – AVI Conversion – Convert, which converts video files directly into the IRIS format (see below). However it has problems with compressed (Lagarith or Huffyuv) files and sometimes it drops images. Therefore I use VirtualDub V1.10.4 for conversion of video files into image sequences (http://www.virtualdub.org/index)
The video file as recorded by UFOCapture (HD2) is loaded and trimmed to length



The extraction is done with File – Export – Image Sequence.
The single images are exported as .BMP (without loss of information) to the working directory of IRIS. It is useful to create a separate directory for each video. This simplifies the processing

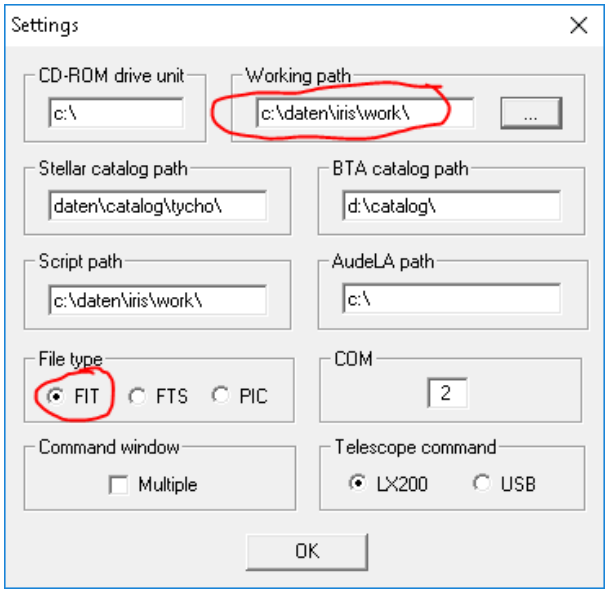
as the same filenames can be used for intermediate steps and the same commands and parameters can be used in many cases. Another possibility is to use a work directory and after finishing the processing move everything to a directory for archiving the data. It is important to set minimum digits to 1, as this produces an IRIS-compatible format



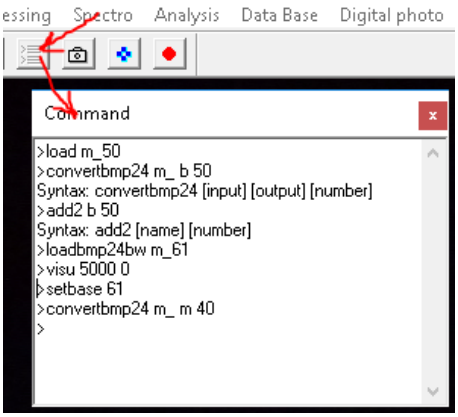
Creates m_0.bmp … m_100.bmp (even if it says otherwise in the image above)
(The image m_0 is not used in IRIS)

Setup of IRIS

IRIS uses different formats (FIT, FTS, and PIC). FIT and the path of the working directory are selected in File - Settings:



The FIT format is selected because it it used in most astronomical spectroscopy prcessing software.
The other entries are not used (except for a star catalog, which is needed for the automatic extraction of laser calibration lines from images, but this can also be done manually).
IRIS is best used with the command window, which is opened from the tool bar:
Here the commands are entered after the “>” and executed with ENTER. By going back to



an earlier command, the command can be modified and repeated with ENTER. This saves much typing ☺. If the parameters of a command are not known, just type in the command without parameters, a Syntax will follow with a short explanation. The meaning of the commands will become clearer in a moment[1].

[1] It is good practice to copy the content of the command window to your logbook periodically, for later reference to the sequence of steps which lead to the final spectrum (also helps if you forgot the command name).

Creation of background image

Usually there is a background visible in the absence of any meteor (sky brightness, stars, moonlight, artificial stationary lights). This should be subtracted from the meteor spectra as a first processing step. The background image is created by averaging a number of images. Typically the video starts with pretrigger, so the first NB frames can be used for the background. A suitable number is converted to FITS:

>CONVERTBMP24 m_ b 50

The corresponding command for b/w images (Watec etc.) is:

>CONVERTBMP m_ b 50

Images from VirtualDub as *.bmp contain 3 (identical) colour planes, these can be converted to monochrome fit-images with the command:

>CONVERTBMP24BW m_ b 50

(See the Appendix for the definition of the commands)

There is a command for averaging images in IRIS, but it was found that it does not always give correct results. Therefore we use the following workaround:

The background images are stacked with the following command

>ADD2 b 40 (40 is the number of images to be stacked, adjust to the length of the pretrigger, check also for overflow, see below)

The result is stored in temporary memory and displayed on screen

>MULT 0.025

>SAVE back

>VISU 10000 0

The average is calculated by multiplying by 1/NB (in this example 1/40 = 0.025) and saved as back.fit

Make sure you do not get overflow in the resulting image after stacking, maximum for IRIS in the FIT image is +/-2^15, the 8-bit image gives 2^8, so do not add more than 2^7 = 128 images. If you convert to b/w you have to add the three channels, so another factor 3 is required, therefore adding 42 images never gives an overflow. The VISU command allows to adjust black and white levels of the image on the screen (does not change the values of the stored image)

Example:

back.jpg, copied to M20160606_230053_VTE_8P.JPG, for use in UFO analyzer, together with M20160606_230053_VTE_8A.xml

Left star: Mars, top centre; alp Boo

Creation of meteor images, subtraction of background, flat field correction

The next step is to create the background corrected meteor images. These can be transformed to a linear wavelength scale before registering them and then stack them to get the time integrated spectrum (or a time series of individual spectra). All commands in IRIS operating on a series of images (such as ADD2 [image] [number]) always assume that the counting index goes from 1… number. For registering the meteor images you need to see it in the image, so you have to find the first image with the meteor (either the zero order or if this is out of the image a prominent line, e.g. the Na-line). This can be done in VirtualDub with the slider for the image number or in IRIS by selecting the image with

>LOADBMP m_xx (for b/w images)

>LOADBMP24BW m_xx (converting colour images → b/w)

Here xx denotes the number of the image you would like to see.

Once the first image in the sequence is found, you set the start index of the input of the command CONVERTBMP24 or CONVERTBMP to this value with e.g.

>SETBASE 61

In this example this means that the following command starts extracting the images from m_61.bmp and saves it as m1.fit up to m40.fit. For a description of the commands see the appendix of this manual.

Then extract the meteor spectra with index starting from 1 with

>CONVERTBMP24 m_ m 40

This creates m1.fit … m40.fit, in the correct notation for further processing with IRIS.

In order not to forget, reset the base index with

>SETBASE 1

The background is subtracted from all these images with

>SUB2 m back mb 0 40

Where the image “back” is subtracted from the images m1… m40 with offset 0 into mb1… mb40.

Notice the structure of this command (for details check the appendix):

SUB2 stands for subtraction of a series of images

m is the root of the image series (m1, m2 …)

“mb” stands for meteor background subtracted, but any other name can be used. Short names are preferred, easier to remember, use of the same names for the same processing step is recommended. It is also useful to copy the content of the command window to a log file for later reference, to remember the processing steps.

The division by a flat field also belongs to the pre-processing; this will be added in a later version.

Use of IRIS script command

Repeating the commands for creating a background image or a series of meteor images is instructive in the beginning. After processing several spectra one may look for a simpler method. IRIS has the possibility to run simple batch commands or scripts with the command RUN [param1] [param2] ... [param5]

Check the IRIS commands for details:

http://www.astrosurf.com/buil/iris/nav_pane/commands_iris_v5.0.html#run

IRIS Version >5.00 implements the possibility to run a succession of commands from a script file in text format. This script file (or batch file) must mandatory have the extension "pgm", for example "myprogram.pgm".

Scripts are run with the RUN command from the console.

The first parameter of the run command is the name of the script file, the other parameters are parameters used in the script file.

For the processing of meteor spectra the following two script s are useful

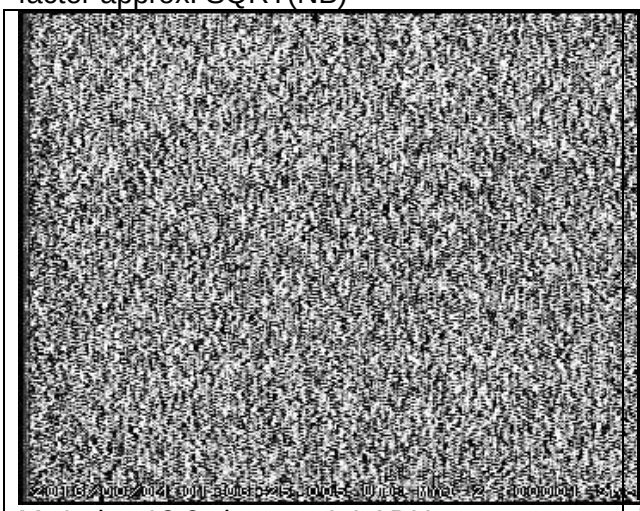
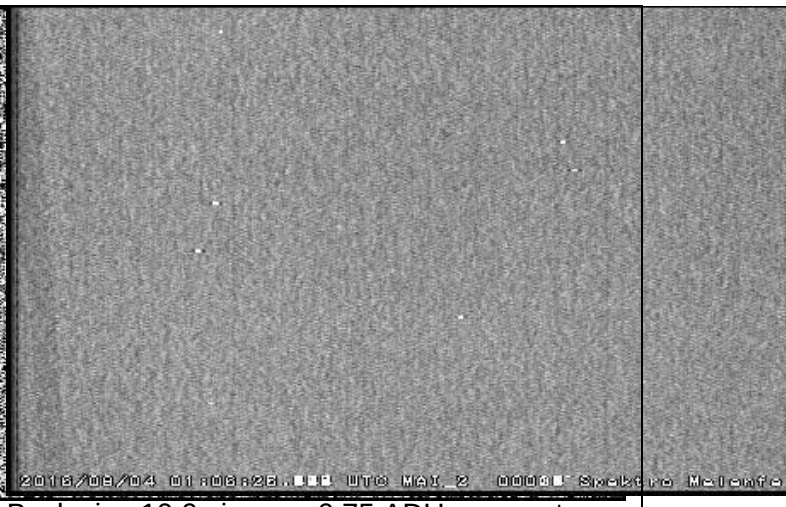
M_BACK.PGM and M_DARK.PGM.

RUN M_BACK [I, B, NB, MULT] calculates background image

- I: Input filename.bmp
- B: Background filename

- NB; number background images
- MULT: multiplier for background B = (Sum I1...I_NB)*MULT
  since the program cannot do arithmetic calculations, MULT has to be calculated externally: MULT = 1/NB and entered as a parameter

The effect of the averaging is seen in the following images, readout noise is reduced by a factor approx. SQRT(NB)

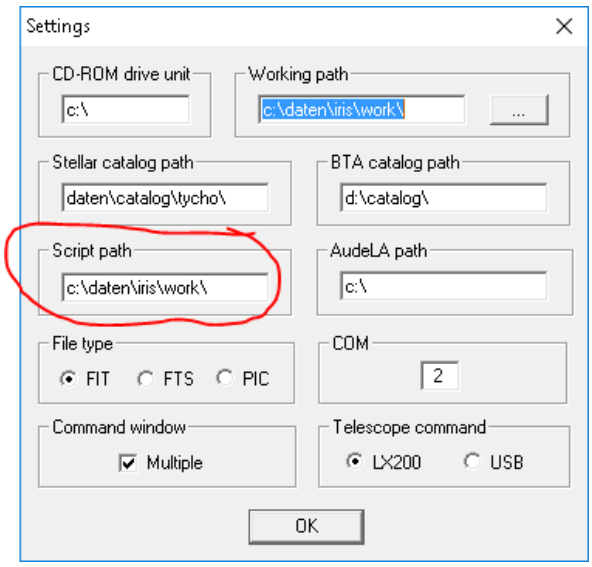
	
M_1 visu 10 0 sigma = 4.4 ADU	Back visu 10 0 sigma = 0.75 ADU, some stars, hot pixels visible

RUN M_DARK [I, B, M, START, NM] reindexes and subtracts background

- START: first index of meteor image (used for stacking, so should be visible)
- NM: number meteor frames

You may have to edit the programs with a text editor to select the correct BMP extraction command (CONVERTBMP24, CONVERTBMPBW or CONVERTBMP) for colour or monochrome images

The program files are stored in a directory which can be defined in the settings of IRIS:

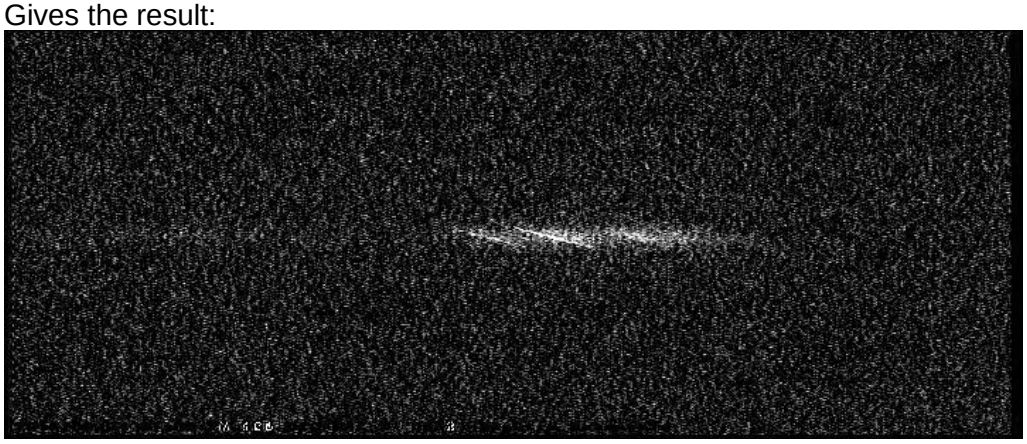


In this case C:\Daten\IRIS\work.

Example of usage:

```
>loadbmp24bw m_1                  ! check correct directory, if image exists
>RUN M_BACK m_ back 40 0.025      ! new command
>visu 10 0                        ! stretch
>savejpg back 2                   ! see image above
>RUN M_DARK m_ back mb 51 20      ! new command
```

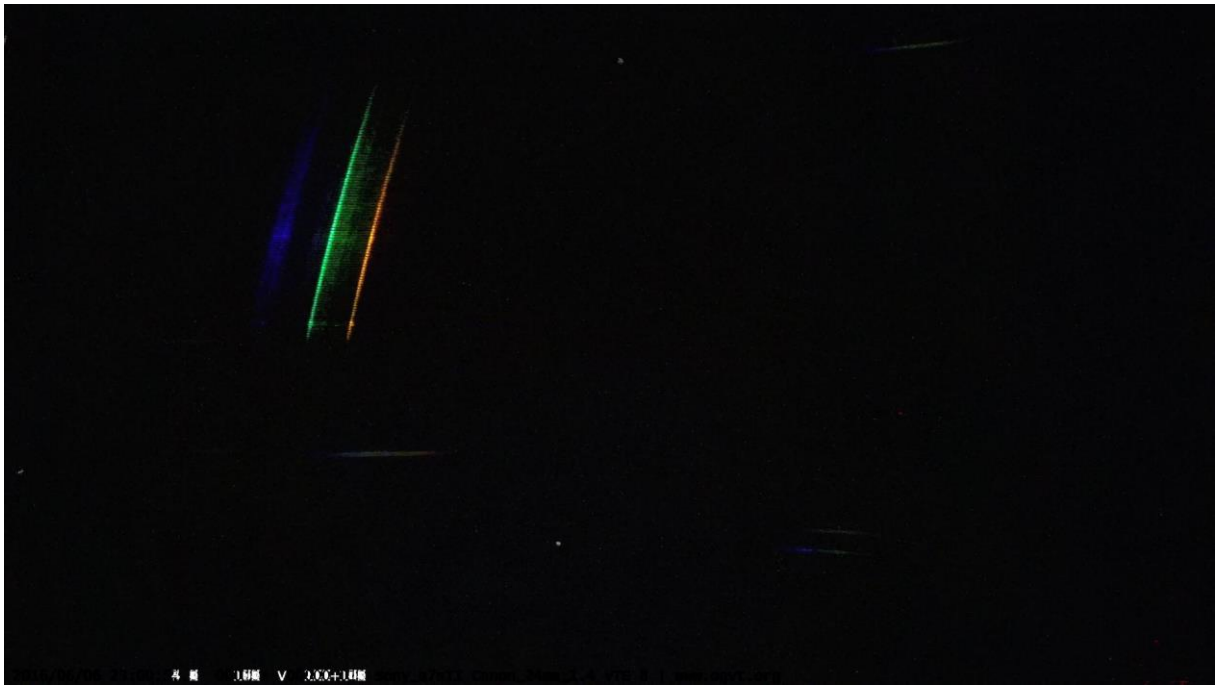
>add2 mb 20
>visu 100 0 ! stretch
>savejpg madd20 2
Gives the result:



(before orthographic projection, registering and stacking)
The preprocessing (without flat correction) is reduced to two command lines!

Creation of peak image

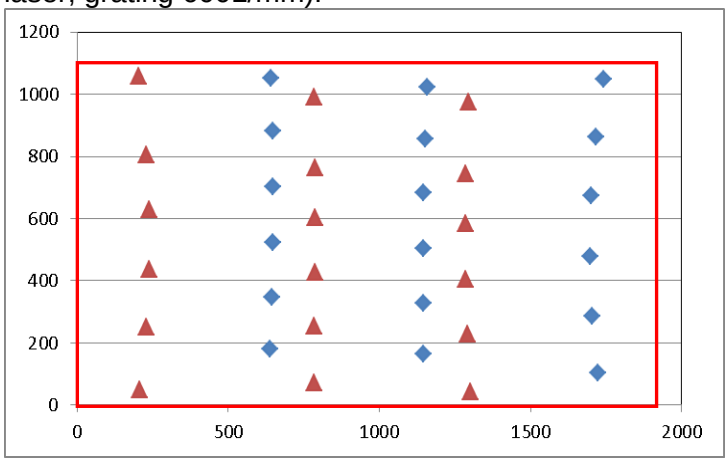
The purpose of this is the addition of images without increasing the background, e.g. for the creation of a meteor trail from individual meteor video frames or for a combined calibration image, showing the nonlinearity of the spectrum in different parts of the image area.
For a given series of images mb1 … mb40 the following command can be used
>ADD_MAX2 mb 40
>SAVE 160606add40b
>SAVEJPG 160606add40b 2
(Saving the JPG requires an additional parameter for the quality, 2 is a suitable value)
With the result:



160606add40b.jpg
Notice that the background has been subtracted in this image; the bright star (mars) is barely visible, the sky black.

Creation of calibration images (required once per camera, lens, grating combination)

(If the transformation parameters to the orthographic projection are already known, this paragraph can be skipped)
For the transformation to linear spectra the parameters of the transformation to the orthographic projection are necessary (X0, Y0: coordinates in the image plane of the optical axis; a3, a5: 3rd and 5th order coefficient of the radial transformation, for non-square pixels yscale, the ratio of pixel height and width). These can be obtained from a least square fit of a model of the lens-grating combination for a suitable spectral light source. The different orders of known spectral lines are measured (xi, yi) and compared to calculated values from the model. As a result also thee dispersion and the rotation of the grating are obtained. Different zero order positions are selected, so the spectra cover most of the image are. This improves the fit (polynomial). If only a restricted area is fitted, the fit outside this area would be quite poor.
A suitable light source is a blue (405nm) laser, it gives many orders, but a green (515nm) laser can be used as well or a red 633nm laser. Notice that the specified wavelength of a semiconductor laser is not very precise, so it is advisable to check the calculated dispersion with an actual meteor spectrum or a precisely calibrated (e.g. HeNe gas laser 632.816nm) light source.
It is not practical to shine the laser into the camera, it is simply too bright. A better way is to shine the laser on the wall of a dark room and take images (or short videos) of it with the zero order in different vertical positions. If the horizontal spacing of the orders does not fill the image area (e.g. for a high dispersion grating or long focal length) different horizontal positions can be used. A minimum of 3, better 4 different orders should be measurable for each image.
Here the measured positions for an example (CanonEOS6D with Sigma 35mm, f/1.4, green laser, grating 600L/mm):



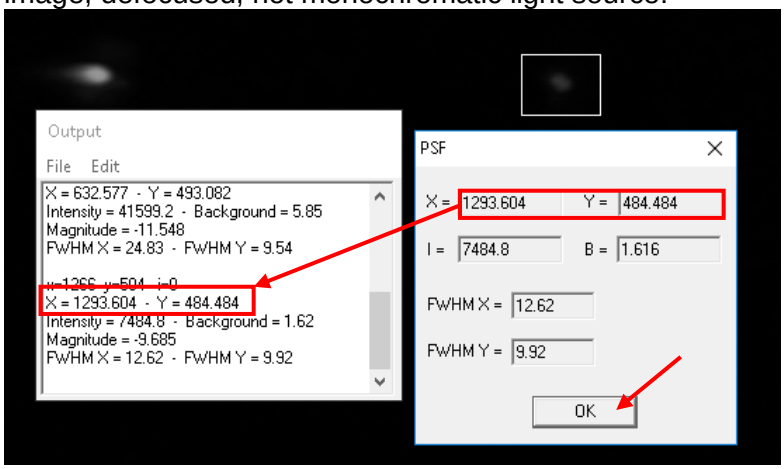
Red: left side of image covered, blue: right side covered)
An example with Sony alpha7s with Canon FD24mmF1.4, green laser, grating 600L/mm:

Here the image format and the shorter focal length allows to measure 4 orders

The video sequences of each laser position can be processed as the background images above (averaging some frames). For an overview they can be stacked as a peak image, but they can also be analysed separately. It is important that the images are obtained under the same conditions as the meteor spectra (same focus and same aperture). Speed and gain, sensitivity or ISO setting may vary. Try not to overexpose as this reduces accuracy.

Measurement of image coordinates

In IRIS you can measure star or spectral line coordinates by making a rectangle around the selected object, and with right click – PSF you obtain the following information (not very good image, defocused, not monochromatic light source:



The information is copied to the output window (In case you do not see the output window, select File – “Image info” from the menu, which shows the FIT-header of the image). Needed in our case are X and Y. With OK you can make the next measurement, starting from the left to the right for all orders. The text in the output window can be copied with edit – copy for further processing to EXCEL. There the unnecessary data can be eliminated, so two columns containing x and y remain (in Iris the value pairs X, Y):

xm	ym
641.793	1049.961
1158.433	1022.883
1741.277	1048.13

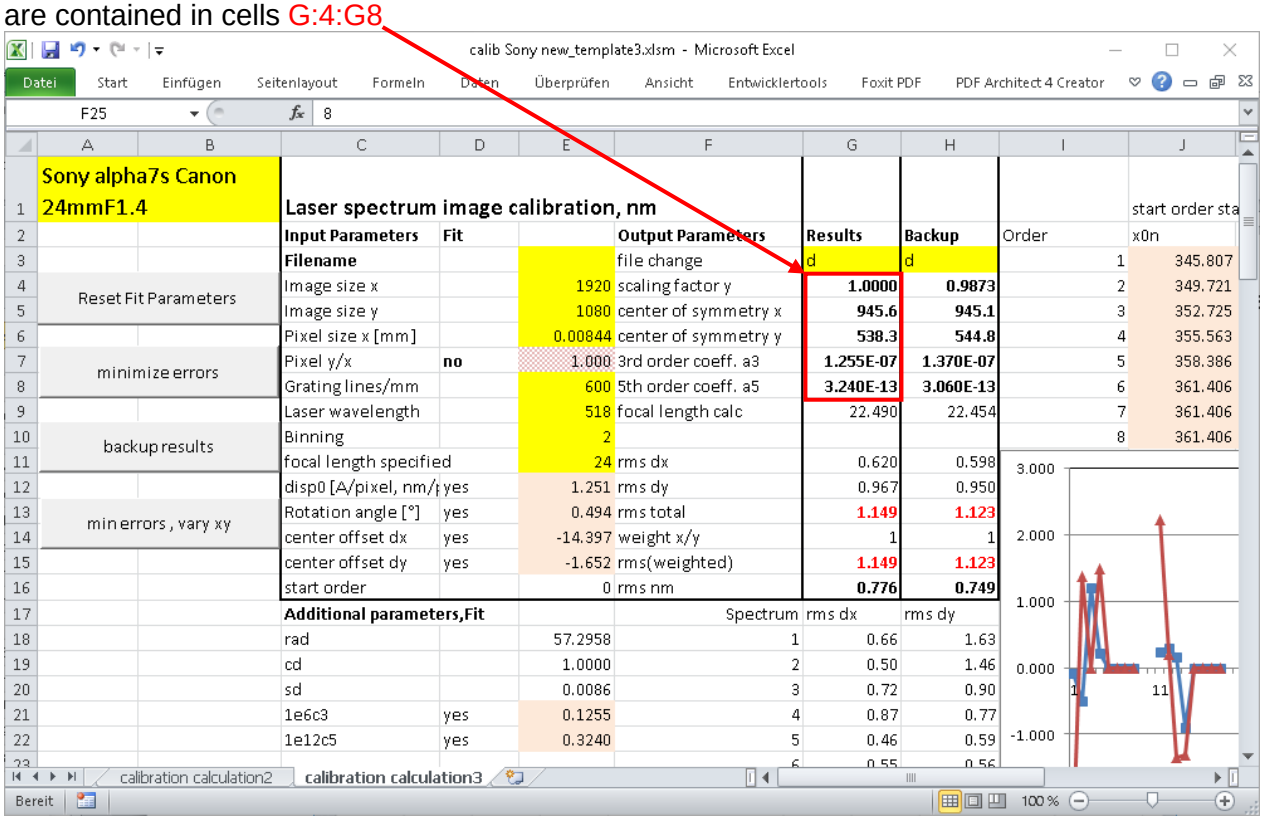
This has to be done for all calibration spectra, 6 to 8 are sufficient to determine the transformation parameters. The data are copied into the EXCEL worksheet for the evaluation of the transformation parameters. The least square fit for the residual errors is done with the

EXCEL solver and the results copied to the transformation window of ImageTools. See here for details. In short, the following steps are required:

- First save the template under the name of the calibration you would like to do and work with this copy, in order to have a backup in case something goes wrong
- There are two different datasheets you can use, one with the 5th order polynomial fit, useful for wide angle lens, the other with a fit to a square root, which is useful for longer focal lengths. Check which gives a better fit.
- Copy the measured positions of the laser lines into the required fields (in columns A:B, starting from row 31)
- Check and adjust the input fields, yellow: required input
- Reset Fit Parameters Choose suitable starting conditions for the Solver
- minimize errors Run EXCEL solver for fixed Pixel y/x ratio. The goal is to minimize the total rms error: sqrt(dx^2 + dy^2) in cell G15
- backup results If you want to try another solution, copy the results in column G to column H

If you do not know the pixel y/x ratio (rectangular pixels), you can also select min errors , vary xy uses y/x, the pixel size ratio (vertical to horizontal dimension) as an additional fit parameter (in cell E7). For square pixels set E7 to 1 and use “minimize errors”.

The results of the parameter fit for the required transformation into an orthographic projection are contained in cells G:4:G8

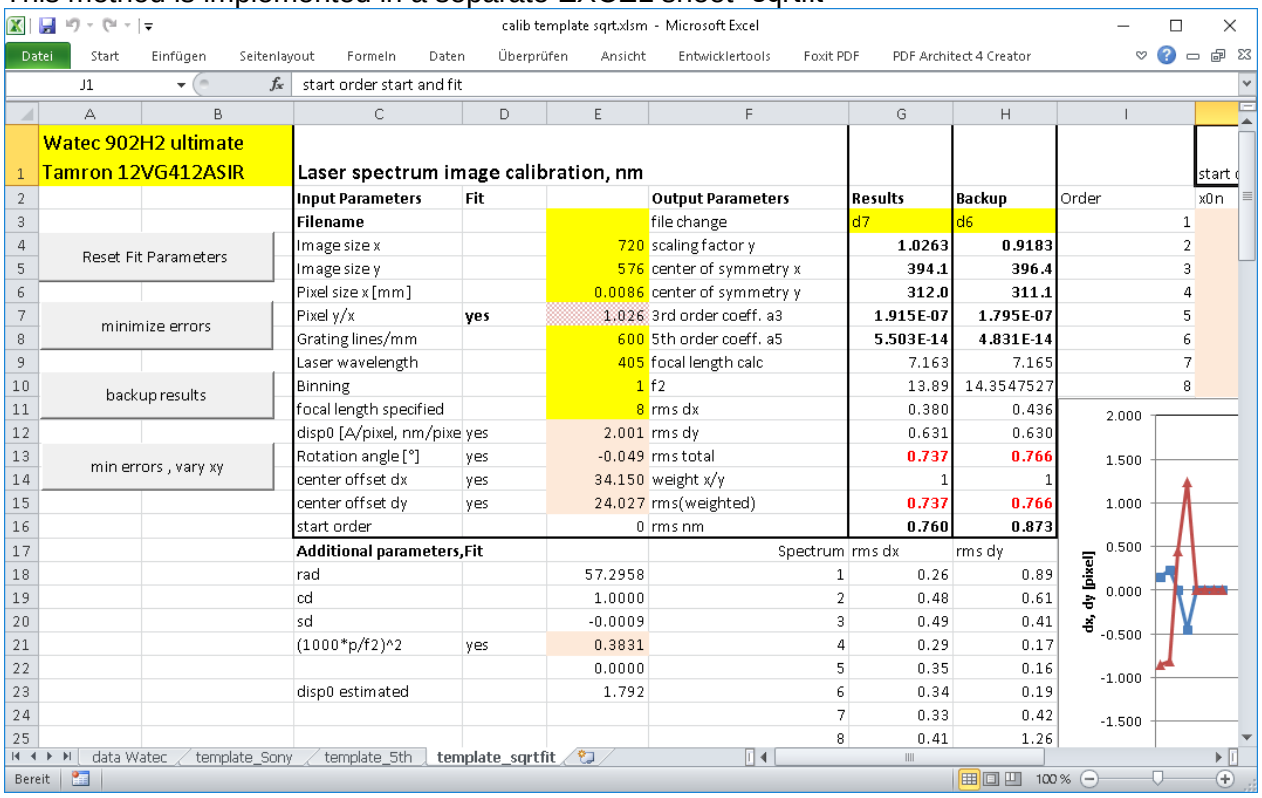


calib Sony new_template3.xlsm

Alternative method for fitting transformation parameters

In the last paragraph the fitting of the transformation was described by a 5th order polynomial. This should be sufficient even for wide angle lenses (except fish-eye lenses). For spectra with higher resolution longer focal lengths should be used. In this case even using a blue (405 nm) laser may only show 3 different orders. The same is true with larger laser wavelength. With only 3 or 4 laser lines per spectrum, fitting a 5th order polynomial may give unstable results. An

alternative is to start from the transformation equation for an ideal lens, as described in equation 14 of:
“A practical method for the analysis of meteor spectra”, Martin Dubs and Peter Schlatter, WGN, the Journal of the IMO 43:4 (2015)
http://www.meteorastronomie.ch/images/Meteor_Spectroscopy_WGN43-4_2015.pdf
r = r’*[1 + 1/2*(r’/f)^2 + 3/8*(r’/f)^4 + …]
for the lens with focal length f. This equation does not contain a fit parameter; it describes the inverse transformation from a tangential to an orthographic projection. For lenses with a small distortion (e.g. telephoto lens) this equation can be used by adjusting the apparent focal length f_2 to describe the actual distortion:
r = r’*[1 + 1/2*(r’/f_2)^2 + 3/8*(r’/f_2)^4 + …]
Most lenses show a distortion in between a tangential and orthographic projection. This leads to f_2 > f. For stability reasons of the EXCEL solver, not f_2 it used as a fit parameter, but (1000*p/f_2)^2, with the pixel size p.
This method is implemented in a separate EXCEL sheet “sqrtfit”



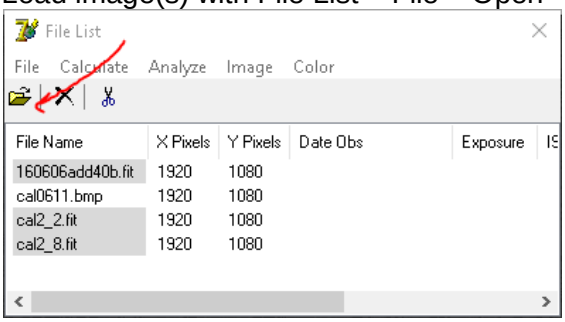
For a focal length f of approx. 7mm, f2 is fitted as 13.89mm, almost the double. The rms values of the fit are almost the same as for a full fit of a3 and a5, but with more reasonable values for the parameters. Threfore it is advisable to use this approximation except for wide angle lenses.

Orthographic Transformation with ImageTools

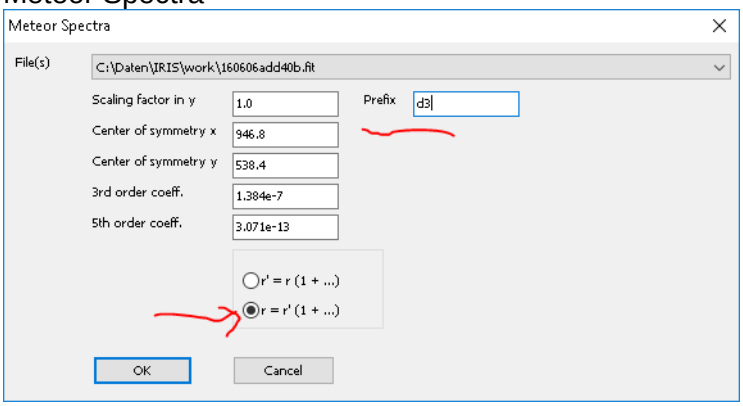
With ImageTools

- Extract ImageToolsV11.zip to a suitable folder
- Start ImageTools

- Load image(s) with File List – File – Open

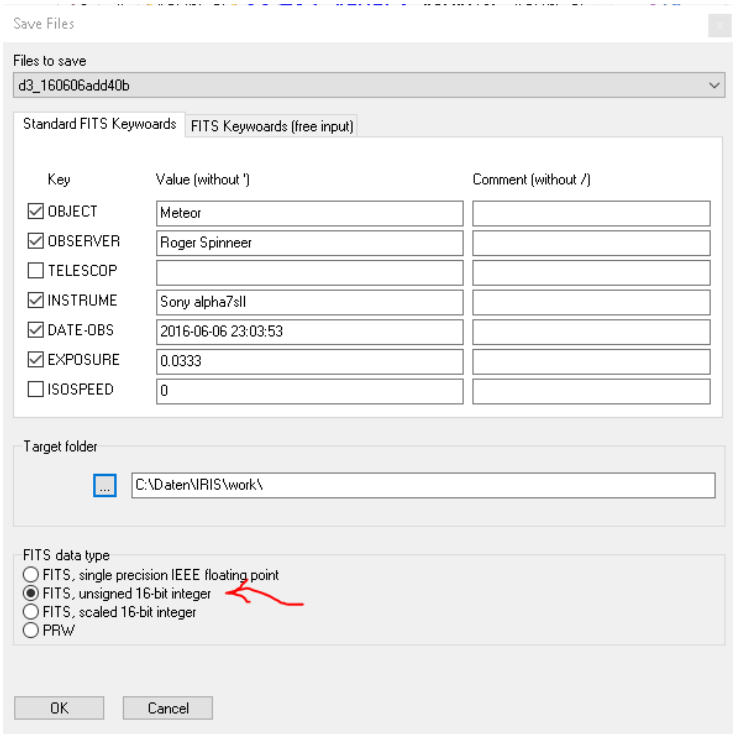


- Select files to be transformed, use CTRL or SHIFT click for multiple selection
- In File List select Image – Meteor Spectra
- Copy the parameters from the EXCEL calibration sheet to the parameter window of Meteor Spectra

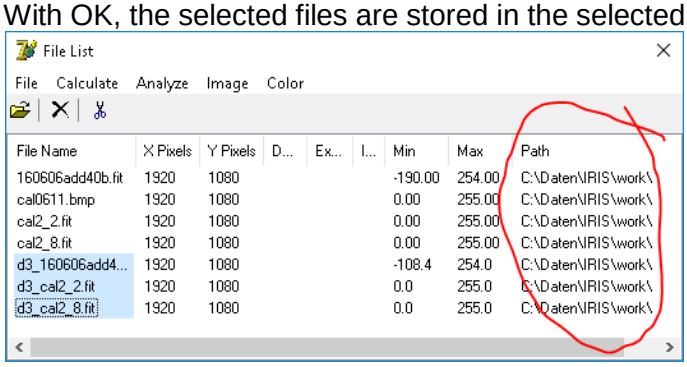


Preliminary values for Sony alpha7s Canon 24mmF1.4 Koji Maeda, 2xbinning notice the prefix to distinguish different parameter sets
select r=r'(1+…), this is the transformation which was fitted in the EXCEL sheet. For each pixel x', y' in the transformed image the values x,y in the original image are calculated and the intensity interpolated.

- With OK, the selected images are transformed; they appear with the prefix (d3_ in this example) in the list. They are stored in memory.
- Select the files you would like to save and save them with File – Save …
- Fill out the FITS-Header as shown below and select a suitable directory!

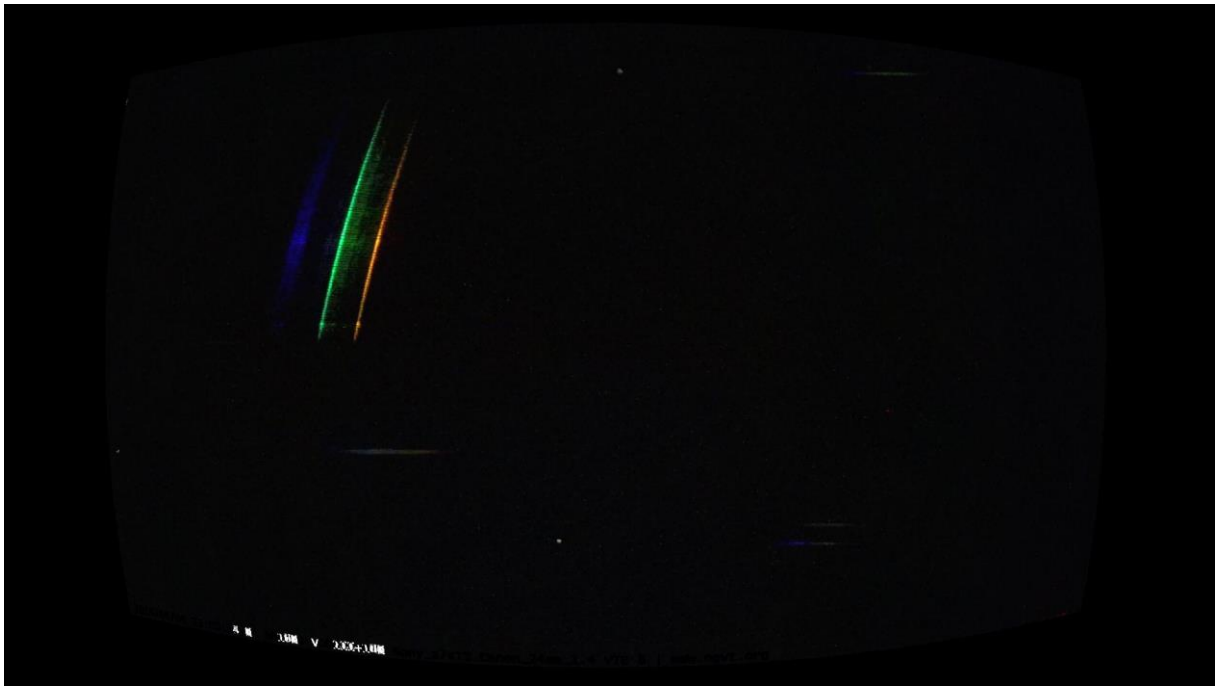


- (The exposure time is needed if the images are further processed in ISIS, so it is good practice to fill it in at this point to avoid additional work later)
- For color images, select *FITS, unsigned 16bit integer* (this produces 48-bit color images readable in IRIS, the highest bit cannot be used as IRIS uses a +/- 15-bit format). Negative values, which may arise from subtracting the background, are clipped. This should be avoided for high precision by adding a suitable offset. This is of minor importance since color images are used mainly for aesthetic reasons, for quantitative results the images are converted first to b/w images, see next point.
- For b/w images, use *FITS, single precision IEEE floating point* for highest accuracy. In this case you do not have to worry about negative values.
- With OK, the selected files are stored in the selected directory



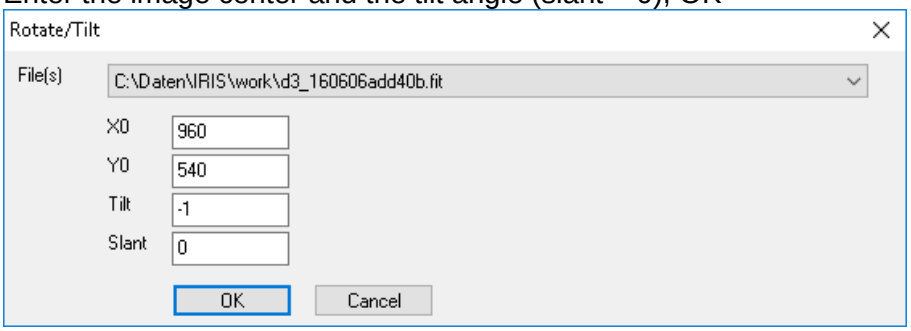
Path indicates, which files have been stored in what place.

→

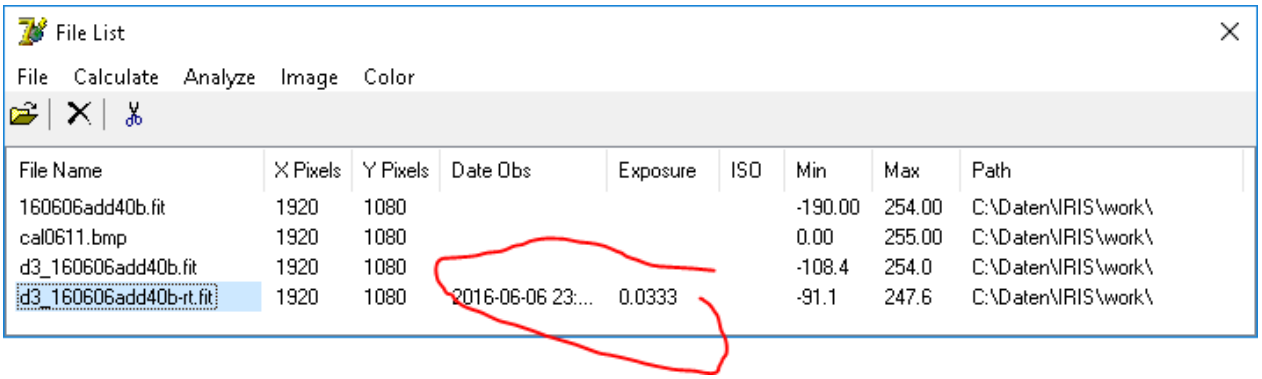


- For easier analysis of the files they may be rotated, so that the spectra are exactly horizontal (this allows also to check if they are exaactly straight). This can be done in ImageTools in the File List. select the files to be rotated, select Image – Rotate/Tilt

Enter the image center and the tilt angle (slant = 0), OK



-rt is added to the filename (appendix is not convenient for multiple files). Save as before.



notice that time and exposure are updated here, missing after the orthographic transformation ;-)

- The transformed files can be used for further processing in IRIS or elsewhere.
  For multiple files use IRIS to rotate with the command
  rot2 [in] [out] [x] [y] [alpha] [number]

Processing and extraction of spectra

Orthographic transformation

After the excursion to the calibration, we will come back to the processing of meteor spectra. In the pre-processing a series NM of meteor spectra mb1…mbNM have been created, with background subtracted. Before they can be processed with standard spectroscopy software they are transformed to the orthographic projection with ImageTools (see above). This can be done in one operation by selecting all the relevant images mb… and transforming them with the same transformation parameters (once entered, these parameters are stored in the INI-file, so after restart of ImageTools there is no need to enter them again. They have to be changed only for a different camera, lens, grating combination).

Only for colour images:

At this point colour images may be converted to b/w images. This is done in IRIS with the command

>COL2BW mb mbbw 40

ImageTools can transform colour images. The advantage of converting them to monochrome is 3x smaller required storage space and 3x faster processing speed. Unless you want to produce a coloured spectrum, this would be a suitable time to do this conversion. The extraction of 1-dimensional spectrum from the 2-dimensional image only works with b/w images (most spectroscopic cameras are monochrome)

- Clear all files from the File List
- Open the required files mb…
- Select all with Ctrl A (If the computer memory limits are reached (out of memory error), select a reduced number (e.g. 20 spectra at once, depending on image and memory size)

- Transform them with Image – Meteor Spectra (check the correct parameters). This may take a while for large colour images)
- If OK, delete the original images from the File List (they are still selected)
- Select the transformed images, with prefix d_ and save them as unsigned 16-bit integer for colour images, IEEE floating point for b/w images, compatible with IRIS. Check the file header, especially date and time, exposure time
- Delete the transformed images from the File List
- Repeat, until all the images have been transformed

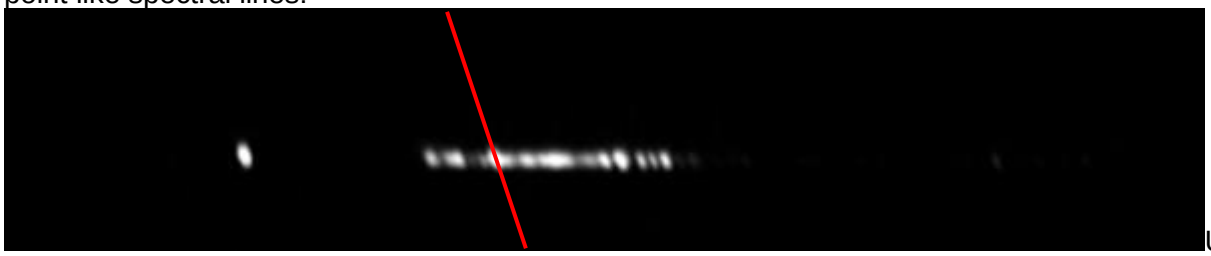
Back in IRIS; align the spectra parallel to the x-axis with the command
>ROT2 d_mb mbdr 960 540 0.494 40 (adjust values to actual image size, angle and number of images)

Stacking

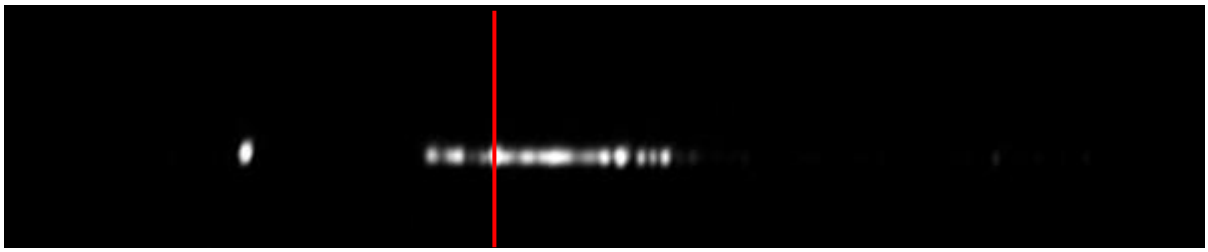
In order to increase S/N the spectra can be stacked. Before this they have to be registered. This is possible, because they are all parallel and with the same dispersion in the orthographic projection, which simplifies the processing considerably (otherwise, the spectra would have to be linearized and calibrated individually before adding them). For the registering to work properly, one well defined and isolated feature of the spectrum has to be used as reference (normally this would be the zero order spectrum, in case this is not visible, another strong isolated line (e.g. the sodium line can be used as well). It should be visible in all spectra, especially the first one. In case this is not the first in the series, the command >REINDEX can be used to correct the numbering acceptable to IRIS.
For registering: load the first image, select the reference by putting a rectangle around it with the mouse and use the command
>REGISTER mbdr mbdrr 40 (select names of your choice, easy to remember and short)
The resulting images should be aligned in wavelength and vertically. They can be processed with standard spectroscopy software. The basic steps are demonstrated here with IRIS.
The simplest way to produce a spectrum is to add (stack) the spectra. With the command >ADD2 mbdrr 10 the first 10 spectra are stacked. The result resides in memory and is shown on screen (use VISU to adjust the intensity thresholds or the sliders of the threshold window). It can be saved as *.FIT with the command
>SAVE mbadd10
You can use reindex to stack the following 10 spectra
>REINDEX mbdrr temp 11 1 10
>ADD2 temp 10
>SAVE mbadd11-20

Correction of slant

The motion of the meteor during the exposure time produces slanted spectral lines instead of point like spectral lines:



Unfortunately neither the speed nor the direction of the meteor can be chosen, so this effect is always present to some degree. Unless the motion is along the x-axis, the x-component of the motion can be corrected with the commands
>LOAD [image]
>SLANT 472 24, where 472 is the y coordinate of the spectrum and 24 the angle of the slanted lines to the vertical. It produces the following result:

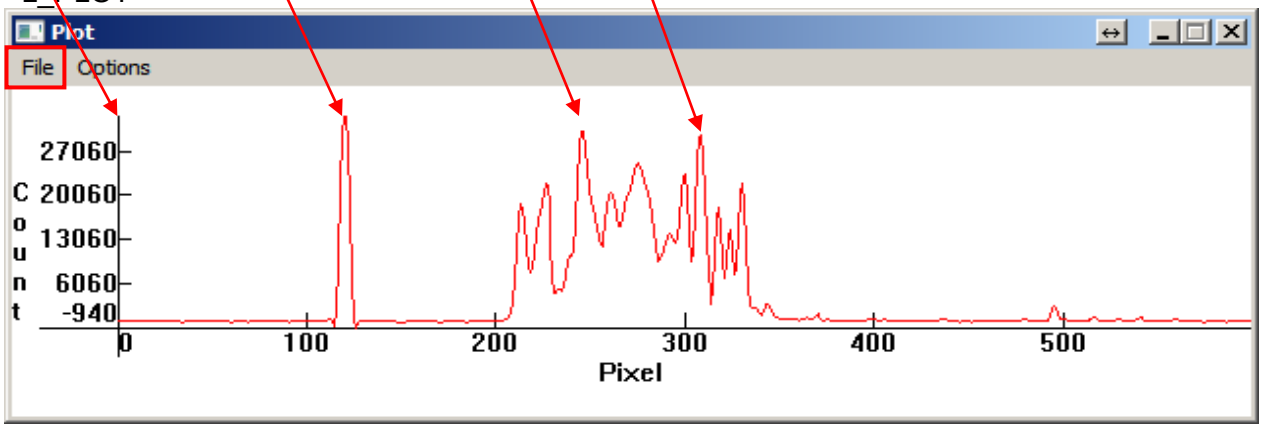


Save this spectrum again

Extract the spectrum

Now you are ready to extract the (uncalibrated) meteor spectrum by adding the rows of the image containing the meteor spectrum with the command
>L_ADD 467 477, assuming that the spectrum extends over 10 pixels vertically, centred on y=472. Make sure that you add all rows containing the spectrum, but not more, as this would only add noise and residual background. The result looks like this:

It looks still like an image, but actually is a 1-dimensional spectrum, stretched vertically for easy visualization. The actual spectrum can be extracted with the command
>L_PLOT



The data can be saved with File – Save as from the menu in the plot window. This produces a file *.DAT containing two columns, first the pixel number, then the corresponding intensity of the spectrum. This is a common data format in amateur spectroscopy; most programs for spectral analysis (Vspec, ISIS, Rspec, and BASS to name just some) can read this format[2]. The IRIS commands used above work both for colour and monochrome images. The L_PLOT command should be used with caution and only on monochrome images, produced from colour images with the command COL2BW. Notice that L_PLOT scales the values to a maximum of 2^15 (32768).

Calibration of meteor spectra

The purpose of the calibration is to convert the pixel scale into true wavelength. For a spectrum extracted from an orthographic projection this is particularly simple, since the spectrum is linear. The dispersion is constant, and the zero point of the wavelength scale is given by the zero order. The wavelength corresponding to pixel p is calculated as
$\lambda(p) = disp0*(p - p_0)$, where p_0 is the position of the zero order.
In the case where the zero order is outside the image area, any spectral line with known wavelength λ_{ref} at position p_{ref} can be used for the calibration:
$\lambda(p) = \lambda_{ref} + disp0*(p - p_{ref})$.

[2] In EXCEL you can read this as a text-file, select the first column and convert the text into columns with the menu Daten – Text in Spalten (german version) and select SPACE as separator. This should produce two columns containing pixel number and intensity as before.

It is always a good idea to check the calibration and refine it if necessary. One source of error is a wrong laser wavelength used for calibration. The typical laser diodes do not emit at a fixed wavelength, but may vary with temperature, laser current or composition of the laser crystal. **Always check with a known spectrum.** Good calibration lines are Na (589 nm) and oxygen (777.4nm) lines in different orders.
The dispersion disp0 (to be precise: the inverse dispersion) can be calculated from two line positions

$$disp0 = (\lambda_i - \lambda_j) / (p_i - p_j)$$

Better is to do a linear regression of pixel positions and known wavelength or λ*order. This gives also a good estimate of the precision. If the calibration is not perfectly linear (perhaps with a grating inclined to the optical axis) a nonlinear calibration may reduce the calibration errors. A third order polynomial should be sufficient in most cases.

Precise determination of dispersion

The linear and nonlinear calibration with fit of a polynomial will be shown with ISIS (personal preference of the author, it has been used in other spectroscopy projects as well). Other programs may be used as well, the principle is the same.

Extraction and calibration of spectra with ISIS

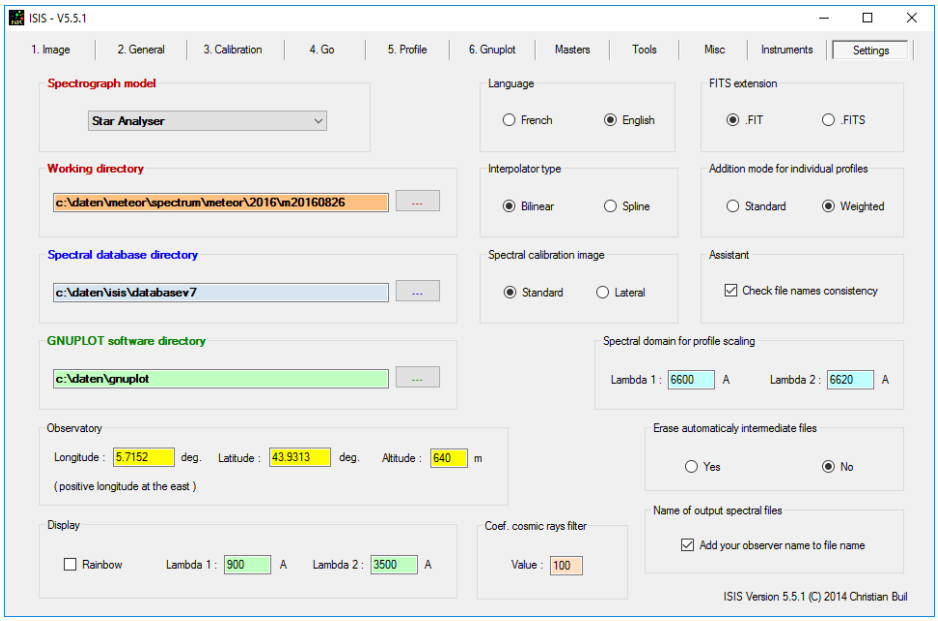
The spectra processing in IRIS is quite straightforward. Advanced methods of spectra extraction are used in ISIS, such as

- Background subtraction from neighbouring region
- Elimination of artefacts such as cosmic rays (more important for long time exposures)

In addition, ISIS allows the determination of the wavelength calibration (linear or nonlinear), useful to check the linearity of extracted uncalibrated spectra.
It is a program for stellar spectroscopy; therefore many functions are specific for that. For meteor spectroscopy it is not well suited, but it can be used with some tricks.
It is well suited for the determination and application of the instrument response function (see below).

Preparation

ISIS can be downloaded from http://www.astrosurf.com/buil/isis/isis_en.htm. Follow the instructions there.
It also allows plotting of spectra in a useful way. You have to install Gnuplot for that, see here: http://www.astrosurf.com/buil/isis/gnuplot/install.htm. There is a bug in ISIS, do NOT install Gnuplot in the program folder of Windows, rather use C:\gnuplot or something similar.
ISIS is by the same author as IRIS (Christian Buil), therefore it has some similarities with this program, in particular the same naming convention for files (m_1, m_2 …) with a root and an index starting from 1. The first step after installation of the program is to select the parameters of the setup page:



Setup

- Select spectrograph model: Star analyzer. This corresponds to a slitless spectrograph such as an objective grating configuration.
- Select directories, in particular the working directory and the Gnuplot directory. Ifyou have installed the database, you can also display the spectra of many reference stars (useful for instrument response).
- Most of the rest is not needed, fill out as the example above (FIT, weighted, standard calibration image.

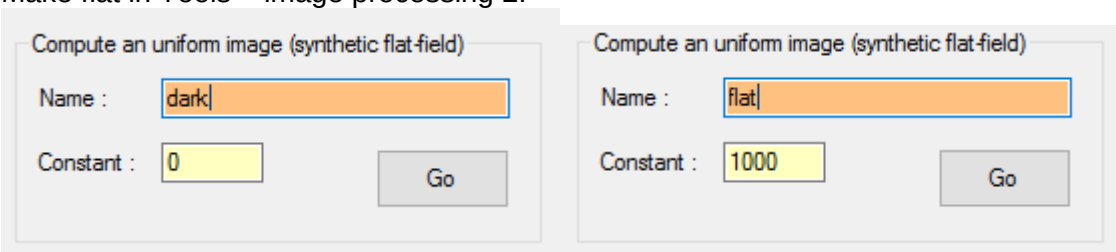
ISIS processing

ISIS can be used to extract uncalibrated spectra from meteor images. As it is optimized for stellar spectra, meteor images have to be pre-processed so that they look like star spectra, which means they should not move from image to image. Therefore the pre-processing including registering (dark subtraction, orthographic transformation, registering have to be done beforehand, ISIS is used only for the extraction of the spectra with better background subtraction and manual calibration with known meteor lines. As the pre-processing is done externally, some preparation is necessary for the processing. The processing in ISIS requires a dark image and a flat image. Since these steps have already been done, a dummy dark and flat have to be created, starting from any meteor image. For the dark also an exposure time is needed in the fit header

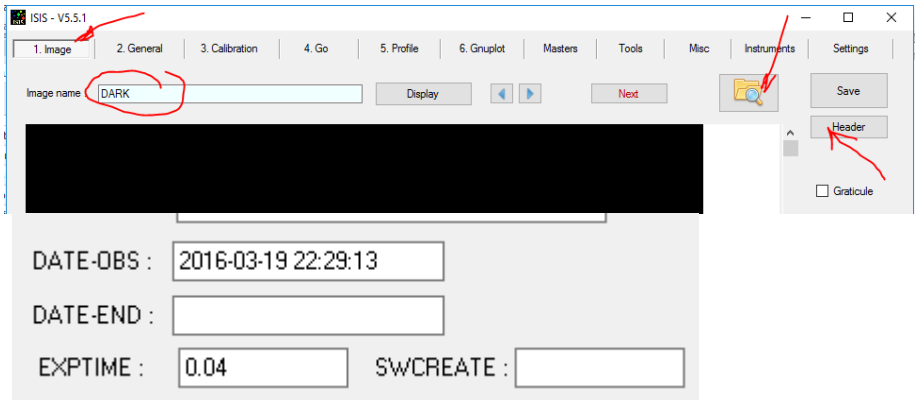
Select working directory

Make dark in Tools – Image processing 1

Make flat in Tools – image processing 2:

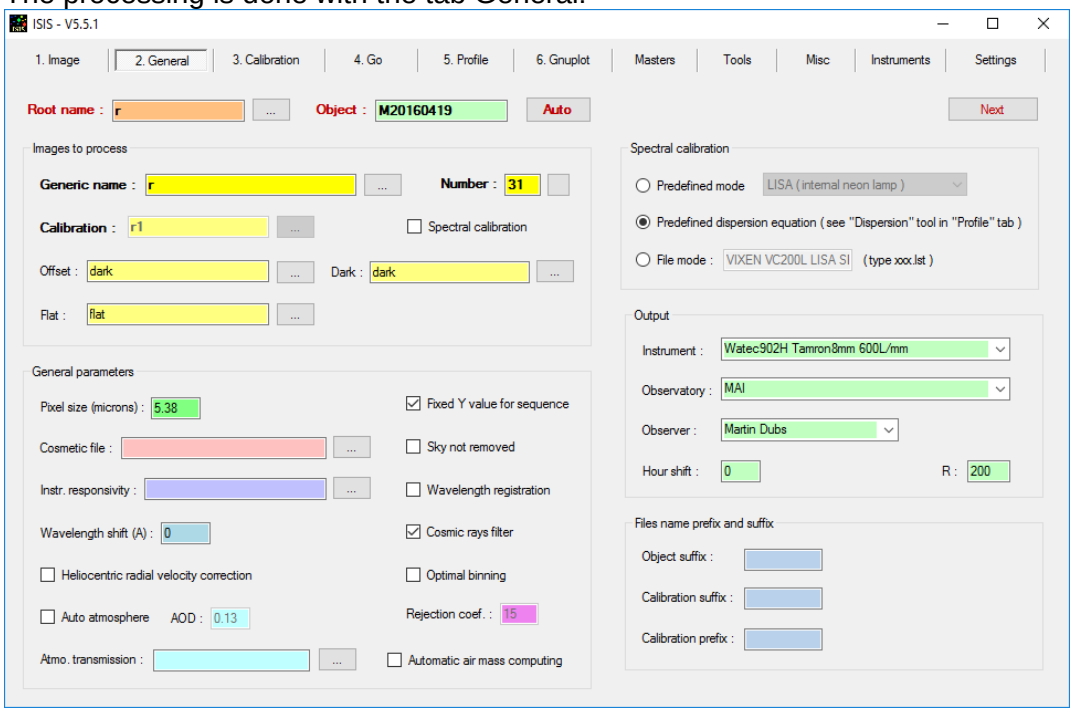


Load the dark image in Image and add exposure time to dark (to avoid division by zero) and save again:



In the following an example of a spectrum contaminated with strong moonlight is used to show the capability of ISIS:

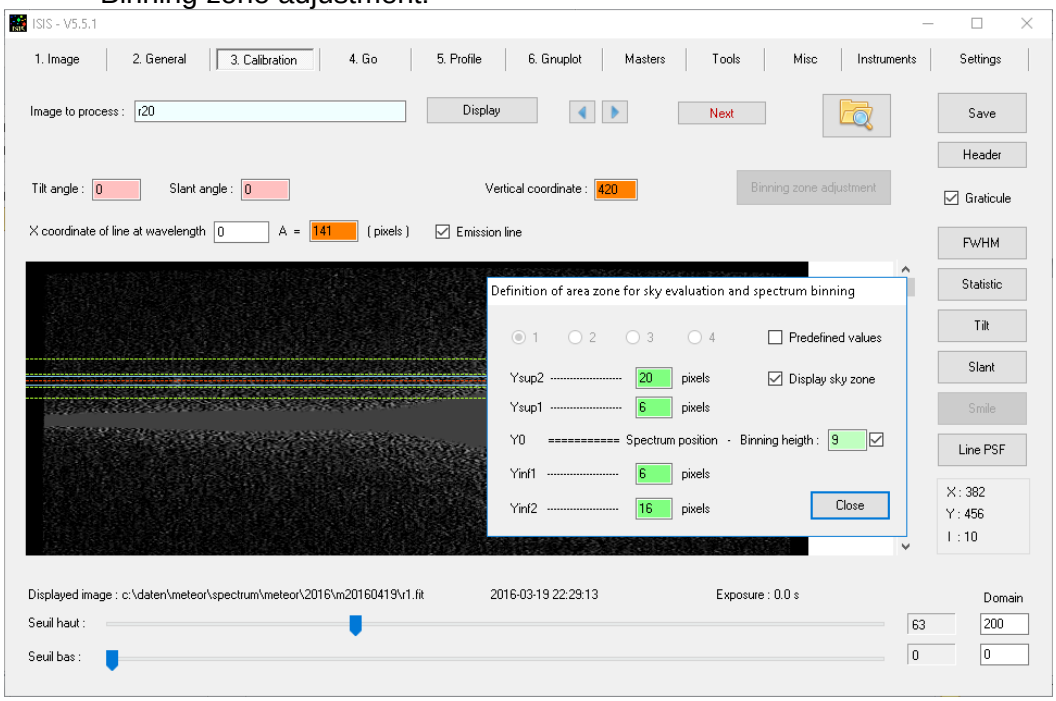
The processing is done with the tab General:



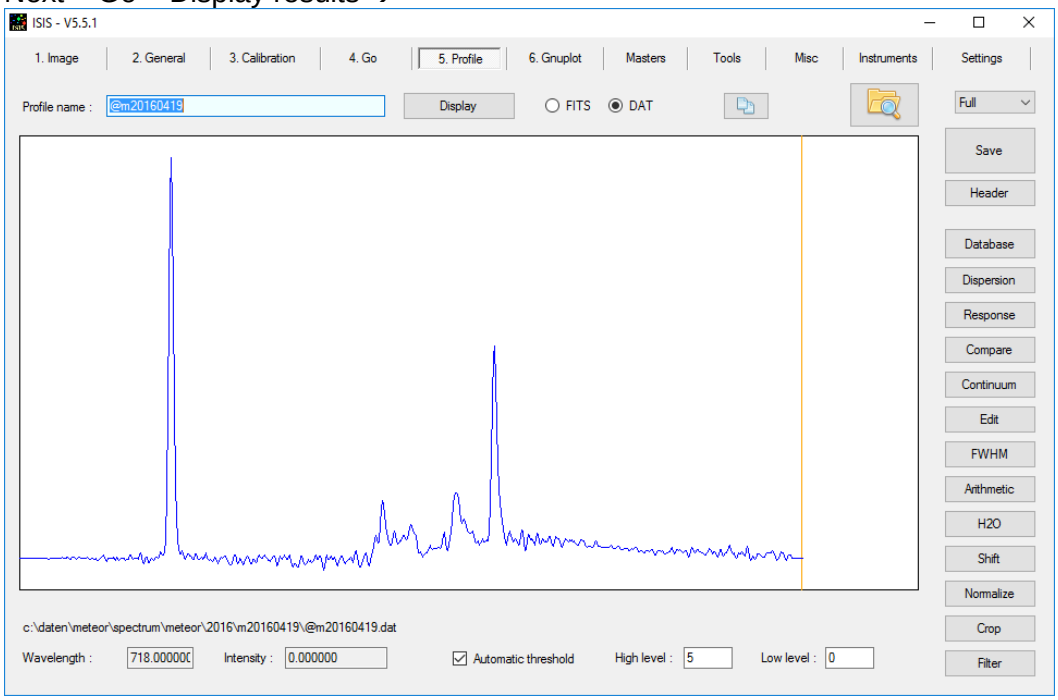
Attention:

- No spectral calibration
- Predefined dispersion equation
- Fixed Y reference value (otherwise weak meteor spectra are not found)
- Offset = dark = DARK

- With Next, go to Calibration tab:
  Binning zone adjustment:

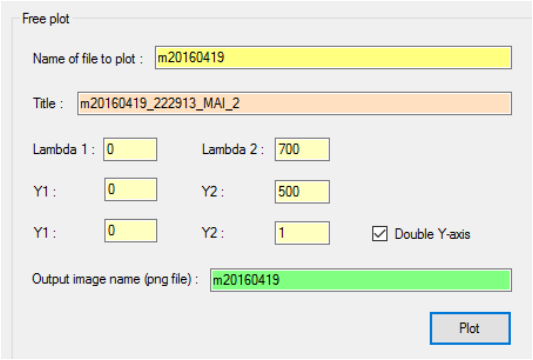


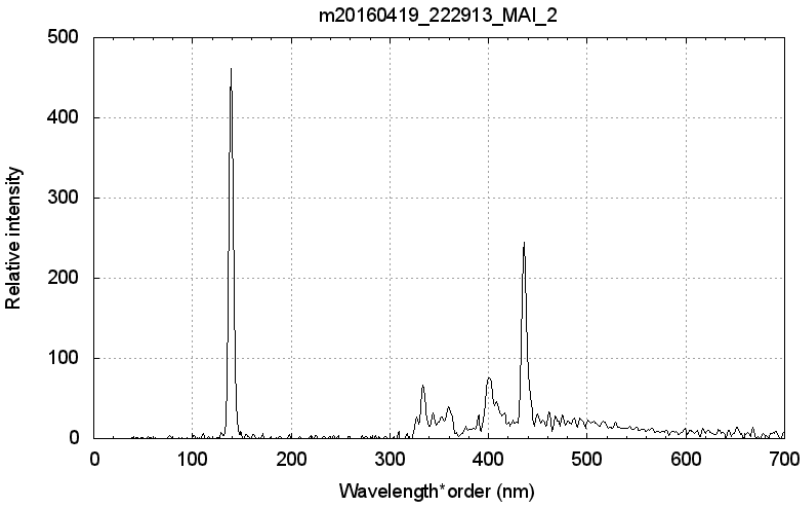
Binning height should enclose spectrum, background nearby
Next – Go – Display results →

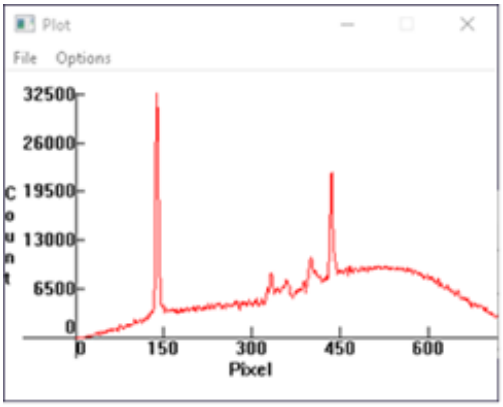


Save result as .FIT
Plot with Gnuplot:

- In Tab Gnuplot
- Free plot uses std2y.gnu
- 1 spectrum, 2 scales
- Check double axis
  (script supresses 2nd scale)
- Plot →



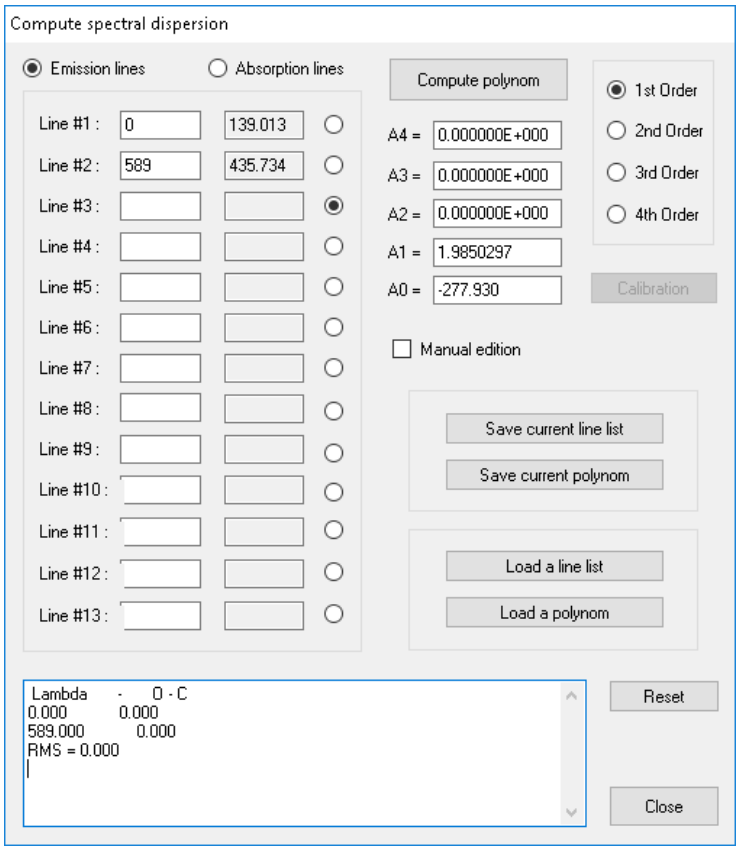




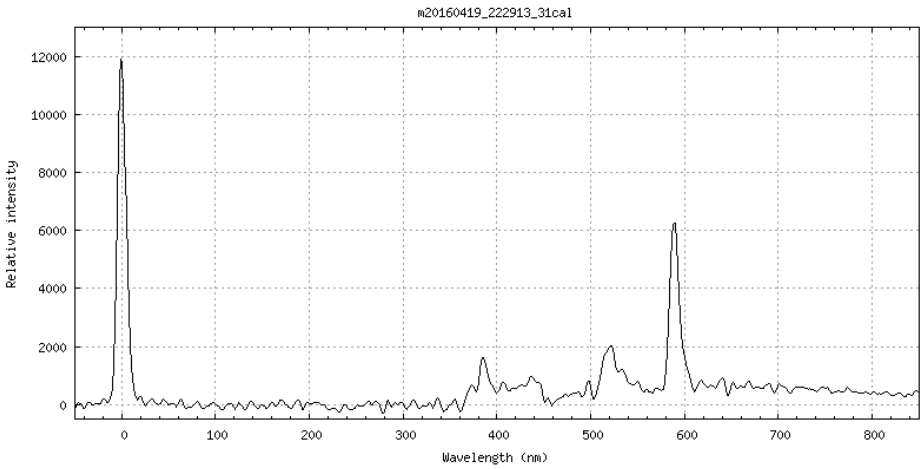
(wrong x-axis label, should be pixel)
The plot style can be adjusted by modifying std.gnu, std2.gnu and std2y.gnu (which reside in the gnuplot directory
For comparison a spectrum extracted with IRIS (L_ADD and L_PLOT). Notice that the background from moonlight has been greatly reduced with ISIS.

ISIS calibration

- Go to the profile tab
- Load an uncalibrated spectrum (*.dat from IRIS or @....dat from ISIS)
- Select dispersion
- Enter wavelength (to be precise wavelength*order) of selected calibration lines (or load from file)
- Double click to the left and right of line to measure pixel position, value is entered into table. If you want to re-measure, select row again. Repeat until all lines have been measured
- Select order (1st order since spectrum should be linear, higher order can be selected if enough well defined lines are visible)
- Compute polynomial
  At the bottom the errors for each line and the rms value are displayed. With two lines only and linear calibration the solution is exact, without errors. It is advisable to use more lines and check for the residual errors. In case of systematic deviation, try a higher order polynomial and see if the errors decrease significantly.
- Calibrate spectrum with zero order and Na:



- With “Calibration” the spectrum is calibrated in wavelength (in nm if calibration lines are entered in nm)
- Save the resulting spectrum (as *cal.dat for further processing with EXCEL or as *cal.fit for processing in ISIS or other astronomical software. Note that the FIT format can store 1-dimensional spectra as well as 2- dimensional images or n-dimensional data cubes)



Notice:
ISIS has a special way to calculate the polynomial:
Lambda = A0 + A1*(x+1) + A2*(x+1)^2 +… (the higher orders have not been checked)
The *.DAT file from IRIS created with L_PLOT starts with index 0 for Pixel1 in the CCD image.
Not very consistent!

Calibration with SpectroTools

(in preparation)

Instrument Response, theory

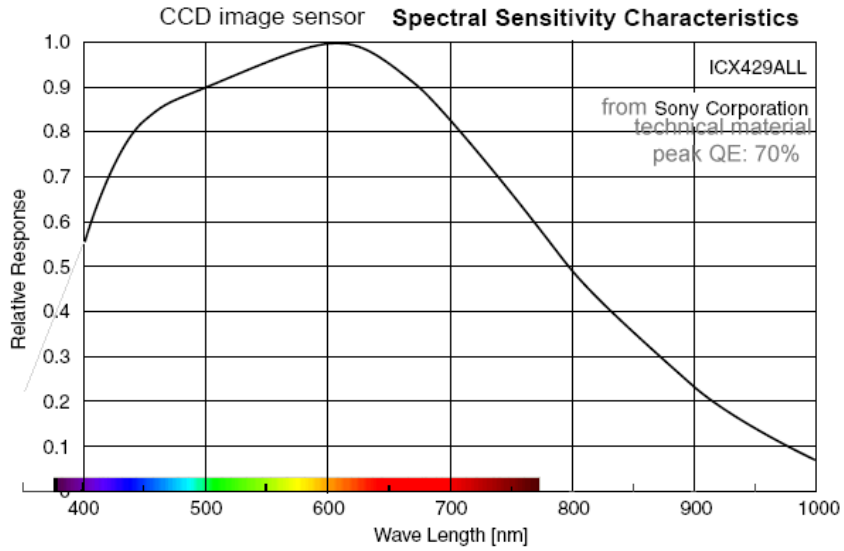
The spectrum calibrated in wavelength is still not the final result of thee processing. One would like to have a plot of energy against wavelength. Unfortunately the measured intensity is influenced by detector sensitivity, grating efficiency, transmission of optics (window, lens, filters) and atmospheric transmittance (all wavelength dependent).
The measured signal by the detector is calculated as
$I(\lambda) = const * \eta_{det}(\lambda) * \eta_{gra}(\lambda) * T_{lens}(\lambda) * T_{atm}(\lambda) * S(\lambda)$,
With

- Const: calibration constant for camera – lens – system (includes lens aperture, detector gain, exposure time etc.)
- $\eta_{det}(\lambda)$: detector response
- $\eta_{gra}(\lambda)$: grating efficiency
- $T_{lens}(\lambda)$: transmission of optics
- $T_{atm}(\lambda)$: atmospheric transmission
- $S(\lambda)$: spectral intensity of meteor, typically measured in W/s/m^2/nm

From the latter, the actual luminous power of the meteor can be calculated if the distance is known from triangulation.
As long as we are interested in only the relative intensities (in order to determine chemical composition ratios e.g.), the different contributions for the detector signal can be combined with
$IR(\lambda) = const * \eta_{det}(\lambda) * \eta_{gra}(\lambda) * T_{lens}(\lambda)$, giving
$I(\lambda) = IR(\lambda) * T_{atm}(\lambda) * S(\lambda)$
From this equation the instrument response corrected spectrum is calculated as
$S(\lambda) = I(\lambda) / [IR(\lambda) * T_{atm}(\lambda)]$
Quite often the instrument response and atmospheric transmission are combined into an overall response
$R(\lambda) = IR(\lambda) * T_{atm}(\lambda)$
The different factors in these equations are described next.

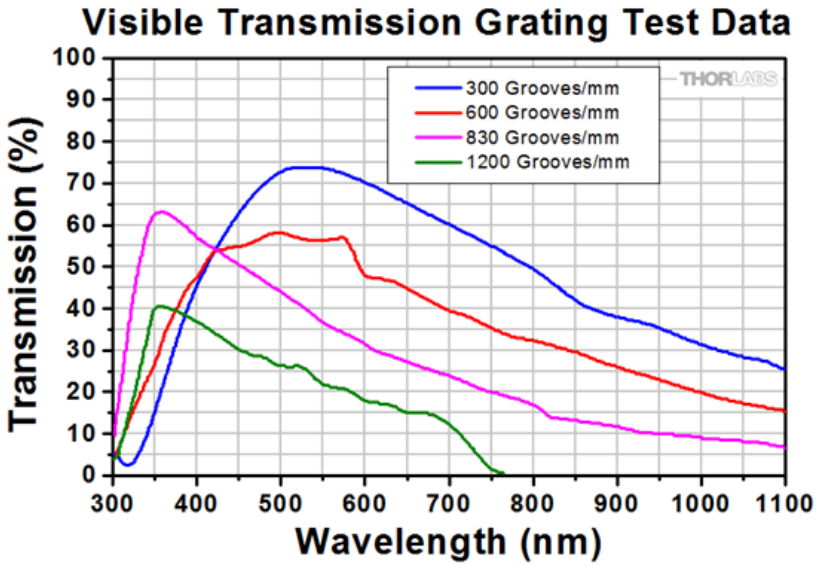
Detector sensitivity

As an example we show the Watec 902 H2ultimate contains a Sony ICX429ALL CCD
http://pdf1.alldatasheet.com/datasheet-pdf/view/95422/SONY/ICX429ALL.html
With the following spectral sensitivity (to be precise, one has to distinguish between response measured in output per incident energy and quantum efficiency measured in electrons per incident photon)

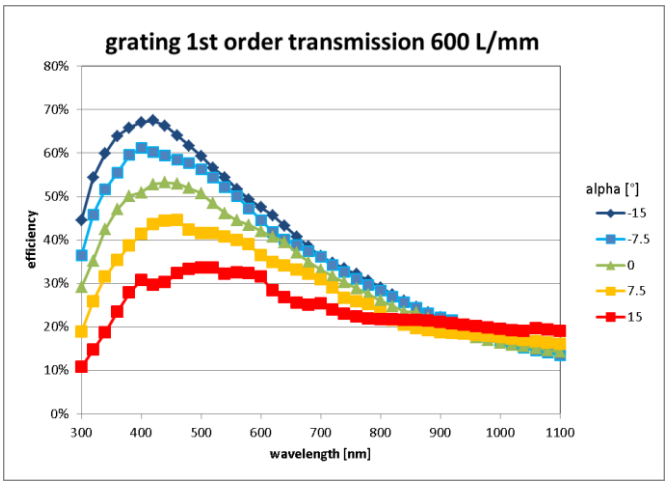


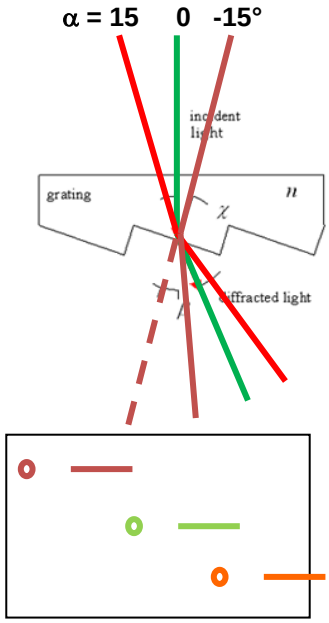
Grating efficiency

Taken from Thorlabs catalogue:
http://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=1123



In particular the 600 L/mm grating is relevant, with an efficiency in 1st order of about 50 % over most of the visible range. Not seen from this diagram is that the efficiency is not only wavelength, but also angle dependent. This is shown in the following graph, calculated with Gsolver for a grating with similar geometry as the Thorlabs 600L/mm grating (groove angle 28.7°, n = 1.52)

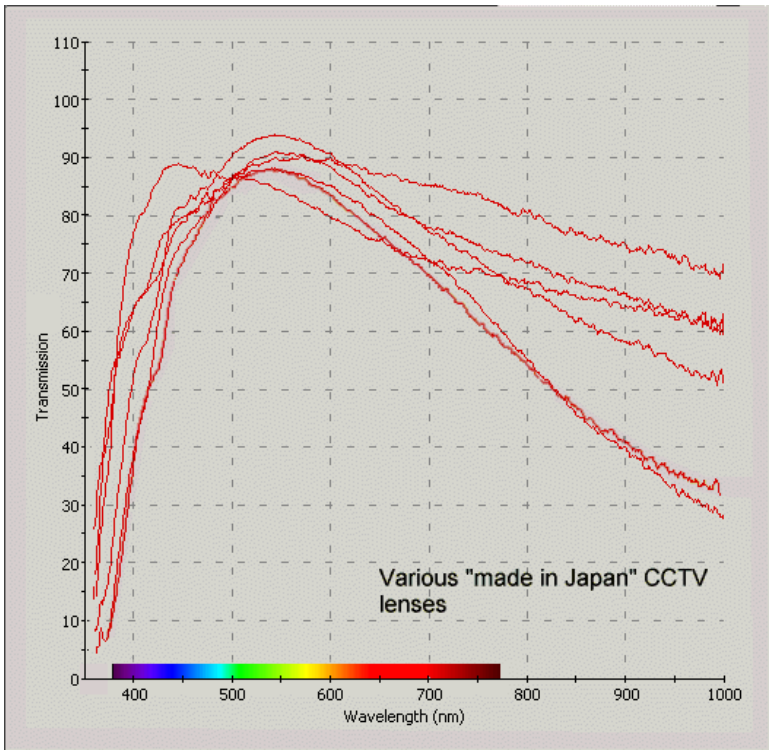




Lens transmission

The following figure shows the general trend of lens transmission, limited by the UV cut-off caused by the glass and the quality of the AR coating. The absolute values of transmission should be treated with caution. For data on quantum efficiency, filter curves sensitivity, see:
http://www.kolumbus.fi/oh5iy/astro/Ccd.html
In addition, the transmittance of the lens is also dependent on the incidence angle. This can be taken care of with the flat field correction in the pre-processing.

Example:



Atmospheric transmittance

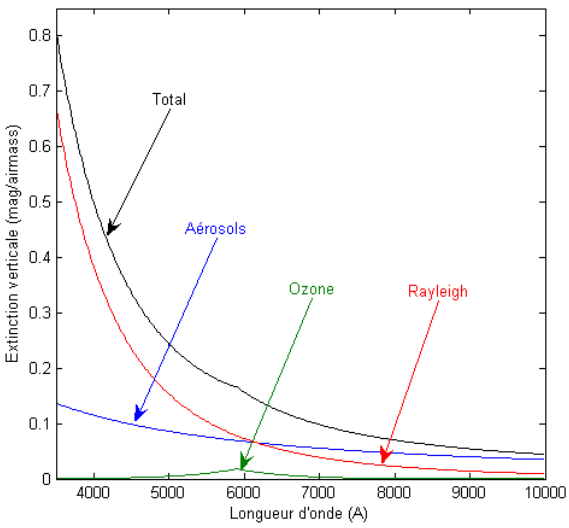
Atmospheric transmittance has been well studied for stellar spectroscopy. For the basic theory see e.g. here: http://www.astrosurf.com/aras/extinction/calcul.htm. Basically atmospheric transmission or extinction depends on the quality of the air (humidity, aerosols) and the path length, depending on the elevation of the observed object.

$T(\lambda) = 10^{[-0.4*A_{z0}(\lambda)/\cos(z)]}$

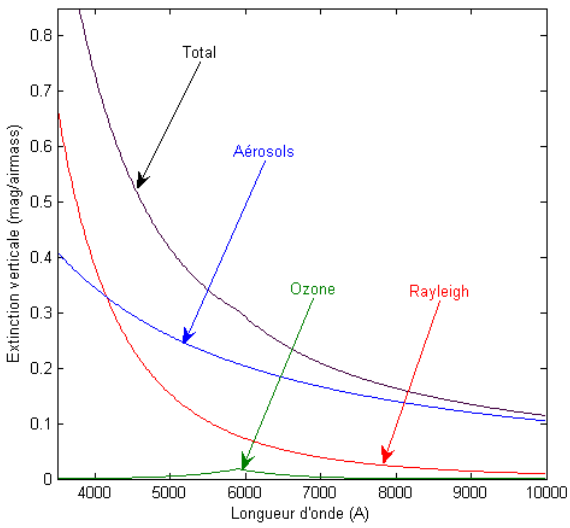
$A_{z0}(\lambda)$ is the extinction, measured in magnitudes, at the zenith (air mass 1)

z is the zenith distance (approximate equation, sufficient for our purpose.

Different factors contribute to extinction, mainly Rayleigh scattering, ozone and aerosols. The first two are rather constant but aerosols vary widely, as shown in the following example:



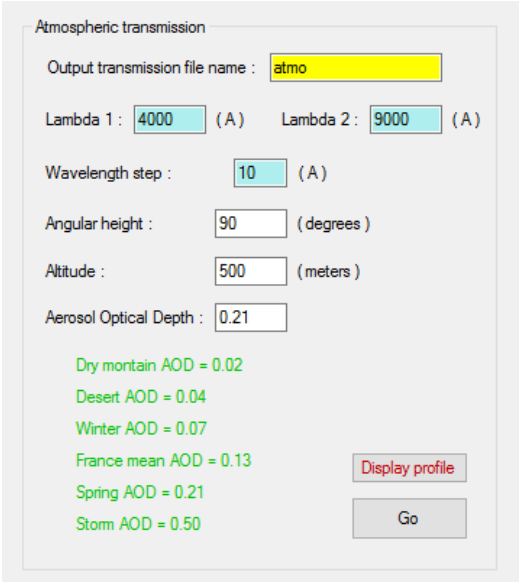
Extinction verticale calculée pour Toulouse (h=0.2 km) par une nuit claire d'hiver (AOD=0.07).

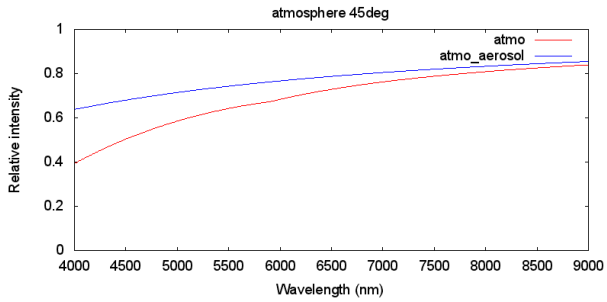


Extinction verticale calculée pour Toulouse (h=0.2 km) par une nuit brumeuse d'été (AOD=0.21).

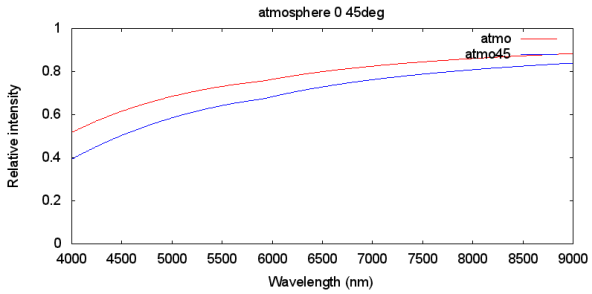
If the aerosol optical density (AOD) is known or can be estimated, then the extinction can be calculated for any elevation

In ISIS, use Misc. – atmosphere:





For AOD 0.21, contribution of aerosol and total transmittance at 45°



Comparison of transmission at zenith (red) and 45°, AOD 0.21

The calculated transmission can be used to correct a response curve R(λ) measured at one elevation to calculate at a different elevation, preferably close by. As shown at right, above an elevation of 45°, the difference in transmission and in particular the differential extinction at different wavelengths is small and can often be neglected. In very clear nights (photometric sky) the contribution of AOD is small and the correction can be evaluated well. In other cases extinction should be measured or a best guess be made. As the meteor spectra are usually only detected at a later time, it is often too late for air quality measurement.

Instrument response in practice

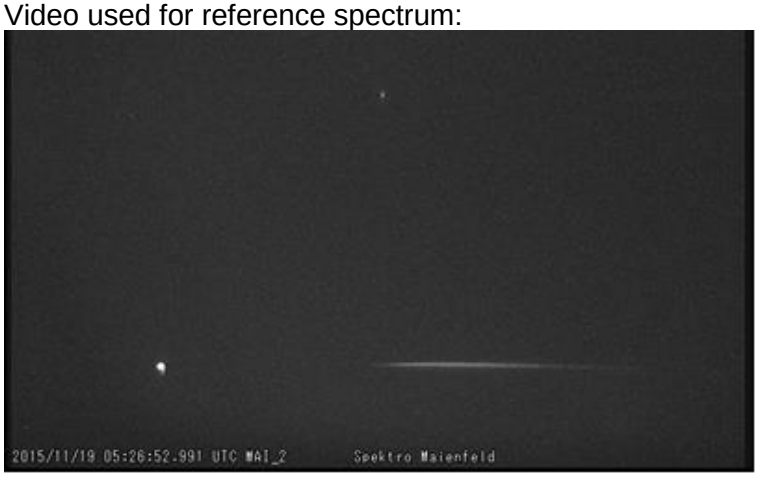
The above considerations are important in order to evaluate their influence and to correct for them in the resulting processing procedure. As they cannot be determined individually without a complex laboratory setup they have to be derived from actual measurements. The main point is that the response is calculated not from its different contributing factors but from the measurement of the spectrum of a calibration source, typically a bright star.
The processing requires two steps:

- Calculating response
  $R(\lambda) = \text{const.} * I(\lambda) / S_{ref}(\lambda)$
  where $I(\lambda)$ is the measured spectrum and $S_{ref}(\lambda)$ is the Flux of the corresponding reference spectrum, taken from a library. Const. is a suitable calibration constant for normalization of the response (e.g. to make the maximum = 1) or for absolute calibration to convert from ADU to physical flux (J/m^2/nm), to be discussed separately)
- Applying instrument response to meteor spectra
  $S(\lambda) = I(\lambda) / R(\lambda)$
  where $I(\lambda)$ is the measured spectrum and $S(\lambda)$ is the response corrected spectrum (relative units)

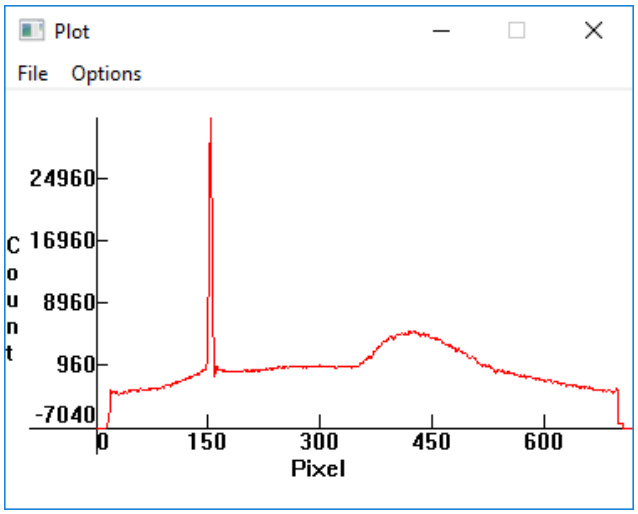
For both steps division of a spectrum by another spectrum (or wavelength dependant response curve) is required. For this, ISIS has been used in the following example, but other software can be used as well (Vspec, SpectroTools, Rspec, EXCEL). ISIS has the advantage that it contains a library of reference spectra.

Calculation of response from measured spectrum

A spectrum of a reference star can be obtained from the background image, where a suitable number of video frames are averaged. Bright stars of spectral class A are best, they have a simple spectrum (Vega, Sirius etc.) and sufficient flux in the blue violet spectral range, where the determination of the response function is most critical. For the following example, Venus was used because it was recorded in the same video as the meteor to be analysed. This has the additional complication that a Venus reference spectrum had to be found. In this particular case, a solar spectrum was multiplied by the Venus albedo from the literature (see appendix).
Video used for reference spectrum:



Averaging 66 frames and transforming to the orthographic projection gives a smoother spectrum, unfortunately the background is quite non-uniform, as the IRIS L_ADD, L_PLOT result shows:



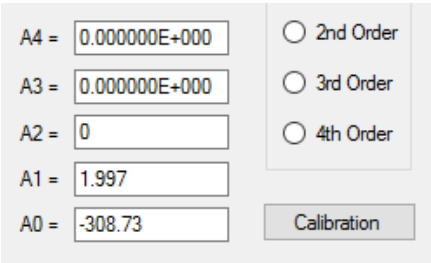
Between the zero order and the start of the spectrum around pixel 350the level should be equal to zero! This is caused by the missing flat field correction.
A better extraction of the spectrum can be done with ISIS, which subtracts the background level correctly.

Extraction and calibration of spectrum with ISIS

Rename 0526add66-d.fit →0526add66-d1 (naming convention ISIS) and process single image as described in ISIS processing.
Save spectrum after normalization to peak spectrum = 1 → venus0526n.fit
Calibrate with dispersion 1.997 nm/pixel and zero order (use ..\calib\calibration tools.xls)

A1	1.997
measured pixel	153.600
measured lambda	0.000
calculated A0	-308.7362

→
Venus0526caln

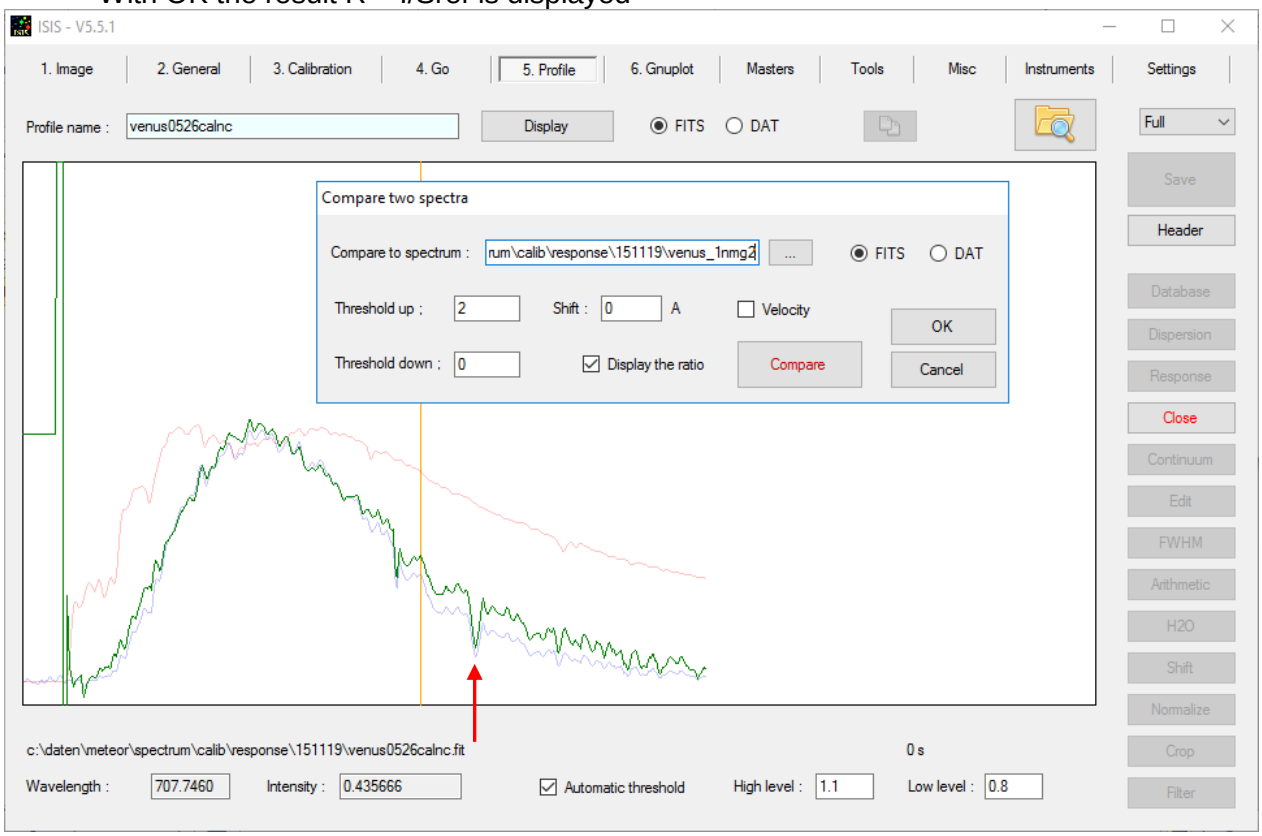


Crop wavelength range to meaningful values 300 – 1000 nm
Save spectrum Venus0526calnc.fit

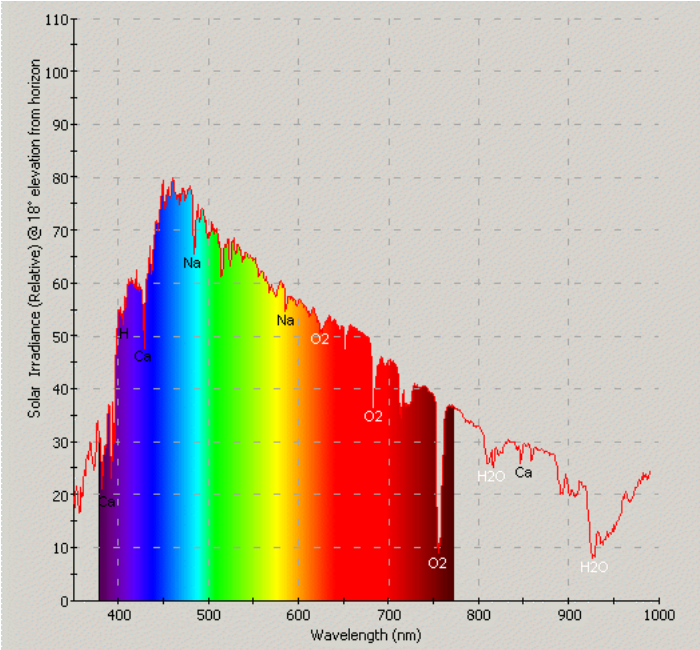
Calculate response:

Divide measured spectrum by reference Venus spectrum (wavelength converted to nm, smoothing with a Gaussian applied so that resolution is similar to measured spectrum:

- Load measured spectrum in Profile
- Select "Compare"
- Load the reference spectrum and file type in the new box and select the range in y (threshold up, down)
- With Compare the two spectra are displayed in blue and red
- With display the ratio and Compare the divided spectrum I/Sref is shown in green
- With OK the result R = I/Sref is displayed

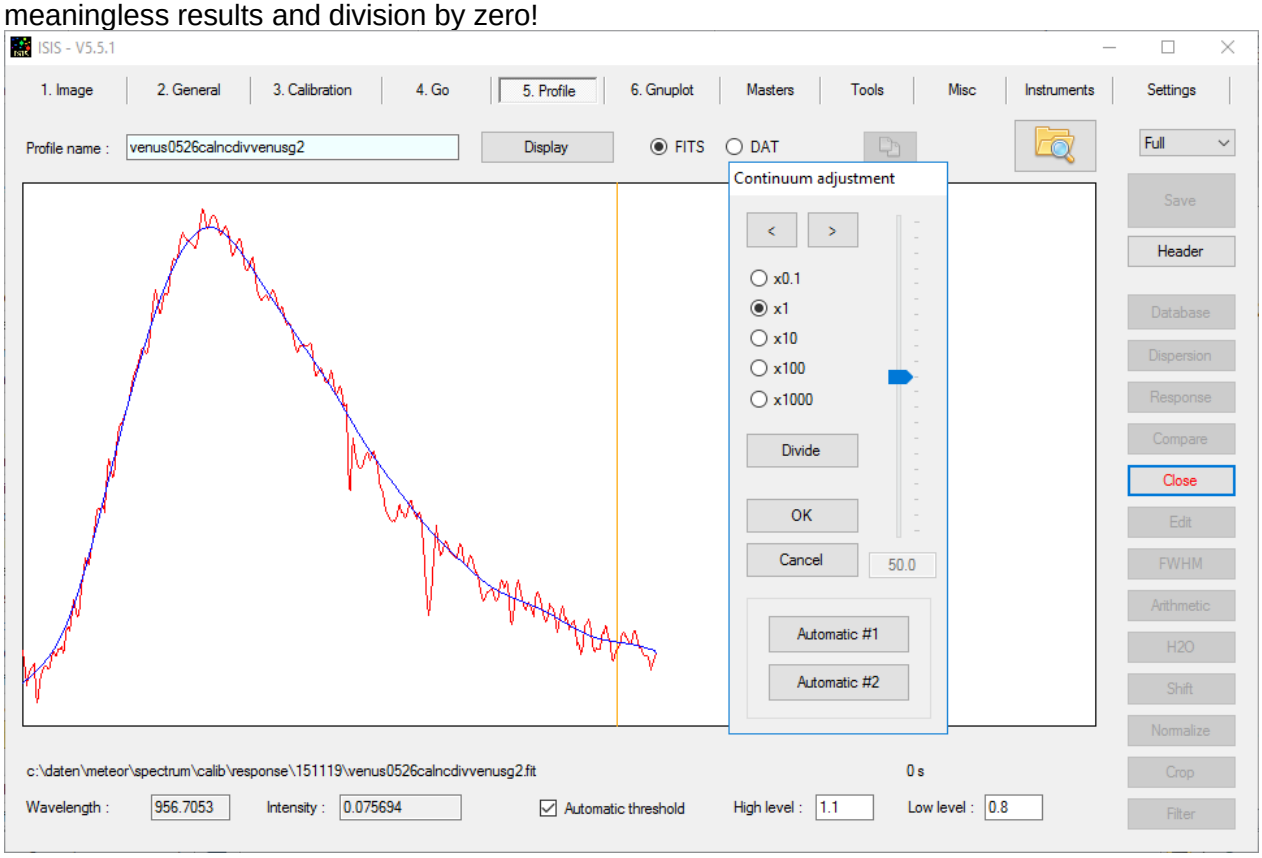


Blue: measured spectrum
Red: calibrated reference, smoothed
Green: raw response = measured/reference
Save to venus0526calncdivvenusg2 after cropping to 345 - 999nm to avoid division by zero
This response has to be smoothed, preferable would be a less noisy spectrum. Visible is the absorption at 760 nm (oxygen, Fraunhofer A-Band) and other atmospheric bands.
Compare with this spectrum of a solar spectrum wih atmospheric absorptions (O2, H2O).

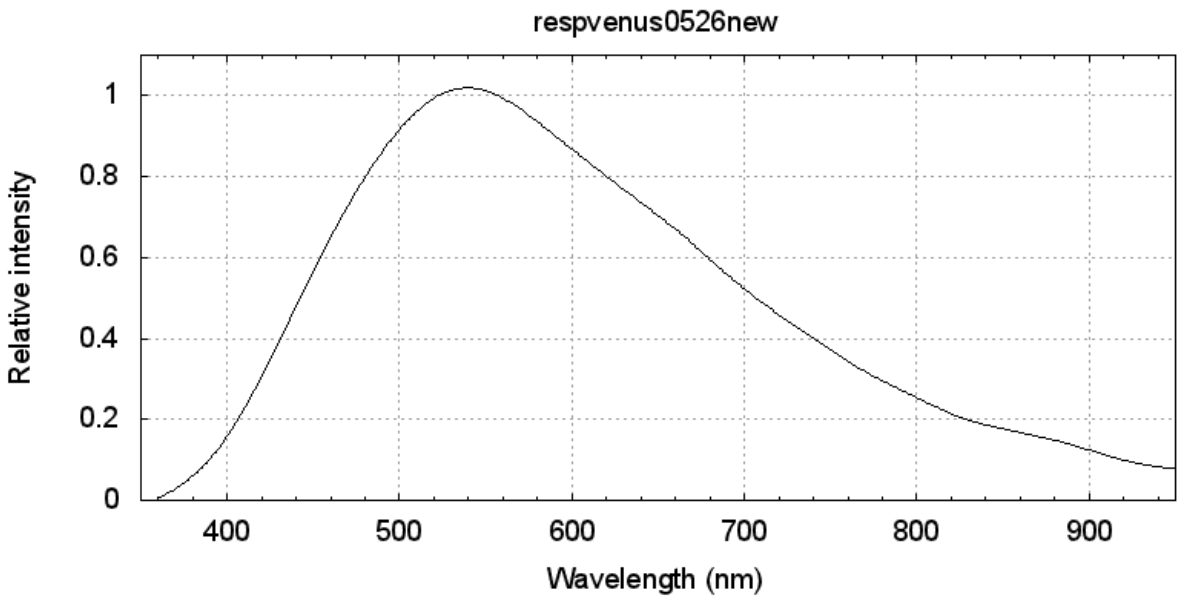


The smoothing is done in ISIS with Profile – Continuum

Cut out the absorption lines with a double click left and right of the undesired region and adjust the slider. Make sure that no negative values at the borders are created, these lead to meaningless results and division by zero!



With OK you accept the result and save it to the response (response.fit for plotting in ISIS and/or response.dat for further use in ISIS):



Do not forget to calculate the elevation of the reference object at the time of acquisition From UFO Analyzer: 27.64°, from Carte de Ciel :27°53' quite low over the horizon, but comparable to the elevation of the meteor M20151124_043551 at an elevation of 31.5°, to which this response was applied. See next.

Apply response to measured spectrum

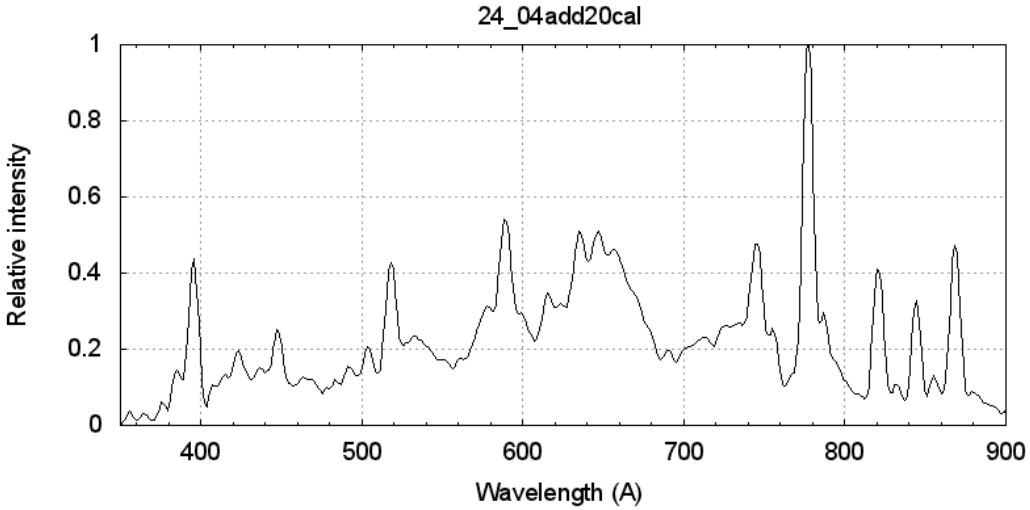
The starting point for this step is a meteor spectrum calibrated in wavelength. For the calculation of the energy spectrum S(λ) (response corrected spectrum) we apply the response equation the following way:

$S(\lambda) = I(\lambda) / R(\lambda)$

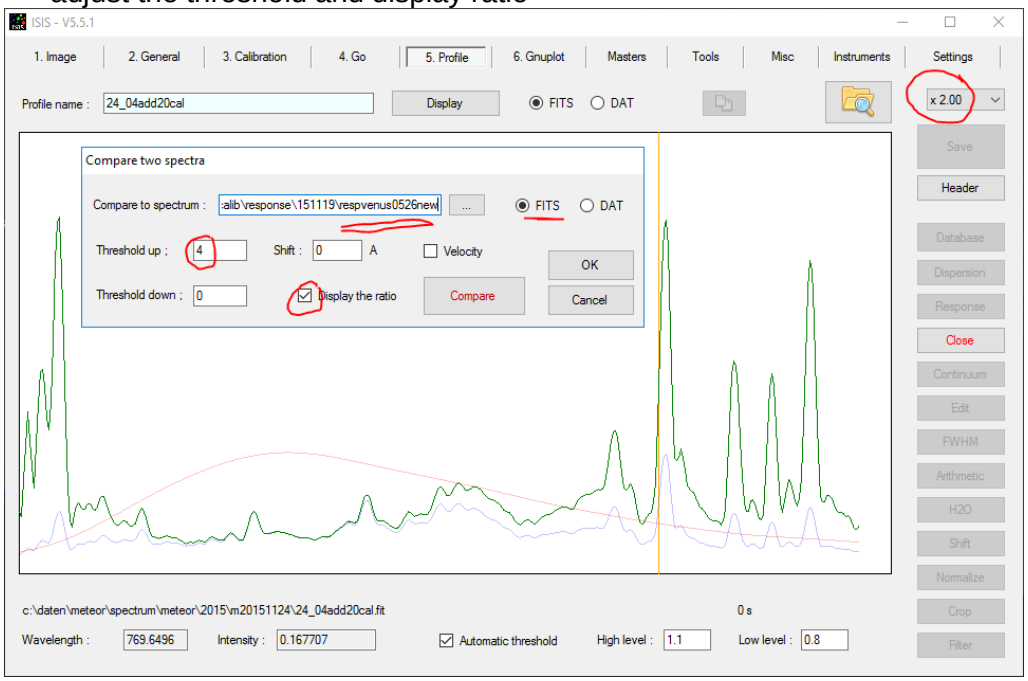
where I(λ) is the measured spectrum and S(λ) is calculated in relative units. Again we work in ISIS, the procedure is quite similar to the calculation of the response, and just the role of R and S are reversed.

As an example I use the following spectrum from 20151124

Adding 20 processed frames resulted in the following spectrum:



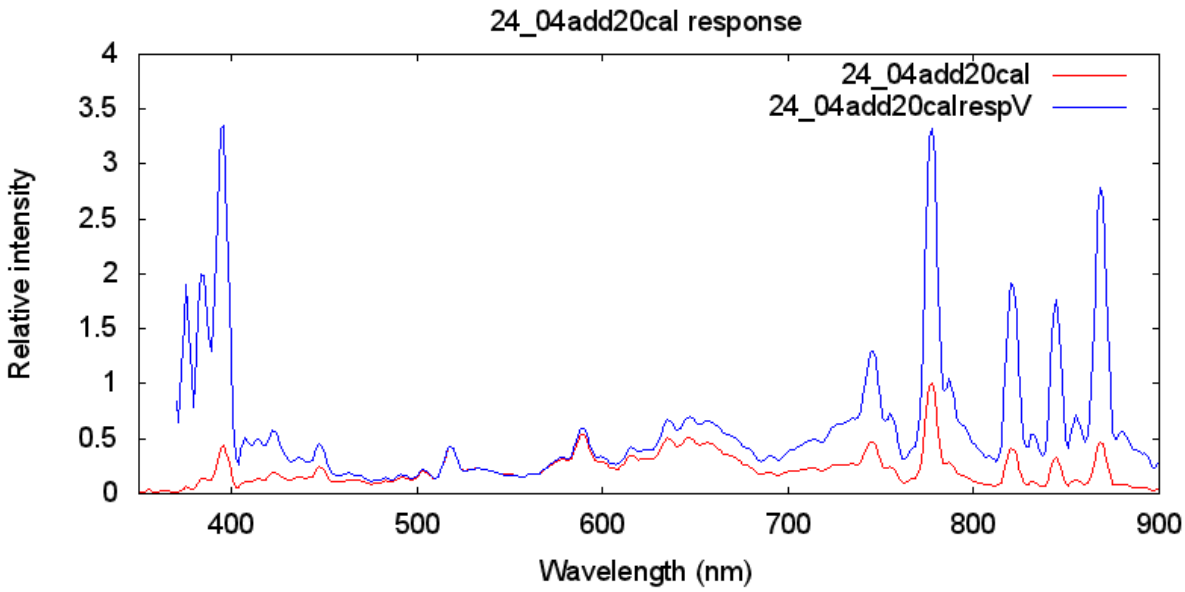
- Load with Profile – Load File in ISIS
- restrict the wavelength range to where the response is meaningful with crop to about 380 – 900 nm
- divide with the response from the previous section with Compare to spectrum: response
- adjust the threshold and display ratio



- The green curve shows the response corrected spectrum.
- With OK – Save save the corrected spectrum
- At this point the atmospheric transmission should be corrected. In this particular case this was not done because the reference spectrum and the meteor spectrum were observed at a similar elevation 4° difference)

Comparison of the two spectra:

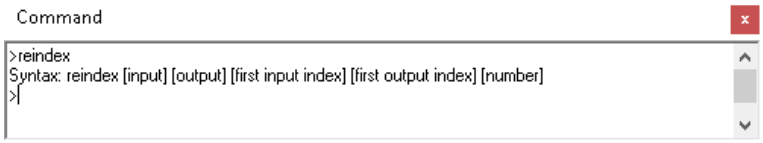
- Red: response not corrected
- Blue: response corrected


24_04add20cal response
24_04add20cal
24_04add20calrespV
Relative intensity
Wavelength (nm)
0
0.5
1
1.5
2
2.5
3
3.5
4
400
500
600
700
800
900

Appendix

Some useful IRIS commands

For a complete list see: http://www.astrosurf.com/buil/iris/nav_pane/CommandsFrame.html
Another method to find out the meaning of the different parameters is to write the command into the command window in IRIS. With parameters missing a short help is shown, which is very helpful if you know the command name (faster than looking it up in the command list):



Correct description of command, which is more useful this way

- ~~CONVERTBMP24 [IN] [R] [G] [B] [NUMBER~~] (wrong in command description)
- CONVERTBMP24 [IN] [OUT] [NUMBER] (correct use of command)

Convert an 24-bits BMP input sequence [IN] into ~~three output generated sequences [r] [g] [b]~~ a sequence of colour images in the current file format (fix the File type in the Settings dialog box - see the File menu). The number of image in the input sequence is [NUMBER]. You can set the base of the first index in the input sequence (see the SETBASE command below). The first index of the output sequence is always 1.

For B/W images use the corresponding command, which creates a 16-bit image

- CONVERTBMP [IN] [OUT] [NUMBER]

- CONVERTBMP24BW [IN] [OUT] [NUMBER]

Convert a 24-bit BMP input sequence [in] into the mean of the RGB planes and copy the result in the output sequence [out]. The number of image in the input sequence is [number]. You can set the base of the first index in the input sequence (see the SETBASE command). The first index of the output sequence is always 1.
Here you lose information by averaging the three channels (division by 3 and rounding, not well! Better to use CONVERTBMP24 and COL2BW)

- SETBASE [BASE]

Define the first index for an input sequence for the commands CONVERTBMP, CONVERTBMP24, CONVERTBMP24BW, CONVERTTIFF, CONVERTTIFF24 and CONVERT24BW. The default value is 1. The over typical value is 0. For this enter the command:
SETBASE 0

Viewing BMP-images in IRIS:

- LOADBMP [NAME]

Load an 8-bits BMP file in memory from the current directory.

- LOADBMP24 [NAME] [R] [G] [B]

Load a 24-bits BMP file from the current directory and copy the RGB planes in the images [r], [g], and [b] respectively.
Does not seem to work properly!

- LOADBMP24BW [NAME]

Load a 24-bits BMP file from the current directory in memory and convert the RGB planes into a B&W images.
Works but loss of information by averaging 3 channels

- COL2BW [INPUT] [OUTPUT] [NUMBER]

Converts a 48-bits true-colours image sequence into a black and white sequence (simple add of the RGB layer).
This can be used together with CONVERTBMP24 without loss of information. For conversion of a single image see SPLIT_RGB

- ADD2 [NAME] [NUMBER]

Adds [number] images in the sequence of images having the generic name [name].

- SUB2 [IN] [OPERAND] [OUT] [OFFSET] [NUMBER]

Subtracts from the [number] images of a sequence of images with the generic name [in] the image [operand] then adds the value [offset] to these images (see the command SUB). [out] is the generic name of the output images.

- ROT2 [IN] [OUT] [XC] [YC] [ANGLE] [NUMBER]

Same as ROT but for a sequence of images.

- REINDEX [IN] [OUT] [FIRST INDEX IN] [FIRST INDEX OUT] [NUMBER]

Reorganize the indices of a sequence. Let us suppose a sequence: I1, I2, I3, I4. One wants to transform it into a sequence J5, J6, J7, J8. One will write:
REINDEX I J 1 5 4
The input and the output sequences cannot have the same name. [NUMBER] is the number of image to be converted.

- REGISTER [IN] [OUT] [NUMBER]

Registers [NUMBER] images of a sequence having the generic name [IN] with respect to the first one. The generic name of the output images is [OUT]. The registration consists here in a simple translation.
Draw a rectangle with the mouse around an isolated, non-saturated star. The registration of the images will be done with respect to that star. The size of the rectangle has to be large enough so that it contains the displacement of the star between two contiguous images (if this not the case, Iris could take a wrong star to perform the registration).

- SPLIT_RGB [R] [G] [B]

Transform the 48 bits image in memory (true colours) into R, G and B separate component files (equivalent to **RGB separation**... command of **Digital photo menu**)[3].

These are just a few of the most useful commands; there are a large number of others, which cover different areas of image processing. Another interesting command is RUN, which allows executing simple batch commands
(http://www.astrosurf.com/buil/iris/nav_pane/CommandsFrame.html).

To be tested, not used so far:

- TCL [SCRIPT] [PARAMETER$_1$] [PARAMETER$_2$] ... [PARAMETER$_N$]

Execute a Tcl script. [SCRIPT] is the name of the scripting file in the disk. [PARAMETER1], [PARAMETER2], etc. is a variable number of parameters for the script. For details about the powerful TCL command see the ASTP protocol Web page.

[3] This command can be used for converting a single colour image into a monochrome image by adding r, g, b. Example
>SPLIT_RGB r g b
>LOAD r
>ADD g
>ADD b

Script files, examples:

For calculation of background image:

```
* M_BACK.PGM
*******************************************************************************
* use RUN M_BACK [I, B, NB, MULT]
-       I: Input filename.bmp
-       B: Background filename
-       NB; number background images
-       MULT: multiplier for background   B = (Sum I1...I_NB)*MULT
   Since the program cannot do arithmetic calculations,
        MULT has to be calculated externally: MULT = 1/NB and entered as a parameter
* Intermediate files (@b...) are deleted at the end
*******************************************************************************
SETBASE 1
CONVERTBMP24bw $1 @b $3
ADD2 @b $3
MULT $4
SAVE $2
REMOVE@
```

For calculation of background corrected meteor images:

```
* M_DARK.PGM
*******************************************************************************
* RUN M_DARK [I, B, M, START      , NM] reindexes and subtracts background

-       I: Input filename.bmp
-       B: Background filename
-       M: Meteor filename
-       START: first index of meteor image (used for stacking, so should be visible)
-       NM: number meteor frames
* Intermediate files (@b...)are deleted at the end
*******************************************************************************
SETBASE $4
CONVERTBMP24BW $1 @m $5
SUB2 @m $2 $3 0 $5
REMOVE@
SETBASE 1
```

(These are the 24 bit b/w versions, for colour images change the bmp conversion to CONVERTBMP24 in both script files or change to CONVERTBMP for 8-bit monocolour images)

Calculation of transformation parameters:

The x, y-coordinates of the different laser spots are measured and assigned to the different orders of the spectra

From a least square fit of the measured positions with lens – grating model the desired transformation parameters is obtained.

As input in the model the following fixed parameters are used:

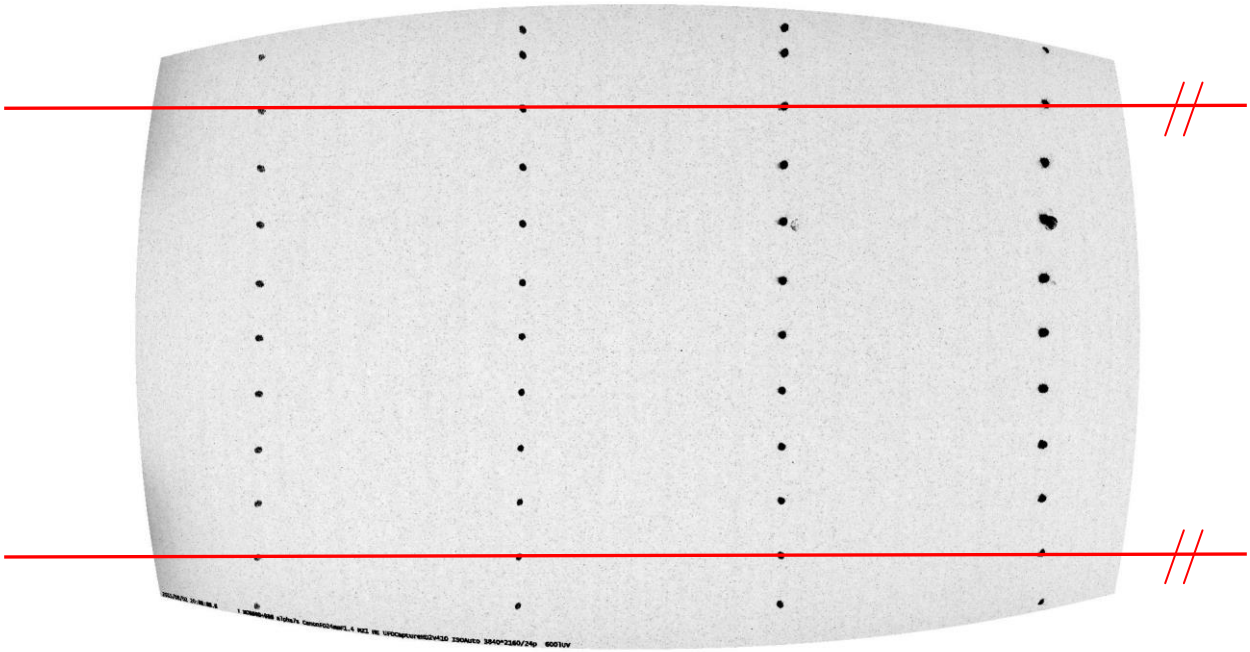
- Lambda: laser wavelength,
- G: grating lines/mm,
- Px: pixel size,
- Nx, Ny: image size
- Binning factor

Fit parameters:

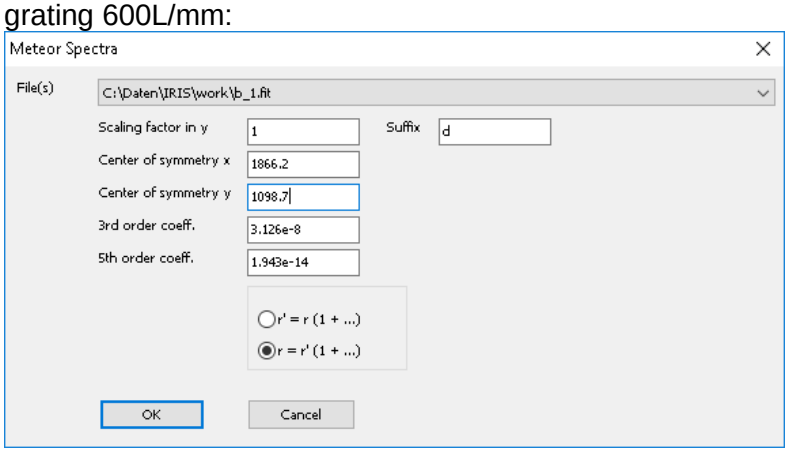
For the least square fit the following parameters were adjusted:

- Disp0: dispersion at lens center → gives dispersion of transformed image
- a3, a5: lens transformation coefficients (r = r'*(1 + a3*r'^3 + a5*r'^5)
  (for a better convergence of the fit 1^e6*a3 and 1^e12*a5 were fitted)
- Alpha: Grating rotation angle, can be used to align transformed spectra parallel x-axis
- dx, dy: offset optical axis from image center in original image
- (yx): py/px, pixel ratio (can be fitted if not known, for Sony alpha square pixels → yx=1.00
- x1, y1, … xn, yn: position of zero order of different spectra

The resulting parameters were inserted in the transfomation equation. With the following result of the transformation:



The spectra are linear, all spectra are parallel and the dispersion is everywhere the same, 0.624 nm/pixel, the laser wavelength of 518 nm was confirmed by comparison with the Na-line of a meteor spectrum.
Transformation parameters Sony alpha 7s, 4k format with Canon FD24mmF1.4, green laser, grating 600L/mm:



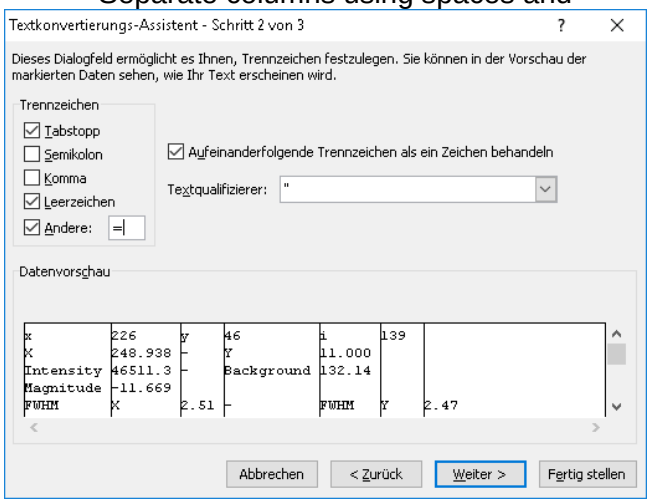
With binning 2x2, older data

scaling factor y	1	
center of symmetry x	942.7	factor 2
center of symmetry y	536.9	factor 2
3rd order coeff.	1.284E-07	factor 4
5th order coeff.	3.058E-13	factor 16

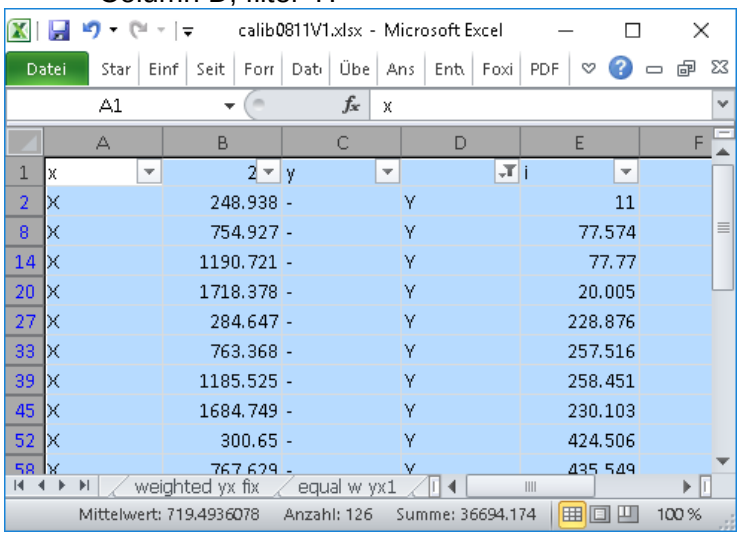
Producing Input for calibration in EXCEL from measured laser line positions

Note: All images from EXCEL sheets and command windows are in German, the EXCEL version 2010 has been used; unfortunately no language packs for English are available anymore, so the windows may look different in Japanese or English.
Extract laser line positions from IRIS output window:

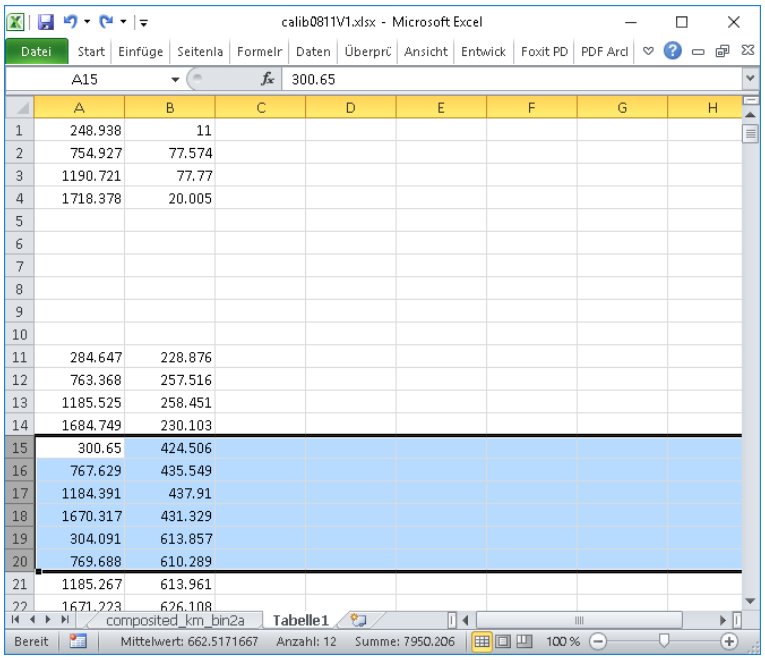
- Copy IRIS Output window into Excel worksheet
- Select first Column
- German EXCEL Version: Daten – Text in Spalten
- Separate columns using spaces and "="



- Finish
- Select all
- Column D, filter Y:



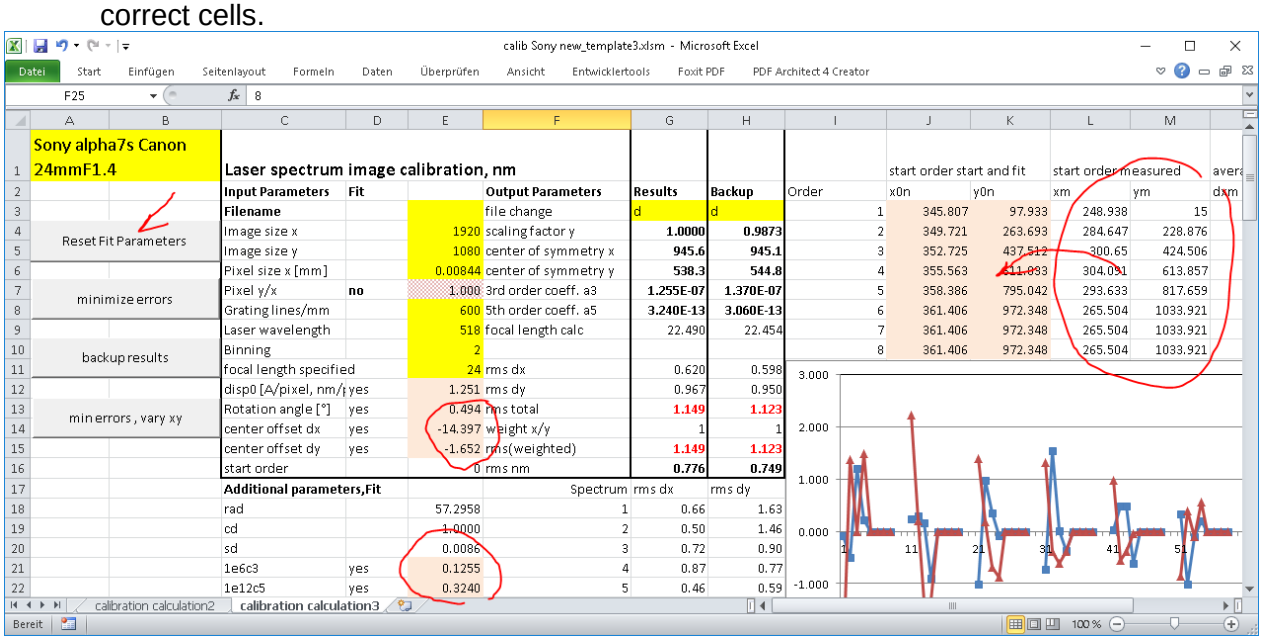
- Copy to new sheet
- Delete unused columns
- Insert 10 - NO rows after each spectrum with NO orders (10 rows per spectrum, independent of number of orders, allows analysis of maximum of 8 orders per spectrum, 4 orders are sufficient):



- Copy (A1:B78) of this sheet to calculation sheet A31 (insert values), overwrite values from earlier calculations.

- Check correct value of fixed parameters (yellow), wavelength, pixel size etc

- Reset Fit Parameters A Macro has been added in calib Sony new_template.xlsm which resets the fit parameters and copies the start values for x0n and y0n into the correct cells.

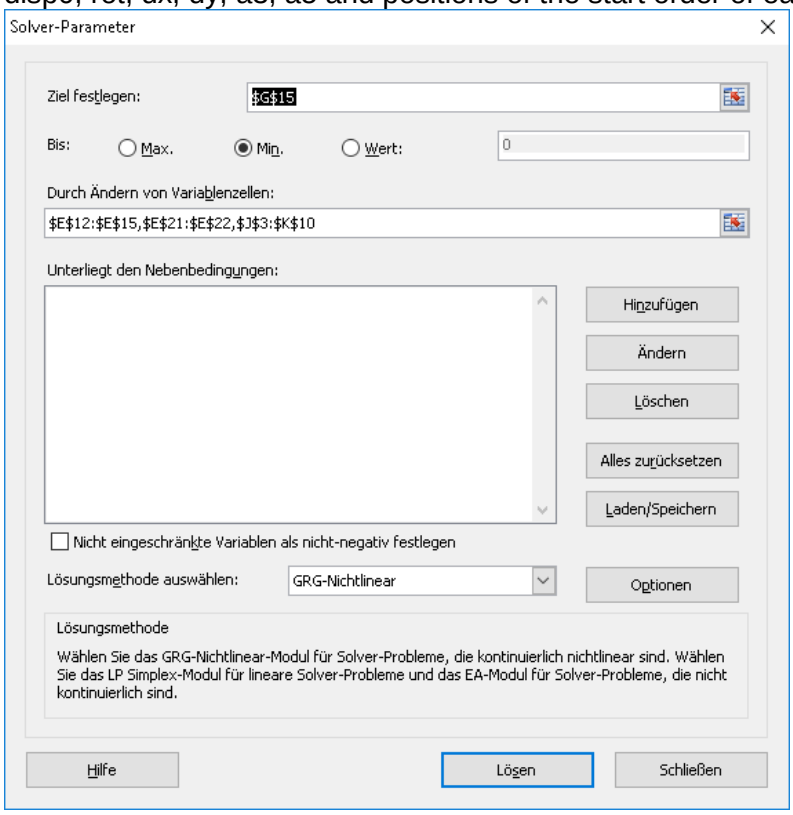


(Solver

In the case that the buttons for the macros do not work, the solver can be started manually with Daten – Analyse - Solver.

Find solution with Daten – Analysis - Solver (if not visible, activate with EXEL – Datei – Optionen – Add-ins – Gehe zu – EXEL-add-ins – check Analyse-Funktionen – OK [4]

The goal is to minimize the RMS error of the calculated – measured line positions =WURZEL(G11^2+G12^2), found in cell G13, with variation of the fit parameters disp0, rot, dx, dy, a3, a5 and positions of the start order of each spectrum:

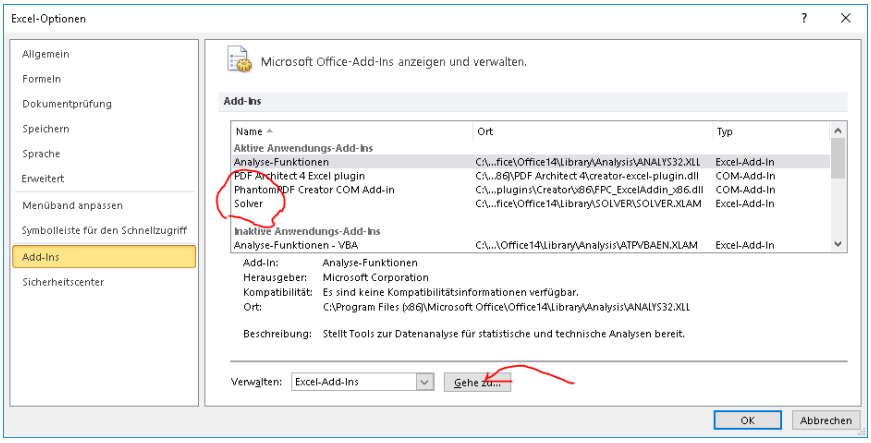


Allow negative values. Select GRG-nonlinear for solution method. With the options you can tweak the finding of a solution.

- minimize errors **Instead of using the Solver from the EXCEL menu, a button has been added to the worksheet "minimize errors", which performs the same task.**

If a solution has been found, the rms error should be much smaller than the start value (typically rms total should be of the order of 1 pixel)
Check if the solution has converged by running the solver again, repeat until no decrease of rms error is observed.

4



New: the x- and y coordinates may be fitted with different weights so that either better wavelength linearity is obtained or better straightness of the spectra. This is done by setting the weight in cell G14 and minimizing cell G15. A larger weight increases wavelength accuracy. Once a solution has been found, check the errors for outliers (measurement errors or overexposed lines). You may remove these from columns A and B (pairwise) and find a better solution.

rms dx	0.620
rms dy	0.967
rms total	**1.149**
weight x/y	1
rms(weighted)	**1.149**
rms nm	**0.776**

Additional notes to the EXCEL sheet

There are two additional buttons in the EXCEL sheet

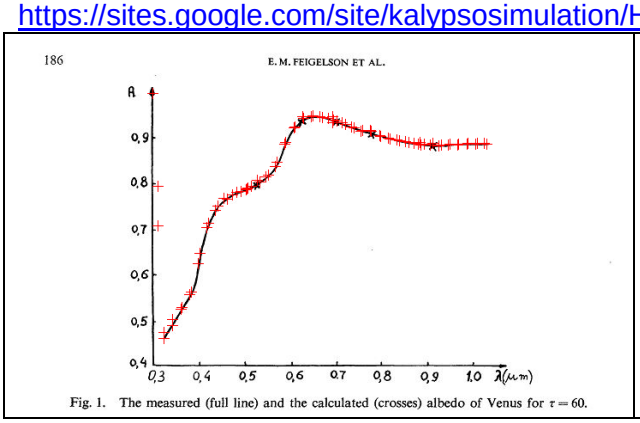
- backup results copies the results in G3:G16 to H3:H16, if you want to do another calculation and keep the old values to see if the solution improves
- min errors , vary xy uses y/x, the pixel size ratio (vertical to horizontal dimension) as an additional fit parameter (in cell E7). For square pixels set this value to 1, for rectangular pixels (such as WATEC) allow the variation. Use the result of the fit and set the scaling factor in y in ImageTools accordingly.

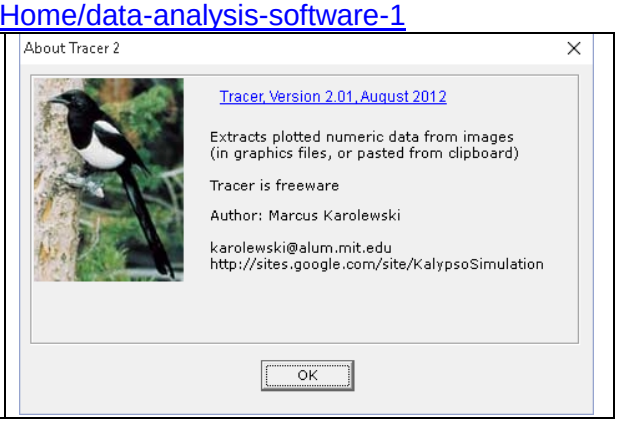
The sheet for the SQRTfit uses the same structure, the only difference is that the cell E22 is empty and the transformation coefficients and f2 are calculated from E21 alone, so that the same macros can be used in both data sheets.

2	**Input Parameters**	**Fit**		**Output Parameters**	**Results**
3	**Filename**			file change	d7
4	Image size x		720	scaling factor y	**1.0263**
5	Image size y		576	center of symmetry x	**394.1**
6	Pixel size x [mm]		0.0086	center of symmetry y	**312.0**
7	Pixel y/x	**yes**	1.026	3rd order coeff. a3	**1.915E-07**
8	Grating lines/mm		600	5th order coeff. a5	**5.503E-14**
9	Laser wavelength		405	focal length calc	7.163
10	Binning		1	f2	13.89
11	focal length specified		8	rms dx	0.380
12	disp0 [A/pixel, nm/pixe	yes	2.001	rms dy	0.631
13	Rotation angle [°]	yes	-0.049	rms total	**0.737**
14	center offset dx	yes	34.150	weight x/y	1
15	center offset dy	yes	24.027	rms(weighted)	**0.737**
16	start order		0	rms nm	**0.760**
17	**Additional parameters,Fit**			Spectrum	rms dx
18	rad		57.2958	1	0.26
19	cd		1.0000	2	0.48
20	sd		0.0009	3	0.49
21	(1000*p/f2)^2	yes	0.3831	4	0.29
22			0.0000	5	0.35

Venus reference spectrum

A spectrum of Venus albedo was digitized with Tracer
https://sites.google.com/site/kalypsosimulation/Home/data-analysis-software-1

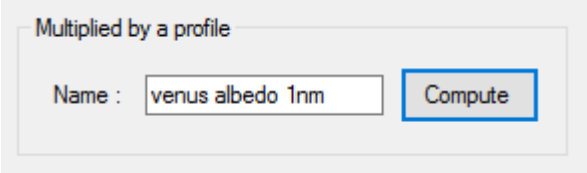




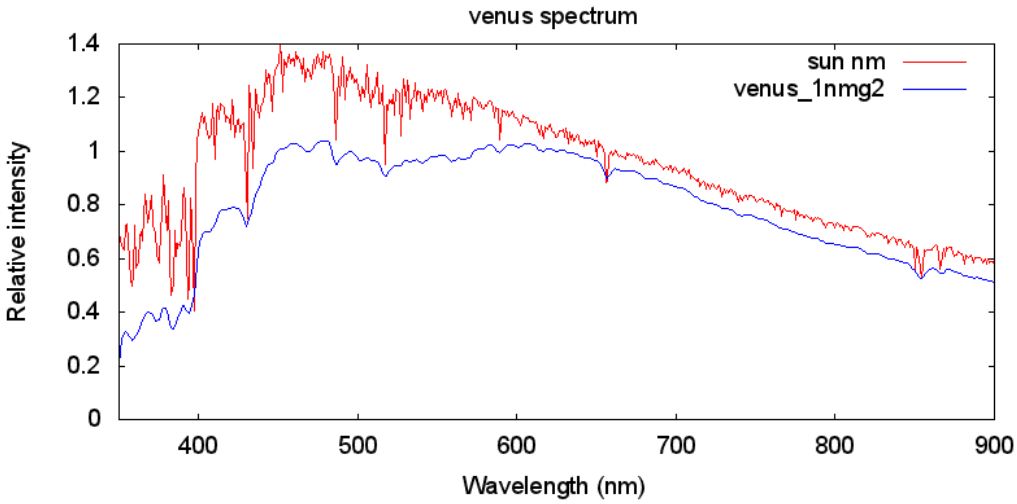
This was multiplied with a sun spectrum (from ISIS database, recalibrated in nm, smoothed to a resolution of 1nm)

- Load sun spectrum

- With Profile – arithmetic multiply with Venus albedo



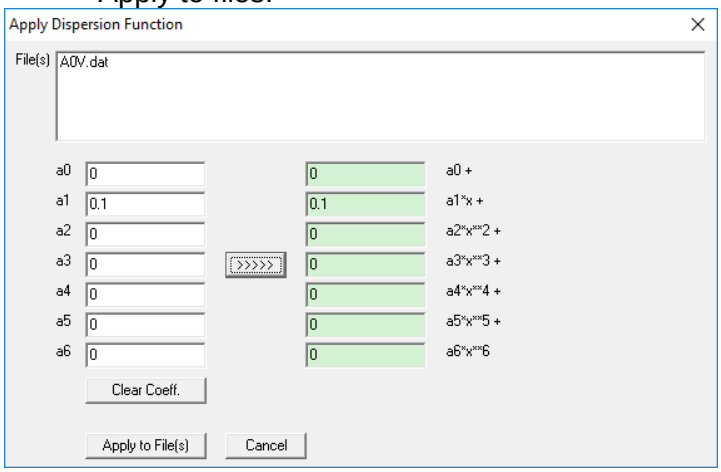
- Compute
- Smooth with Filter – Gauss 2 to a resolution comparable to the meteor spectra
- Save as Venus_1nmg2.fit blue curve



Wavelength conversion

The reference spectra in ISIS are measured in A. In meteor spectroscopy, nm is used as a SI standard, so a wavelength conversion is necessary. For this SpectroTools is useful, with the following procedure

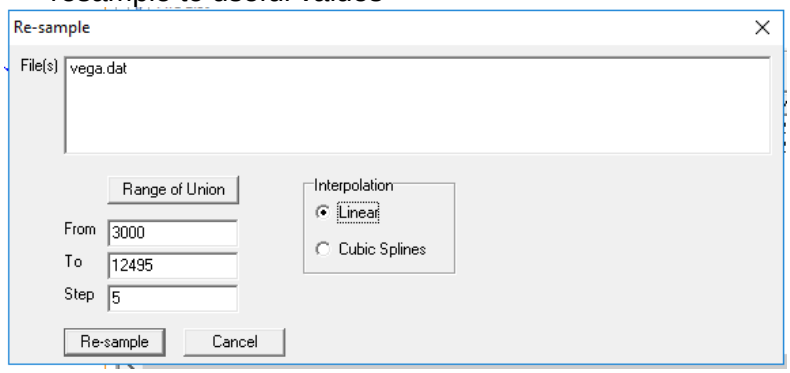
- Load reference from database in ISIS or elsewhere. Most of the stars in the database are not bright enough, but you can choose from the Pickles list if you know the spectral class. This should be precise enough for our purpose. For Vega select A0V.
- Save as *.dat in ISIS (SpectroTools expects a FITS header with wavelength units, missing in the database files)
- Load in SpectroTools, select the file(s) in FileList and choose X-operators – Dispersion function
- Set clear coefficients, a1=0.1 >>>
- Apply to files:



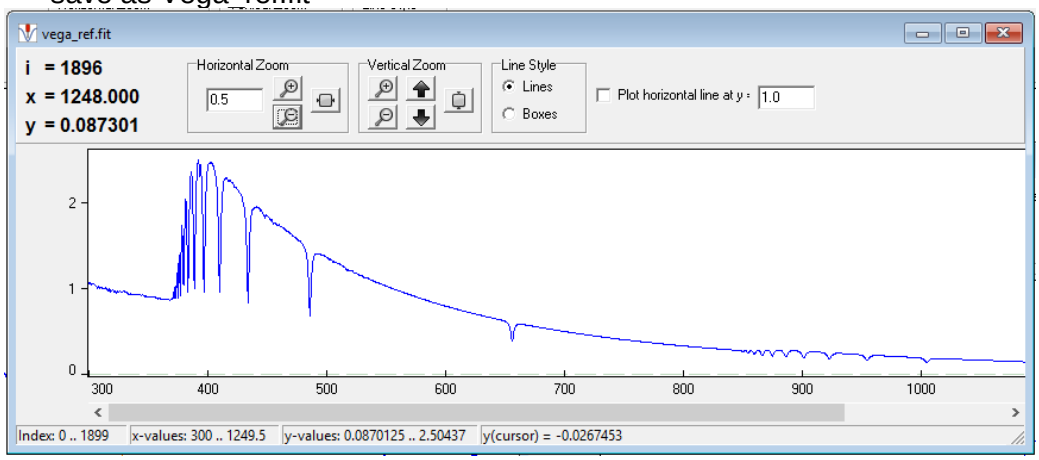
- Rename files to A0V_ref or Vega_ref
- Save as *.fit
- Edit keywords, change CUNIT1 to ‘nm’
- save

For Vega, there is a more precise method, as this is in the CalSpec database, a collection of primary standards for flux calibration

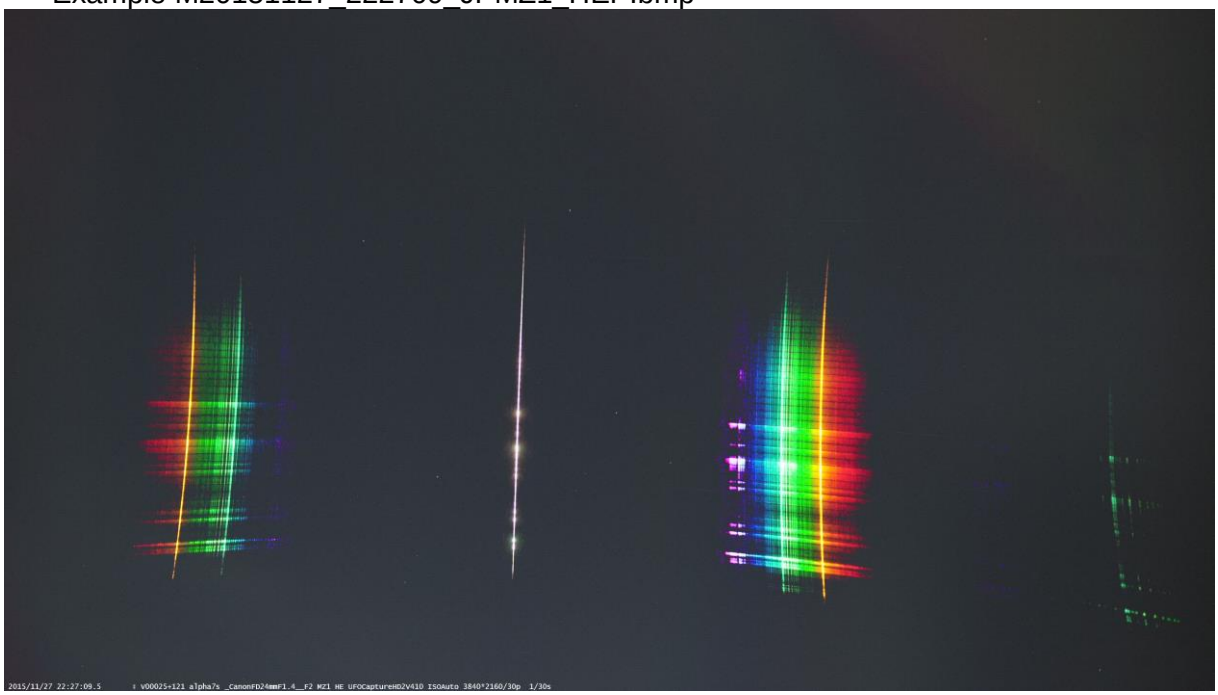
- load the Calspec spectrum from ISIS database
- normalize the spectrum to 1 at 5500A, otherwise you do not see much
- save as Vega.dat
- resample to useful values



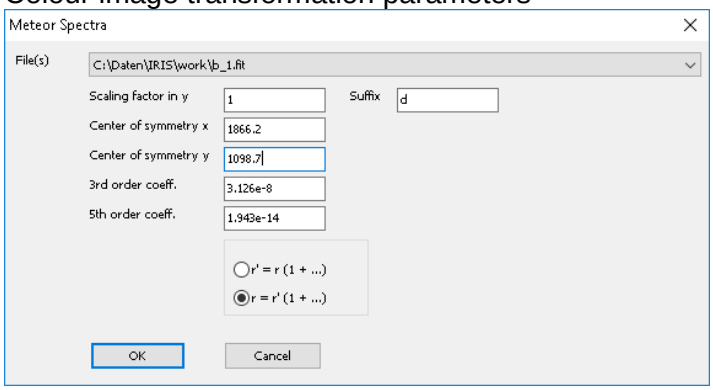
- convert A to nm as above
- save as Vega_ref.fit



Example M20151127_222709_JPMZ1_HEP.bmp



Colour image transformation parameters

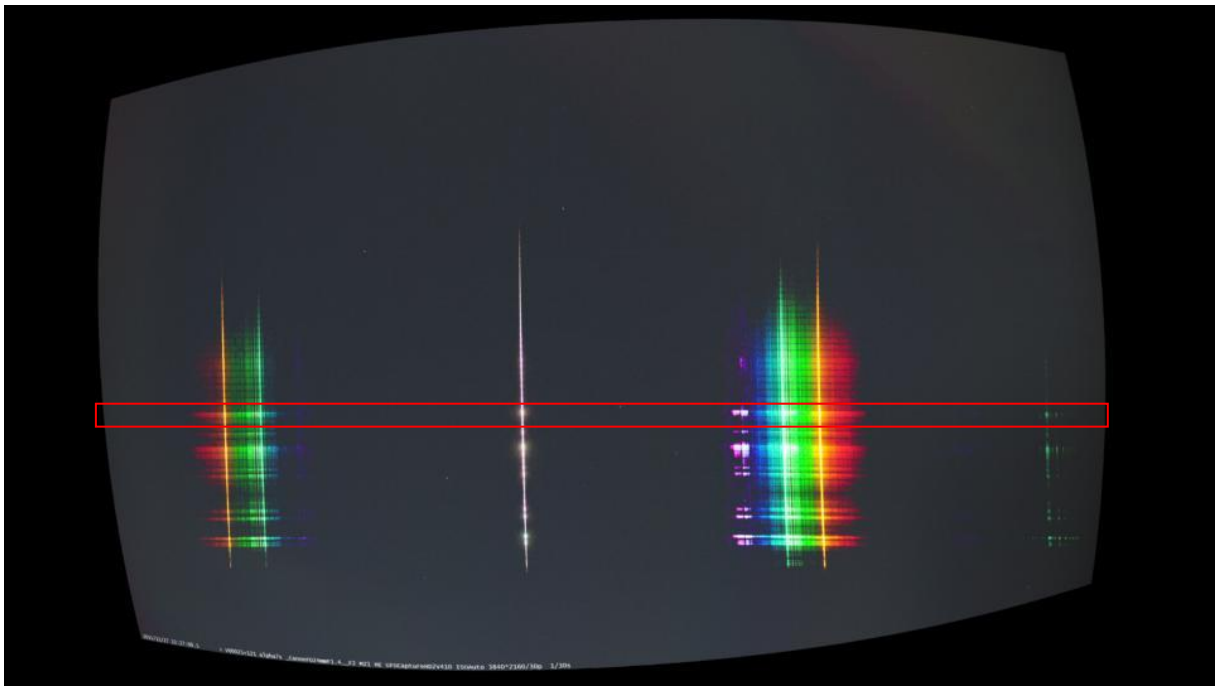


After the transformation the spectra are tilted somewhat. For analysis it is preferable to rotate them around the center of the image (the angle can be taken from the calibration worksheet:

Rotation angle [°]	yes	3.05

After rotation the spectrum should be aligned to the x-axis, otherwise change the angle. The rotation is done in IRIS with the command ROT. A positive angle rotates the image anticlockwise:

```
>rot 1920 1080 3.05
>save M20151127_222709_JPMZ1_HEP-dnr
>savejpg M20151127_222709_JPMZ1_HEP-dnr 2
```



Fit of Na lines order -1, 0, 1, Mg order 2
spectrum\calib\Koji\1127\fit1127 Na Mg.xlsx

4k image format!
>rot2 d_ r_ 1920 1080 3.05 56
>load r_1
>register r_ rr_ 56 ! linear spectrum parallel x-axis

Add exposure time and OBS-DATE to header:
EXPTIME = 0.033
OBSERVER= 'Koji Maeda'
INSTRUME= 'Sony alpha 7'
DATE-OBS= '2015-11-27 22:27:09'

Fit of first 20 spectra with lines of Mg, Na orders -1, 0 and 1:

-589.425	0.425
-517.625	-0.175
0.667	-0.667
516.628	1.172
589.755	-0.755

RMS = 0.931 disp = 0.6243

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