

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 analog 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 Although a little bit outdated, it has the advantage that most operations required for the spectra processing can be done and it has a simple script language which allows describing the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

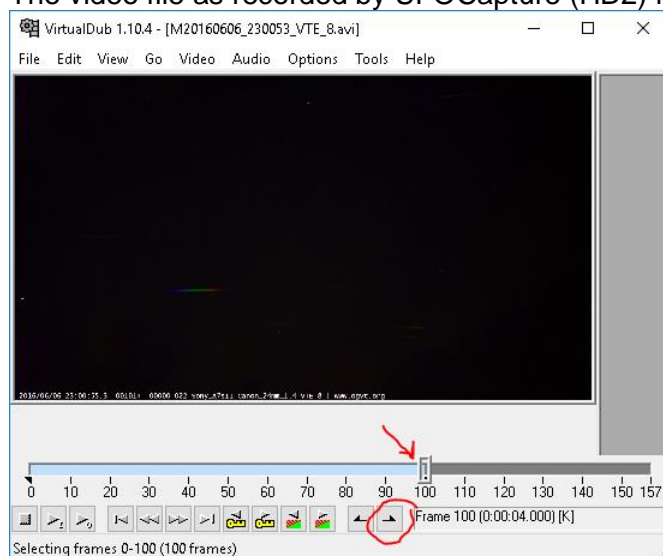
<http://imc2016.amsmeteors.org/>, where other interesting papers on current activities in meteor observation may be found.

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 Huffuyv) 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>)

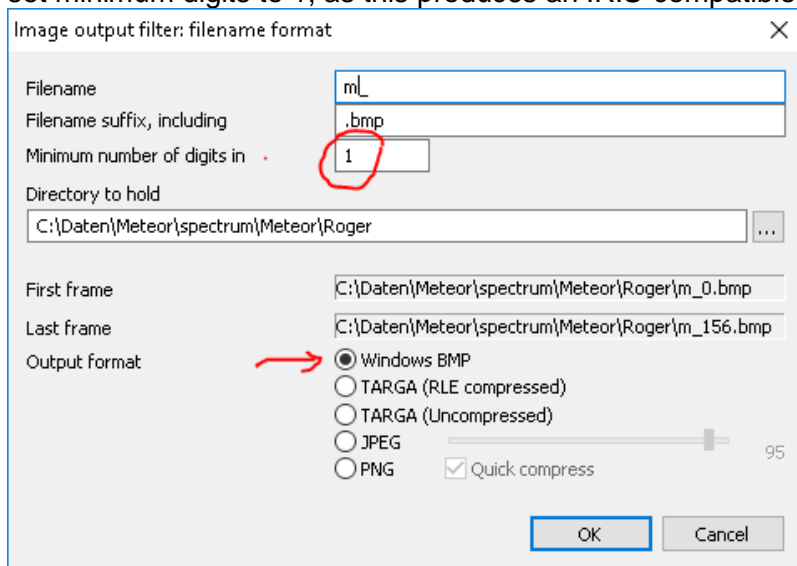
The video file as recorded by UFOCapture (HD2) is loaded and trimmed to length



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

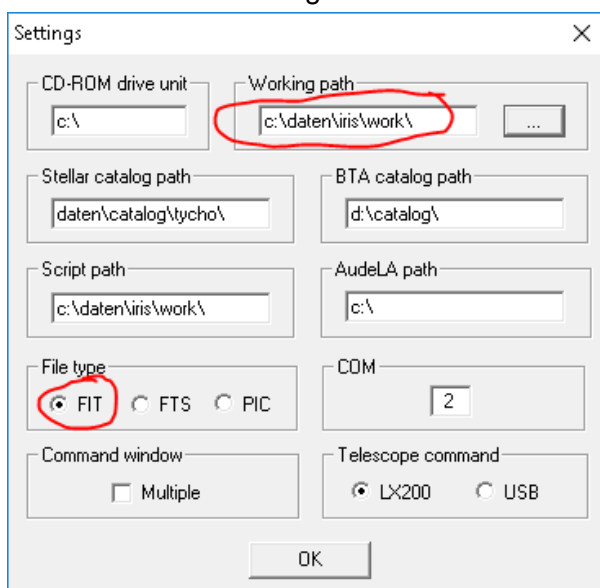
as the same filenames can be used for intermediate steps and the same commands and parameters can be used in many cases. Another possibility is to use a work directory and after finishing the processing move everything to a directory for archiving the data. It is important to set minimum digits to 1,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

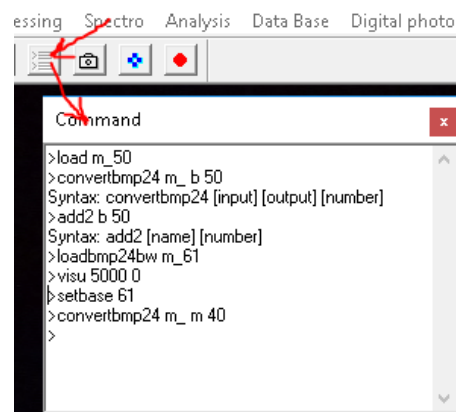


The FIT format is selected because it is used in most astronomical spectroscopy processing software.

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 moment¹.

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 $\pm 2^{15}$, 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

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

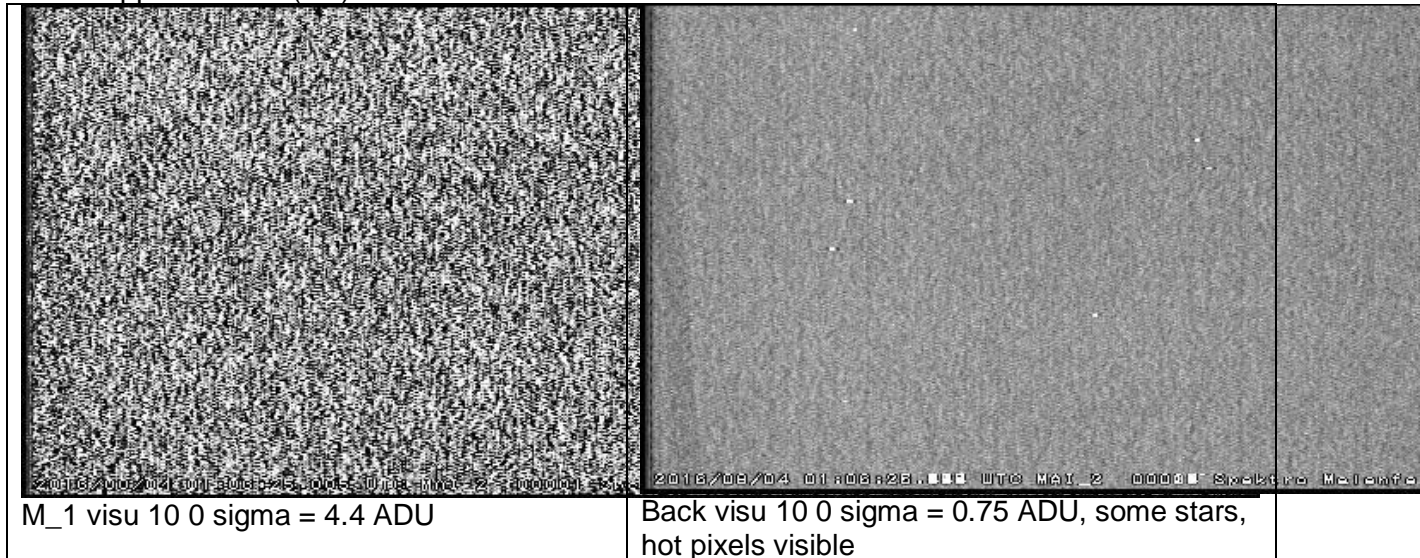
M_BACK.PGM and M_DARK.PGM.

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 $B = (\text{Sum } I_1 \dots I_{NB}) * \text{MULT}$
since the program cannot do arithmetic calculations, MULT has to be calculated externally: $\text{MULT} = 1/\text{NB}$ and entered as a parameter

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

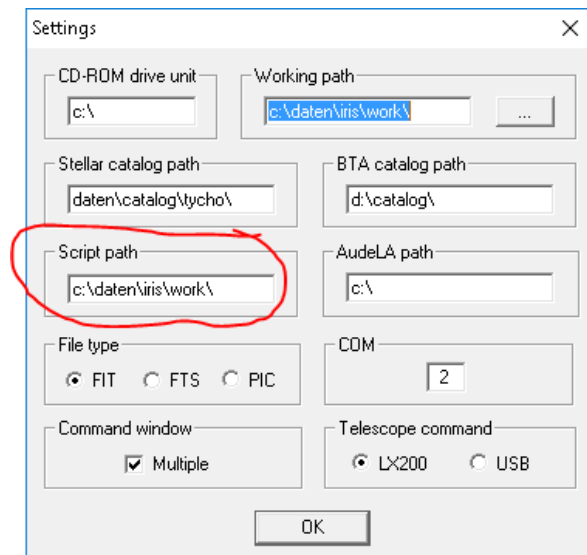


RUN M_DARK [I, B, M, START, NM] reindexes and subtracts background

- 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:

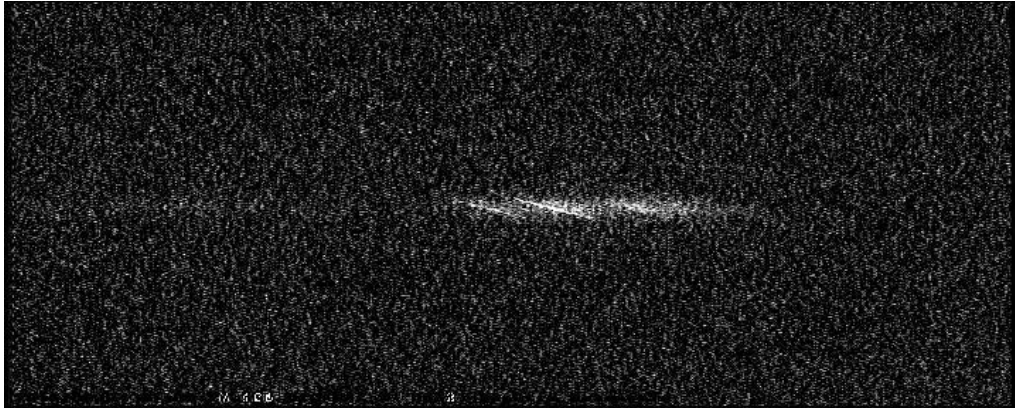


In this case C:\Daten\IRIS\work.

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

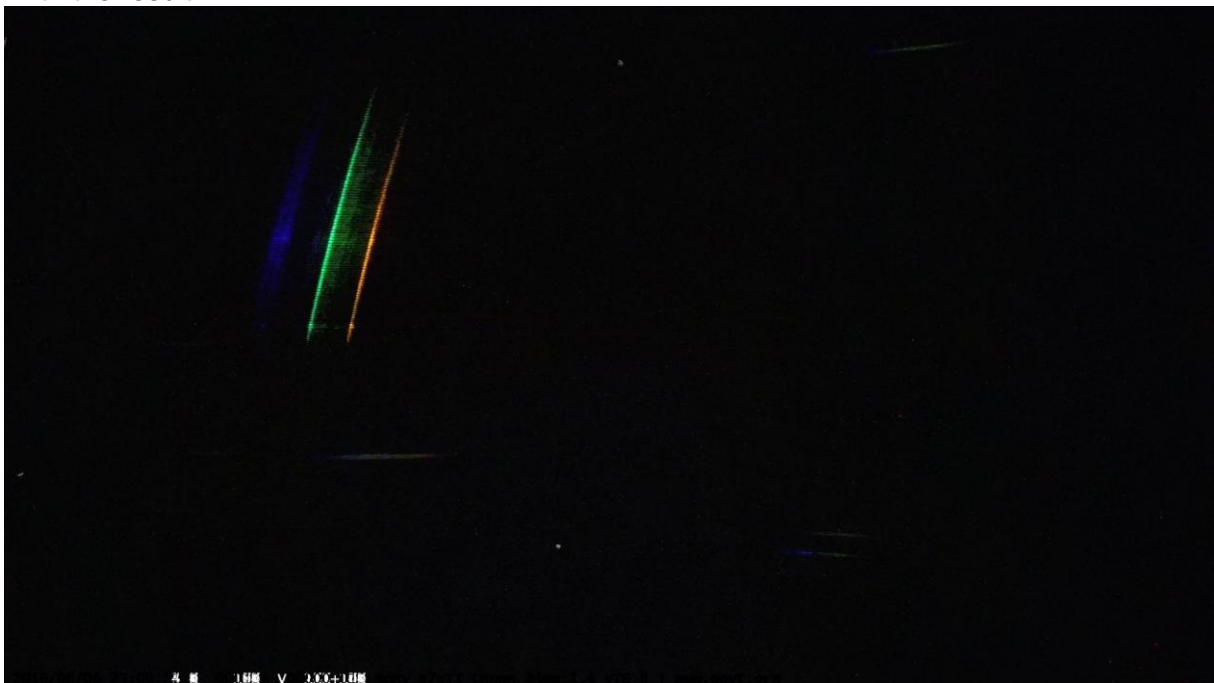
The purpose of this is the addition of images without increasing the background, e.g. for the creation of a meteor trail from individual meteor video frames or for a combined calibration image, showing the nonlinearity of the spectrum in different parts of the image area.

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.

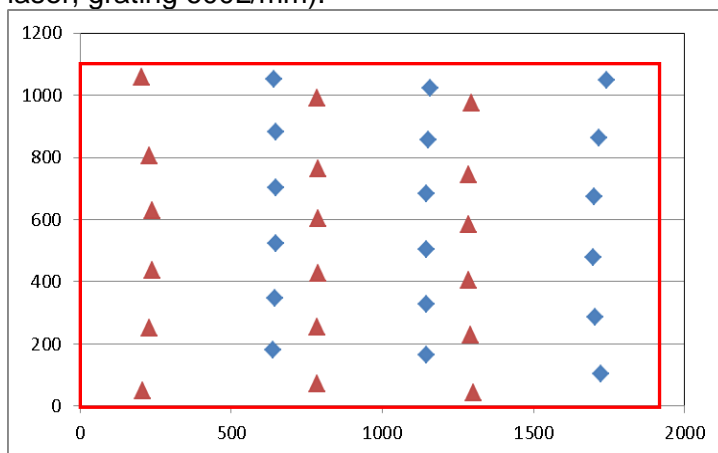
Creation of calibration images (required once per camera, lens, grating combination)

(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 (X_0 , Y_0 : coordinates in the image plane of the optical axis; a_3 , a_5 : 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 (x_i , y_i) and compared to calculated values from the model. As a result also the dispersion and the rotation of the grating are obtained. Different zero order positions are selected, so the spectra cover most of the image area. 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:

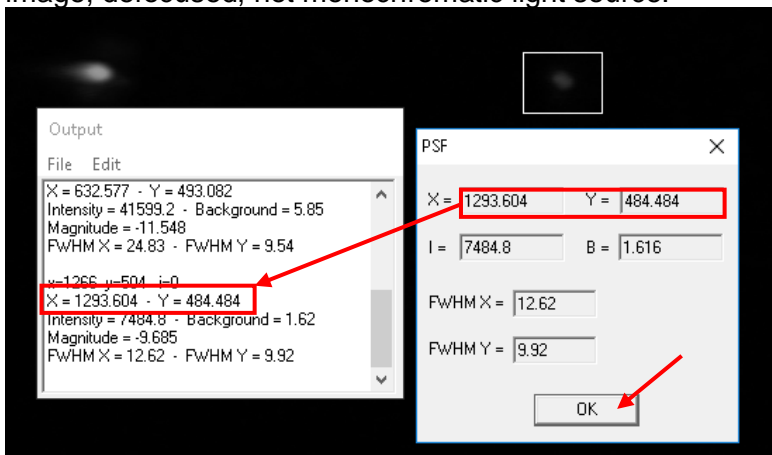


Here the image format and the shorter focal length allows to measure 4 orders

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

- 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

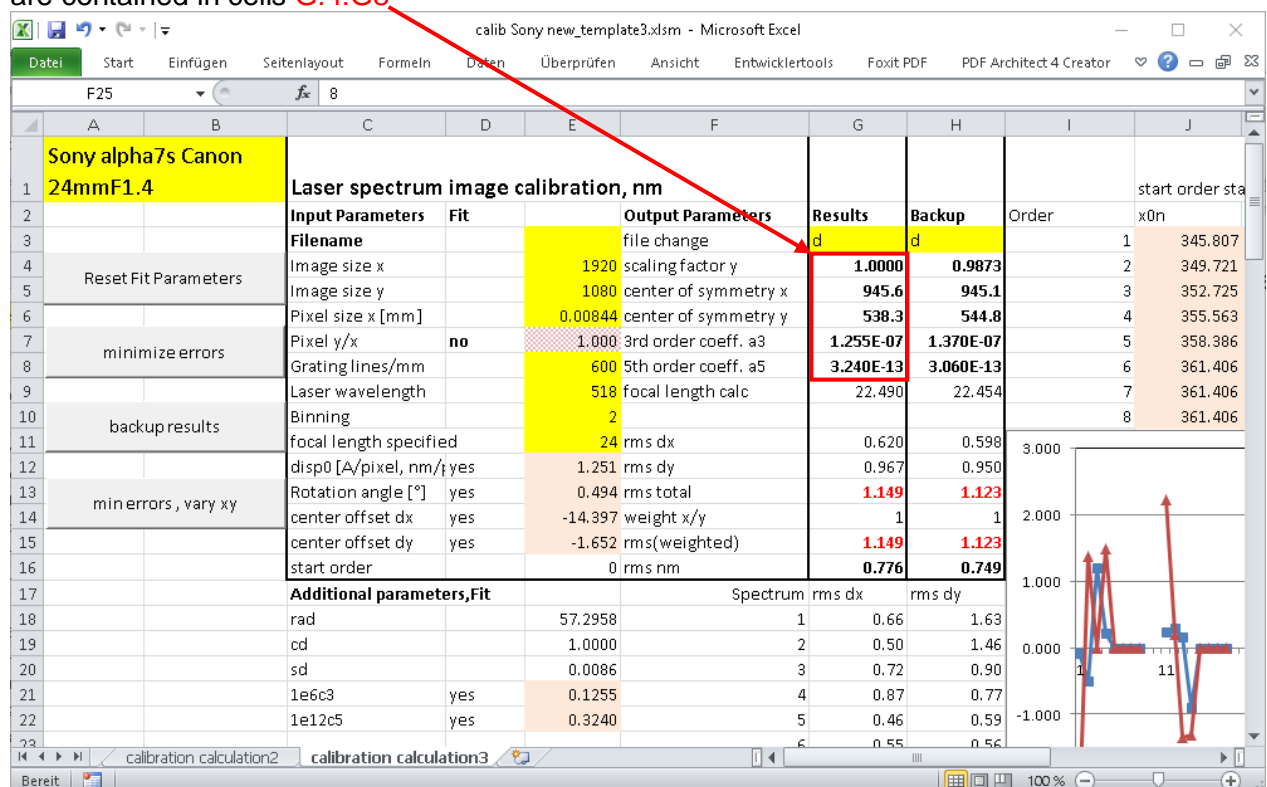
- backup results

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

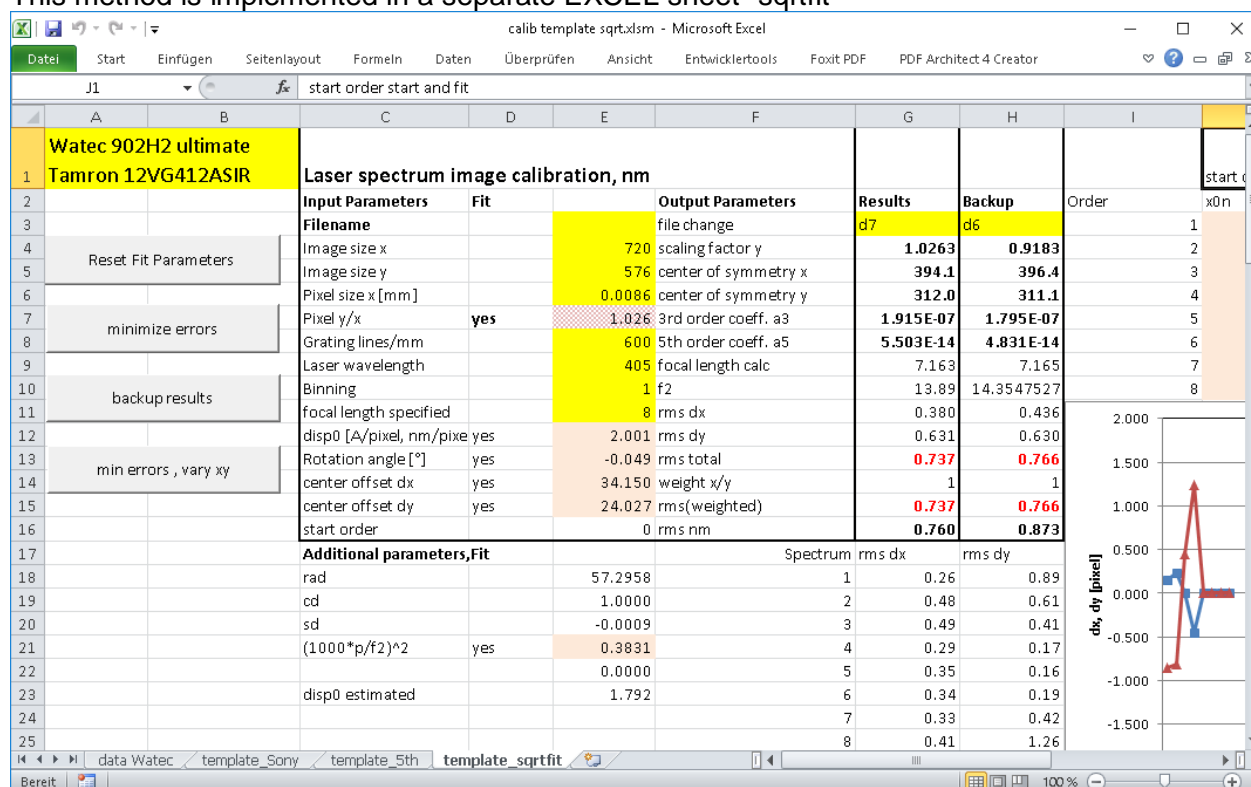
$$r = r' \cdot [1 + 1/2 \cdot (r'/f)^2 + 3/8 \cdot (r'/f)^4 + \dots]$$

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:

$$r = r' \cdot [1 + 1/2 \cdot (r'/f_2)^2 + 3/8 \cdot (r'/f_2)^4 + \dots]$$

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 $(1000 \cdot p/f_2)^2$, with the pixel size p .

This method is implemented in a separate EXCEL sheet “sqrtfit”



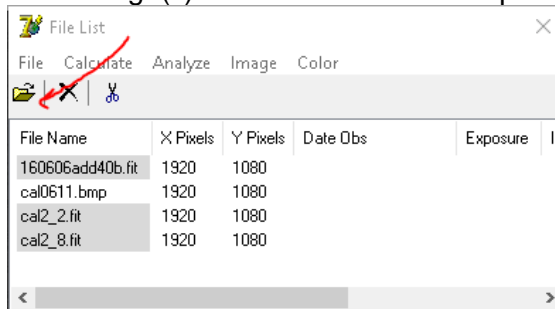
For a focal length f of approx. 7mm, f_2 is fitted as 13.89mm, almost the double. The rms values of the fit are almost the same as for a full fit of a_3 and a_5 , but with more reasonable values for the parameters. Therefore it is advisable to use this approximation except for wide angle lenses.

Orthographic Transformation with ImageTools

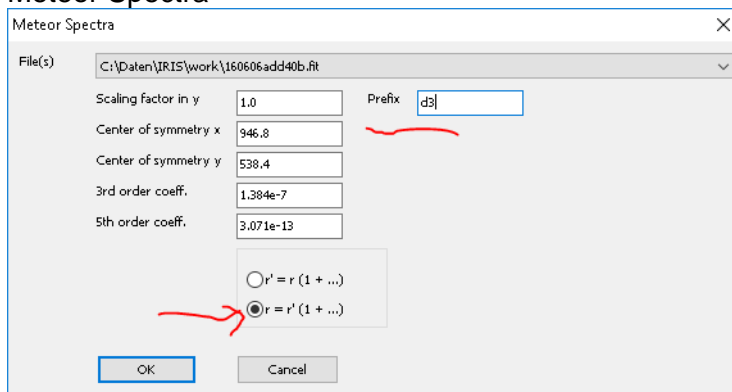
With ImageTools

- 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

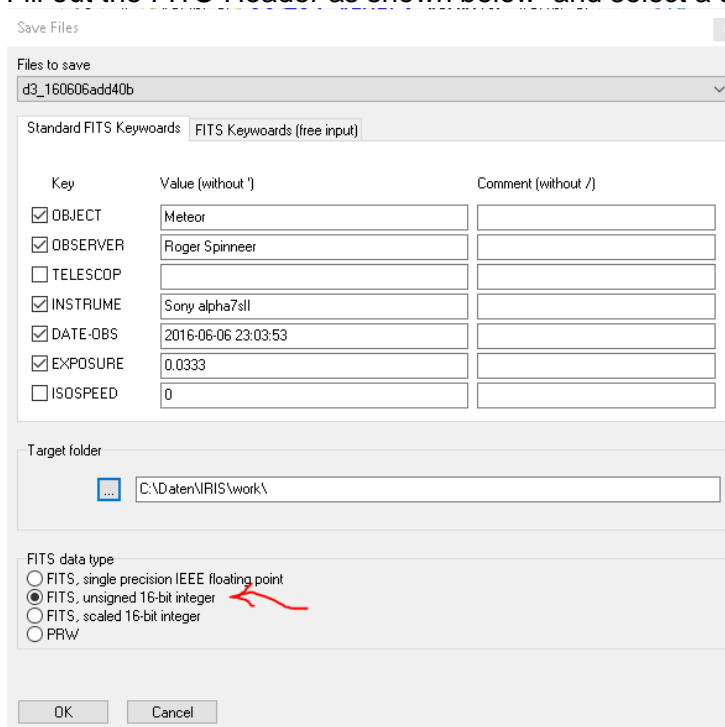


Preliminary values for Sony alpha7s Canon 24mmF1.4 Koji Maeda, 2xbinning

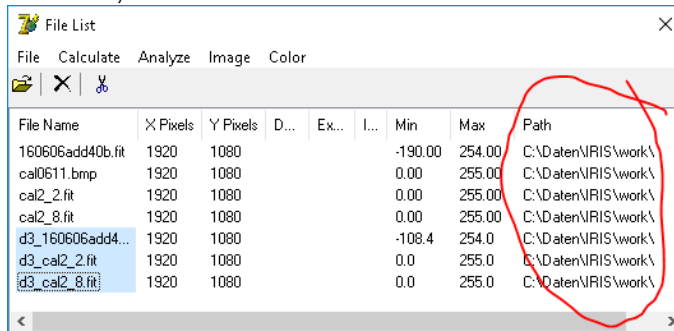
notice the prefix to distinguish different parameter sets

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



- 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



File Name	X Pixels	Y Pixels	D...	Ex...	I...	Min	Max	Path
160606add40b.fit	1920	1080				-190.00	254.00	C:\Daten\IRIS\work\
cal0611.bmp	1920	1080				0.00	255.00	C:\Daten\IRIS\work\
cal2_2.fit	1920	1080				0.00	255.00	C:\Daten\IRIS\work\
cal2_8.fit	1920	1080				0.00	255.00	C:\Daten\IRIS\work\
d3_160606add4...	1920	1080				-108.4	254.0	C:\Daten\IRIS\work\
d3_cal2_2.fit	1920	1080				0.0	255.0	C:\Daten\IRIS\work\
d3_cal2_8.fit	1920	1080				0.0	255.0	C:\Daten\IRIS\work\

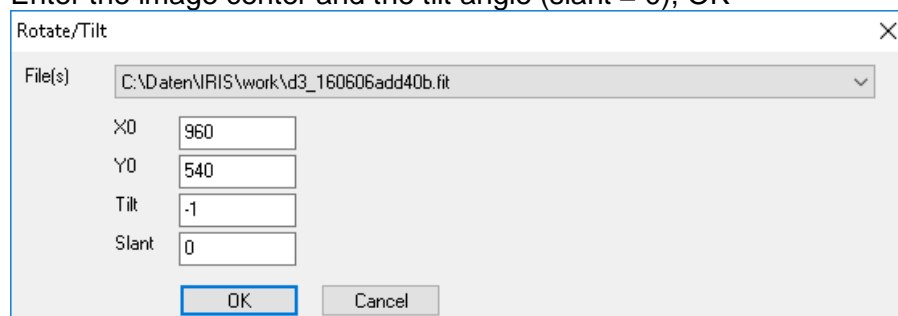
Path indicates, which files have been stored in what place.

→



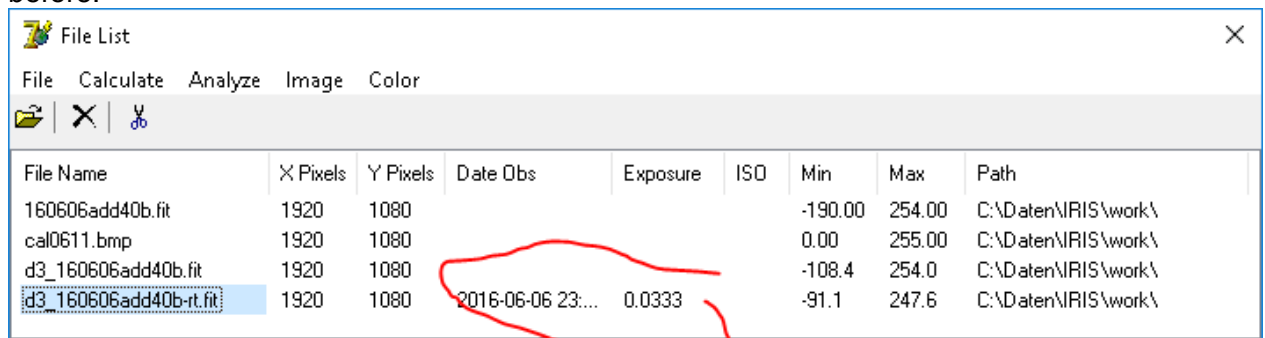
- For easier analysis of the files they may be rotated, so that the spectra are exactly horizontal (this allows also to check if they are exactly straight). This can be done in ImageTools in the File List. select the files to be rotated, select Image – Rotate/Tilt

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



Rotate/Tilt	
File(s)	C:\Daten\IRIS\work\d3_160606add40b.fit
X0	960
Y0	540
Tilt	-1
Slant	0
<input type="button" value="OK"/> <input type="button" value="Cancel"/>	

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



File Name	X Pixels	Y Pixels	Date Obs	Exposure	ISO	Min	Max	Path
160606add40b.fit	1920	1080				-190.00	254.00	C:\Daten\IRIS\work\
cal0611.bmp	1920	1080				0.00	255.00	C:\Daten\IRIS\work\
d3_160606add40b.fit	1920	1080				-108.4	254.0	C:\Daten\IRIS\work\
d3_160606add40b-rt.fit	1920	1080	2016-06-06 23:...	0.0333		-91.1	247.6	C:\Daten\IRIS\work\

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 mbdr 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 mbdr 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

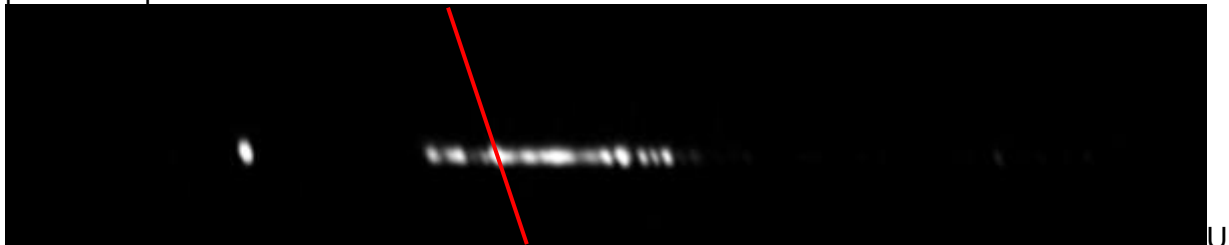
`>REINDEX mbdr temp 11 1 10`

`>ADD2 temp 10`

`>SAVE mbadd11-20`

Correction of slant

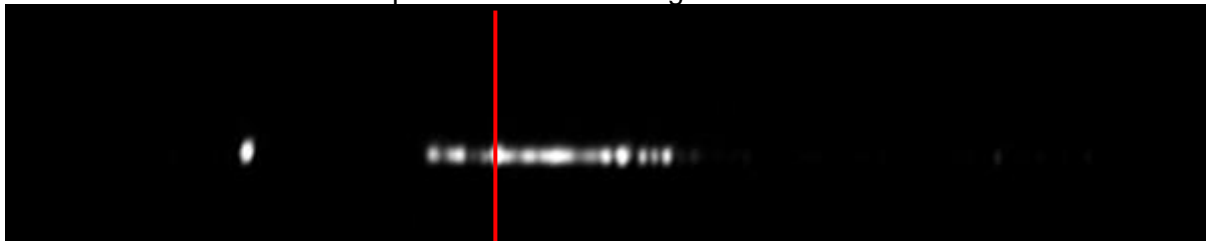
The motion of the meteor during the exposure time produces slanted spectral lines instead of point like spectral lines:



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

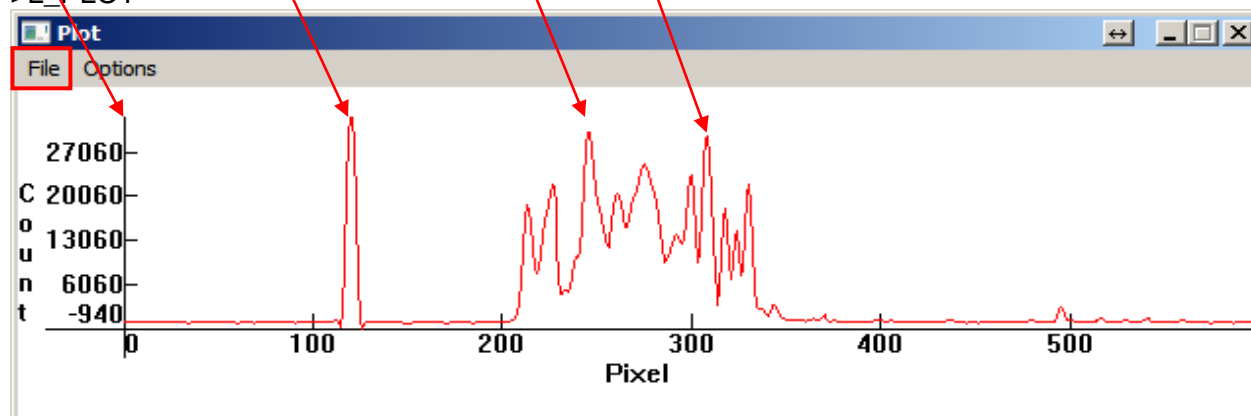
Extract the spectrum

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, BASS to name just some) can read this format². 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 2¹⁵ (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

$\lambda(p) = \text{disp0} * (p - p_0)$, 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:

$\lambda(p) = \lambda_{\text{ref}} + \text{disp0} * (p - p_{\text{ref}})$.

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

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

Better is to do a linear regression of pixel positions and known wavelength or $\lambda * \text{order}$. This gives also a good estimate of the precision. If the calibration is not perfect linear (perhaps with

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.

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.

...

Instrument Response

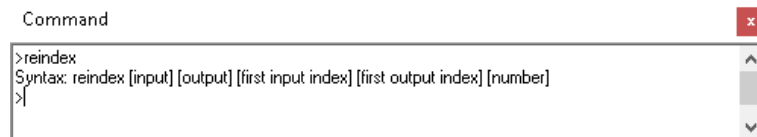
[To be completed]

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] [PARAMETER₁] [PARAMETER₂] ... [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:

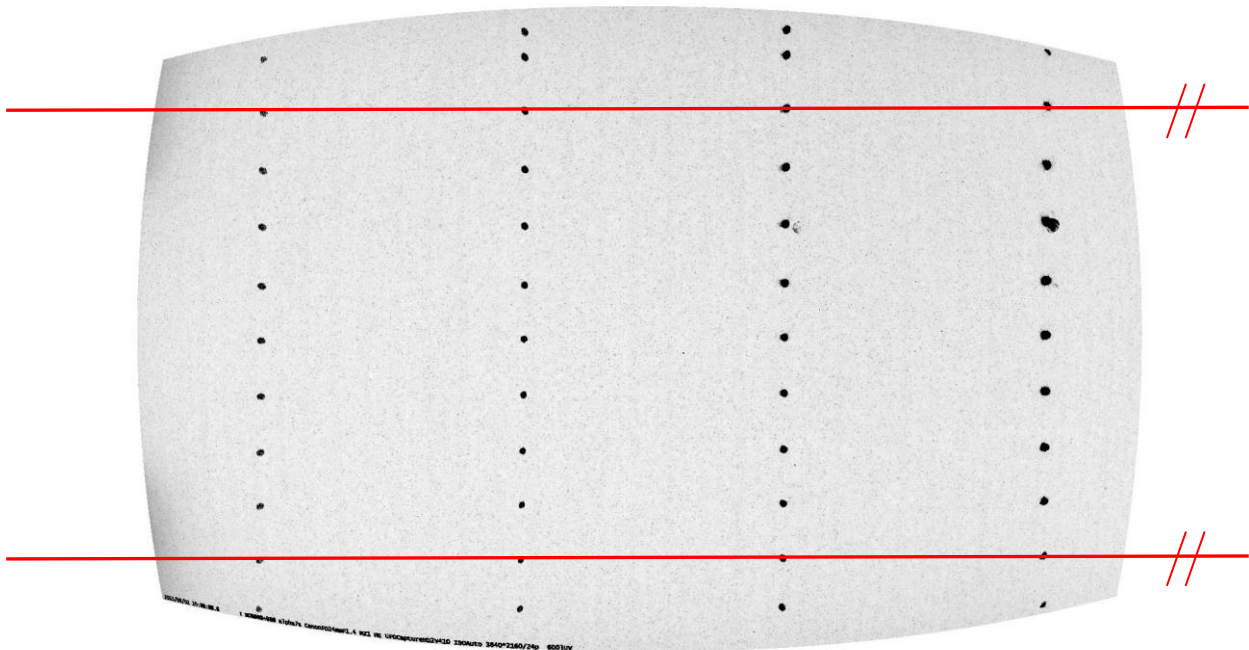
- Lambda: laser wavelength,
- G: grating lines/mm,
- Px: pixel size,
- Nx, Ny: image size
- Binning factor

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 ($r = r' \cdot (1 + a3 \cdot r'^3 + a5 \cdot r'^5)$)
(for a better convergence of the fit $10^6 \cdot a3$ and $10^{12} \cdot a5$ 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 transformation 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:

Meteor Spectra

File(s)
C:\Daten\IRIS\work\b_1.fit

Scaling factor in y
1
Suffix
d

Center of symmetry x
1866.2

Center of symmetry y
1098.7

3rd order coeff.
3.126e-8

5th order coeff.
1.943e-14

☐ $r' = r \cdot (1 + \dots)$
☒ $r = r' \cdot (1 + \dots)$

OK
Cancel

With binning 2x2, older data

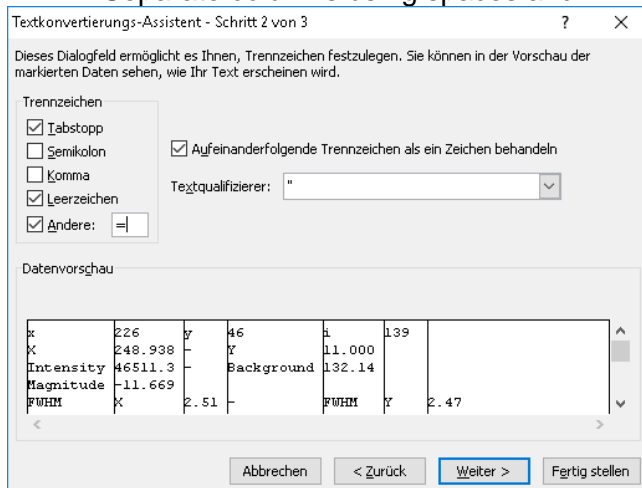
scaling factor y	1	
center of symmetry x	942.7	factor 2
center of symmetry y	536.9	factor 2
3rd order coeff.	1.284E-07	factor 4
5th order coeff.	3.058E-13	factor 16

Producing Input for calibration in EXCEL from measured laser line positions

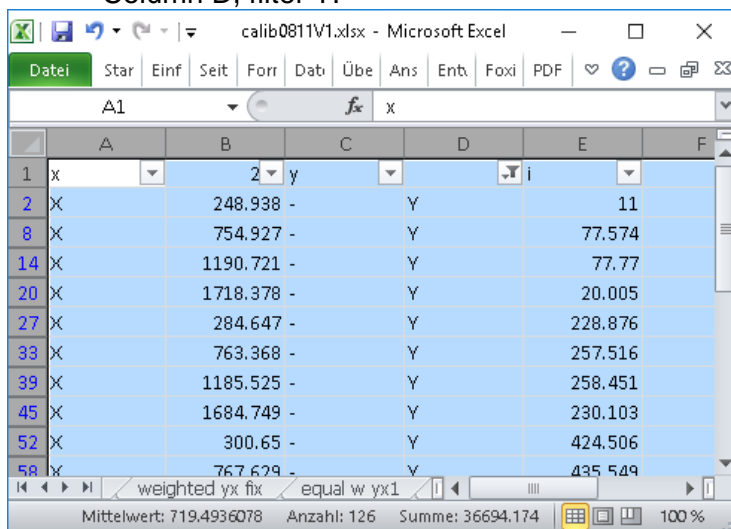
Note: All images from EXCEL sheets and command windows are in German, the EXCEL version 2010 has been used; unfortunately no language packs for English are available anymore, so the windows may look different in Japanese or English.

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):

	A	B	C	D	E	F	G	H
1	248.938	11						
2	754.927	77.574						
3	1190.721	77.77						
4	1718.378	20.005						
5								
6								
7								
8								
9								
10								
11	284.647	228.876						
12	763.368	257.516						
13	1185.525	258.451						
14	1684.749	230.103						
15	300.65	424.506						
16	767.629	435.549						
17	1184.391	437.91						
18	1670.317	431.329						
19	304.091	613.857						
20	769.688	610.289						
21	1185.267	613.961						
22	1671.223	626.108						

- 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.

correct solid.

calib Sony new_template3.xlsm - Microsoft Excel

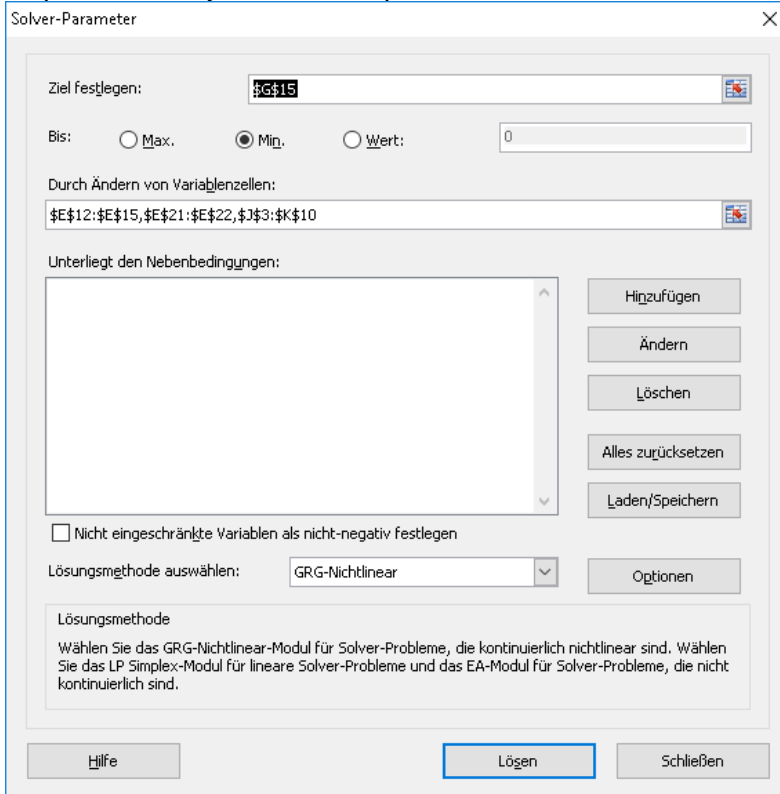
Datei	Start	Einfügen	Seitenlayout	Formeln	Daten	Überprüfen	Ansicht	Entwicklertools	Firefox PDF	PDF Architect 4 Creator					
F25				B											
Sony alpha7s Canon 24mmF1.4		Laser spectrum image calibration, nm													
Reset Fit Parameters		Input Parameters		Fit	Output Parameters		Results	Backup	Order	start order	start and fit	start order	measured	aver	
		Filename			file change		d	d		x0n	y0n	xm	ym	d, nm	
		Image size x			1920 scaling factor y		1.0000	0.9873	1	345.807	97.933	248.938		15	
		Image size y			1080 center of symmetry x		945.6	945.1	2	349.721	263.693	284.647		228.876	
		Pixel size x [mm]			0.00844 center of symmetry y		538.3	544.8	3	352.725	437.512	300.65		424.506	
minimize errors		Pixel y/x		no	1.000 3rd order coeff. a3		1.255E-07	1.370E-07	4	355.563	411.893	304.091		613.857	
		Grating lines/mm			600 5th order coeff. a5		3.240E-13	3.060E-13	5	358.386	795.042	293.633		817.659	
		Laser wavelength			518 focal length calc		22.490	22.454	6	361.406	972.348	265.504		1033.921	
backup results		Binning			2				7	361.406	972.348	265.504		1033.921	
		focal length specified			24 rms dx		0.620	0.598	8	361.406	972.348	265.504		1033.921	
		disp0 [A/pixel, nm/y]		yes	1.251 rms dy		0.967	0.950							
minerrors, vary xy		Rotation angle [°]		yes	0.494 rms total		1.149	1.123							
		center offset dx		yes	-14.397 weight x/y		1	1							
		center offset dy		yes	-1.652 rms(weighted)		1.149	1.123							
		start order			0 rms nm		0.776	0.749							
		Additional parameters, Fit													
		rad			57.2958		1	0.66	1.63						
		cd			1.0000		2	0.50	1.46						
		sd			0.0086		3	0.72	0.90						
		1e6c3		yes	0.1255		4	0.87	0.77						
		1e12c5		yes	0.3240		5	0.46	0.59						

(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 EXCEL – Datei – Optionen – Add-ins – Gehe zu – EXCEL-add-ins – check Analyse-Funktionen – OK ⁴

The goal is to minimize the RMS error of the calculated – measured line positions
 $=\text{WURZEL}(G11^2+G12^2)$, 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:



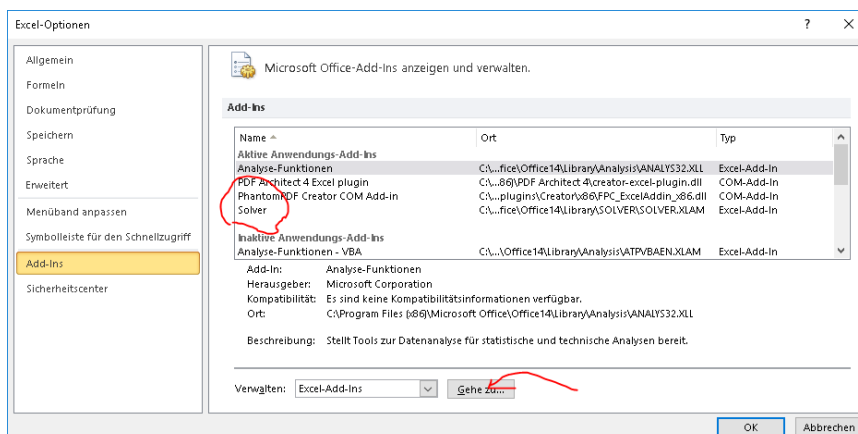
Allow negative values. Select GRG-nonlinear for solution method. With the options you can tweak the finding of a solution.

-  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

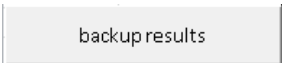
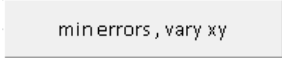


New: the x- and y coordinates may be fitted with different weights so that either better wavelength linearity is obtained or better straightness of the spectra. This is done by setting the weight in cell G14 and minimizing cell G15. A larger weight increases wavelength accuracy. Once a solution has been 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

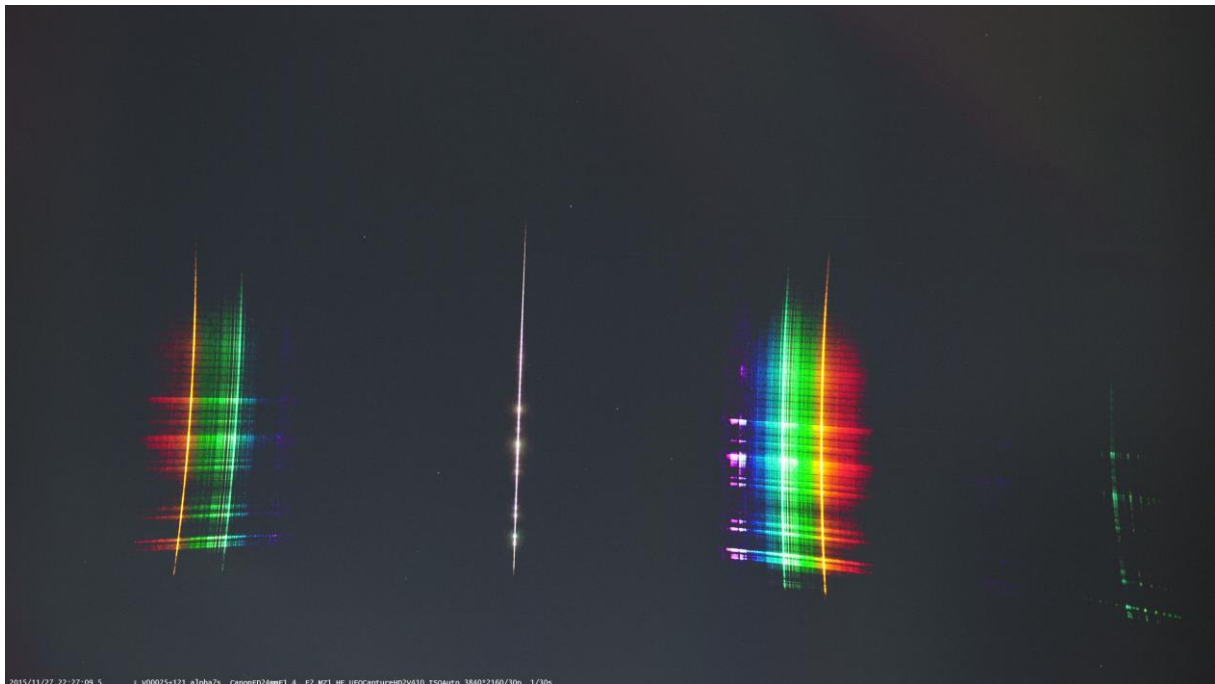
There are two additional buttons in the EXCEL sheet

-  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
-  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 [Å/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

Example M20151127_222709_JPMZ1_HEP.bmp



Colour image transformation parameters

Meteor Spectra

File(s): C:\Daten\IRIS\work\b_1.fit

Scaling factor in y: 1 Suffix: d

Center of symmetry x: 1866.2

Center of symmetry y: 1098.7

3rd order coeff.: 3.126e-8

5th order coeff.: 1.943e-14

☐ $r' = r (1 + \dots)$

☒ $r = r' (1 + \dots)$

OK Cancel

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:

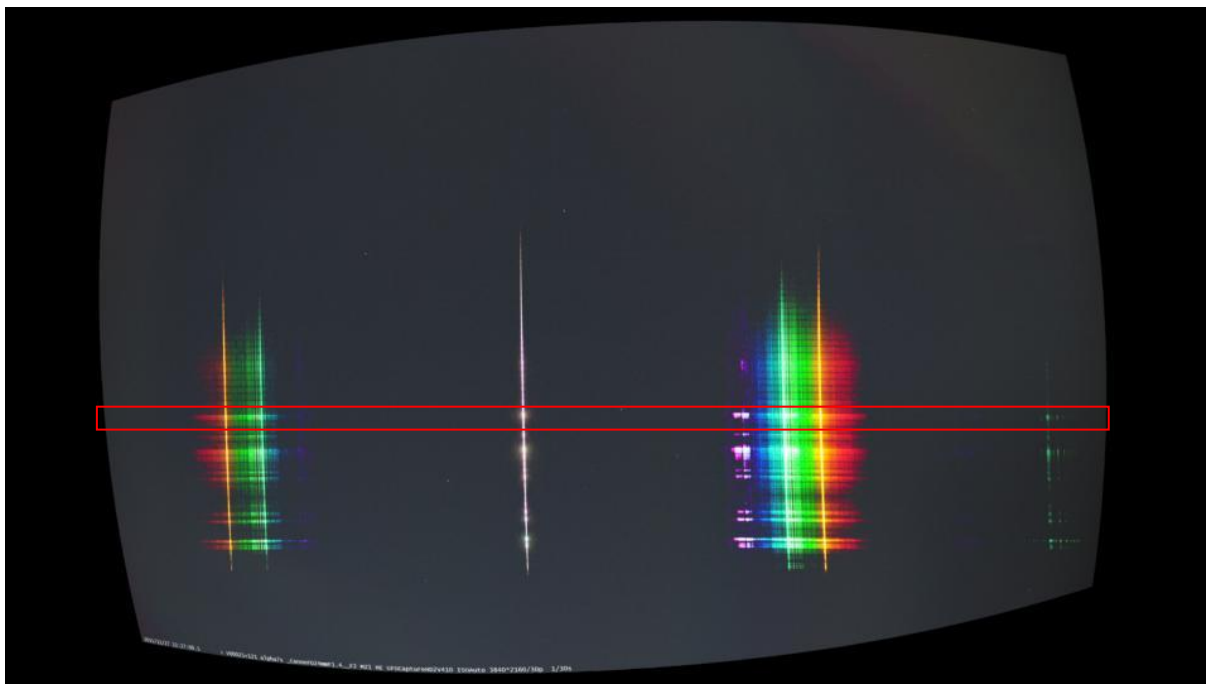
Rotation angle [°]	yes	3.05
--------------------	-----	------

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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