Meteor Spectroscopy, Instrument Response

Martin Dubs, FMA

Theory

The spectrum calibrated in wavelength is still not the final result of the 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

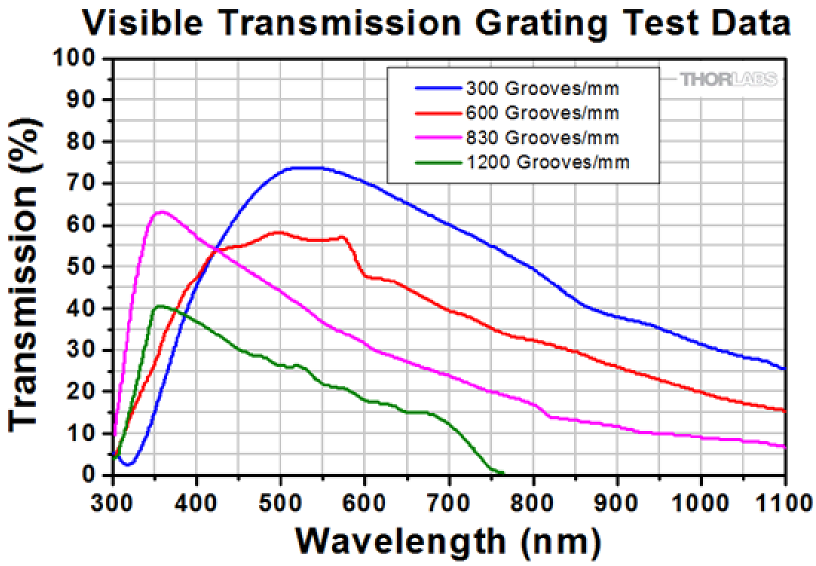
From the latter, the actual luminous power of the meteor can be calculated if the distance is known from triangulation.
As long as we are interested in only the relative intensities (in order to determine chemical composition ratios e.g.), the different contributions for the detector signal can be combined 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

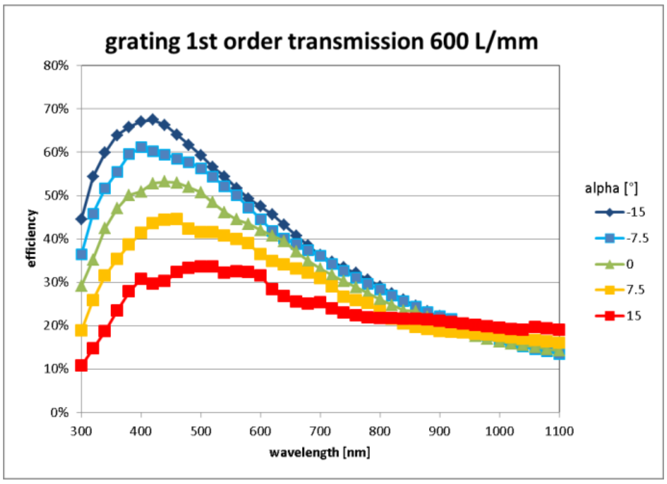
As an example we show the spectral response of Watec 902 H2ultimate sensor; a Sony EXview HAD ICX429ALL CCD http://pdf1.alldatasheet.com/datasheet-pdf/view/95422/SONY/ICX429ALL.html
(to be precise, one has to distinguish between response measured in output per incident energy and quantum efficiency measured in electrons per incident photon. In the literature, it is not always obvious, which of the two definitions are used). By calculating the instrument response as described in the next section, the spectra will be calibrated in relative energy / wavelength interval.

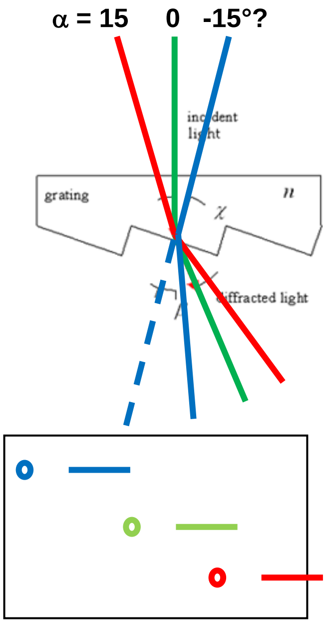
Grating efficiency

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)

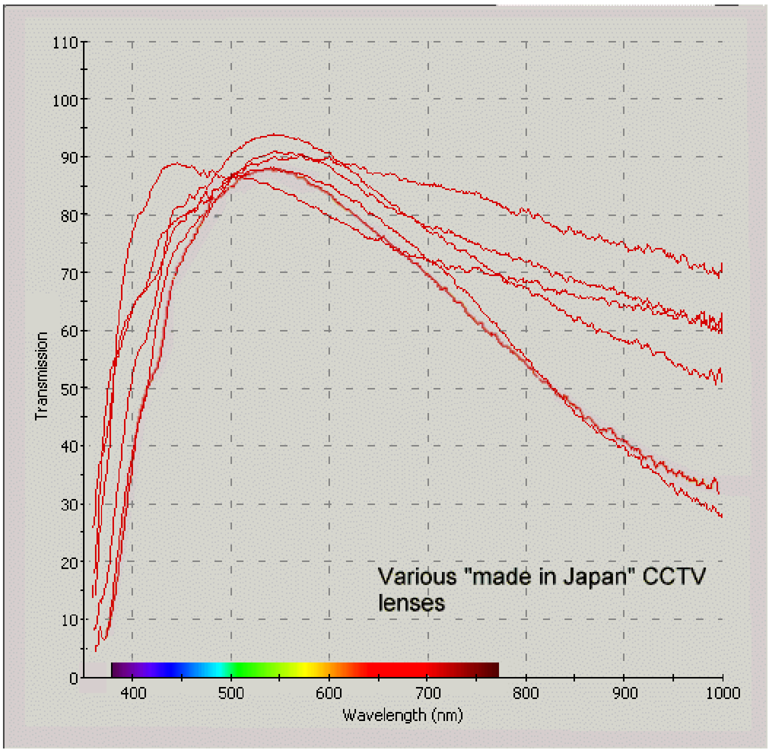




Lens transmission

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 some cameras an infrared filter is included to reduce chromatic aberrations. Colour cameras show a more complex transmittance, making instrument response correction more difficult.
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 and altitude of the observer location.

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

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

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

For the extinction, different units are used. In chemistry the absorbance is used

A = -log10(T) = 0.4*A(magnitudes)

In physics, optical depth is used

tau = - ln(T) = A*ln(10) = 2.302*A = 0.4*2.302*A(magnitudes) = 0.921*A(magnitudes)

The transmission depending on elevation is then rewritten as

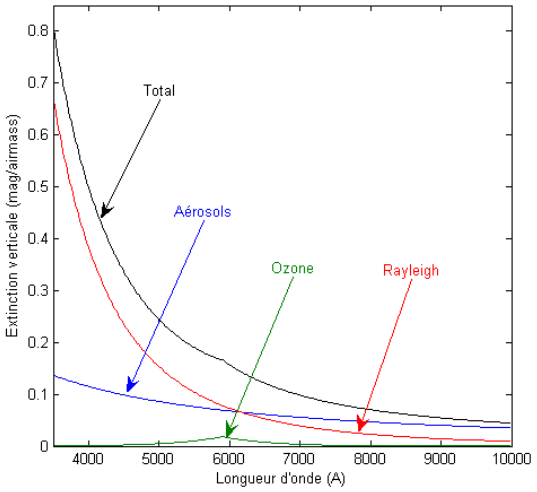
$T(\lambda) = \exp[-tau_{z0}(\lambda)/\cos(z)]$

Where the air mass is approximately calculated as 1/cos(z)

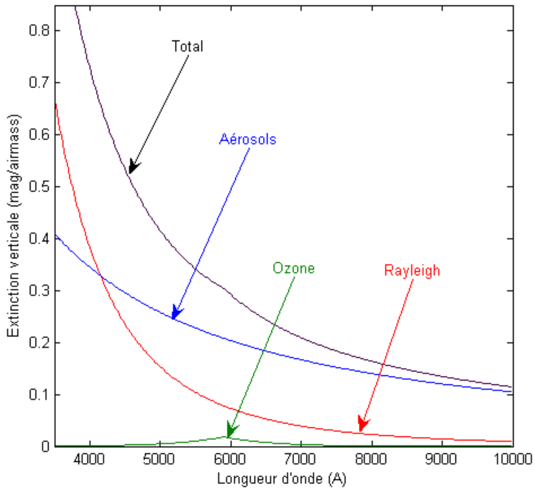
Taking into account the curvature of the earth surface, a more precise function for the air mass is used:

AM = 1.0/(cos(z+ 0.025 * exp(-11.0 * cos(z))))

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:

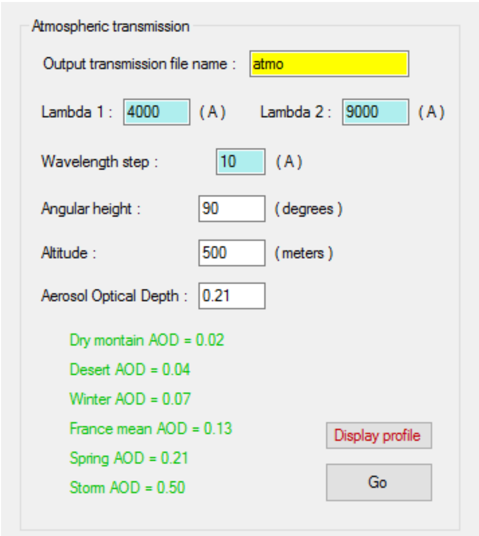


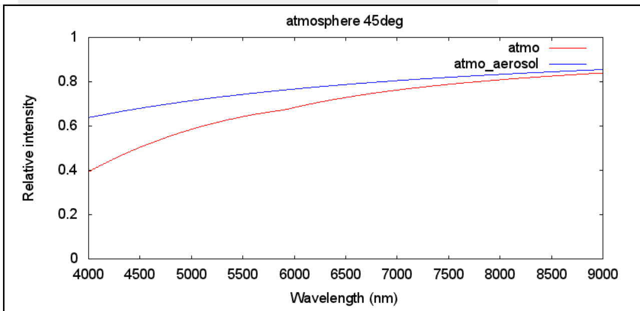
Extinction verticale calculée pour Toulouse (h=0.2 km) par une nuit claire d'hiver (AOD=0.07).



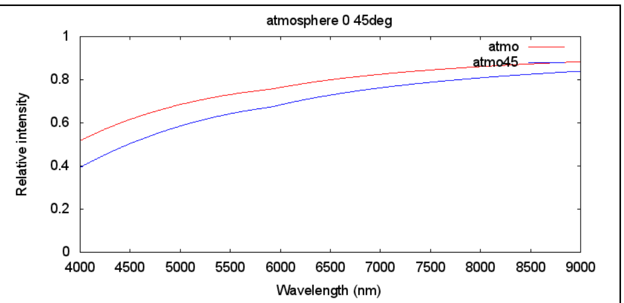
Extinction verticale calculée pour Toulouse (h=0.2 km) par une nuit brumeuse d'été (AOD=0.21).

If the aerosol optical density (AOD) is known or can be estimated, then the extinction can be calculated for any elevation with ISIS: http://www.astrosurf.com/buil/isis-software.html
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

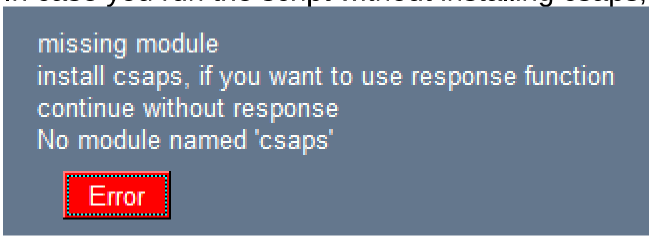
The above considerations are important in order to evaluate their influence and to correct for them in the resulting processing procedure. As they cannot be determined individually without a complex laboratory setup, they have to be derived from actual measurements. The main point is that the response 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
  $R(\lambda) = const. * I(\lambda) / S_{ref}(\lambda)$
  where $I(\lambda)$ is the measured spectrum and $S_{ref}(\lambda)$ is the Flux of the corresponding reference spectrum, taken from a spectroscopic 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. This has been implemented in the “Instrument response” tab in m_spec, but other software can be used as well (Vspec, SpectroTools, Rspec, EXCEL). ISIS is quite useful, because it contains a library of reference star spectra.

Installation

Download the latest version of m_spec from Github as described in the m_spec Python manual. In addition to the modules mentioned there, you have to install csaps. I installed it with
`conda install -c davidbroadhurst csaps.`
Or you may install it with:
`pip install csaps`
In case you run the script without installing csaps, a warning appears:



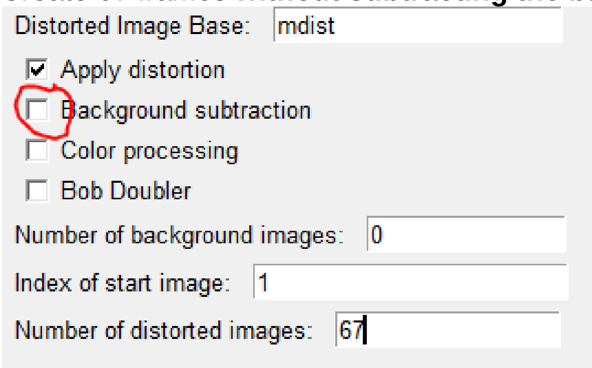
But you can use the script without this module, except that you cannot create a response function (which uses csaps for smoothing the response function).

Calculation of response from measured spectrum

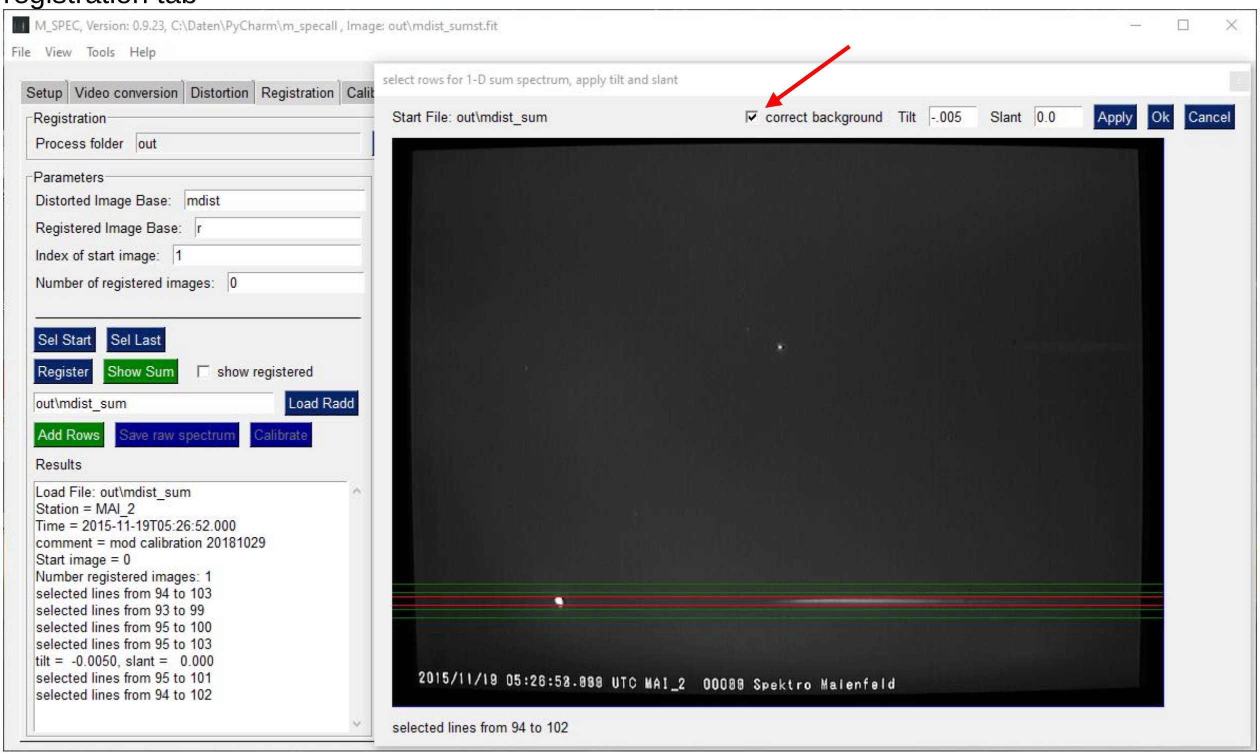
Star spectrum

A spectrum of a reference star can be obtained from the background image of a video sequence, 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 around the same time and altitude 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 (peak image from UFO Capture):
M20151119_052652_MAI_2.avi (unzip M20151119_052652_MAI_2.zip first)

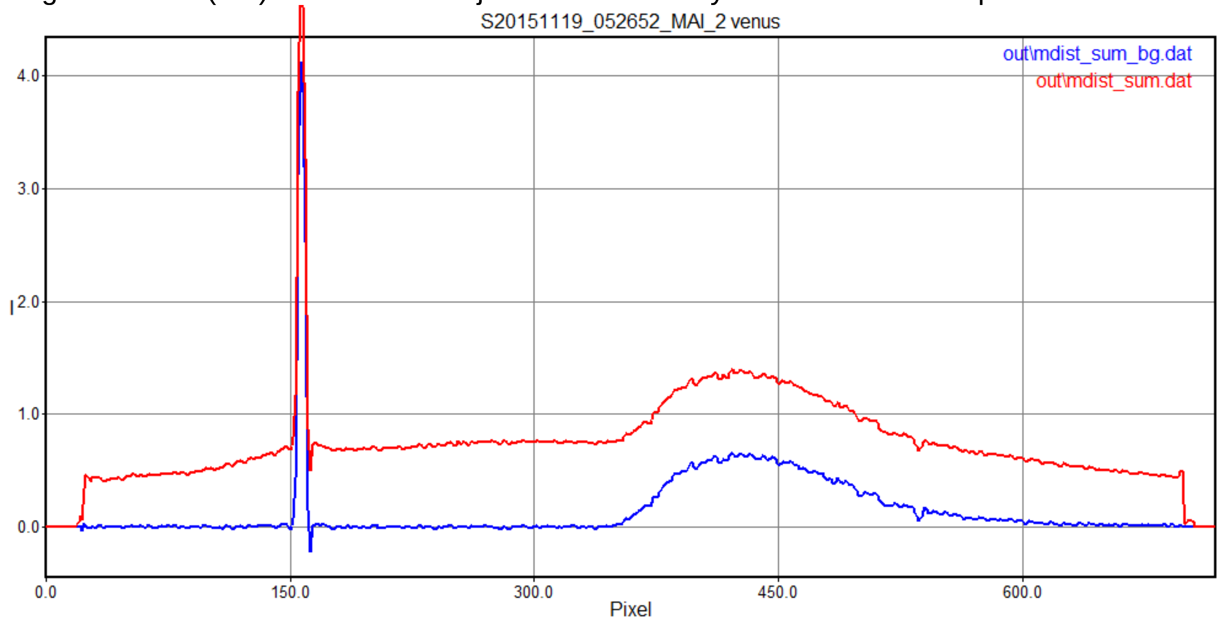
Create 67 frames **without subtracting the background,**



as is usually done for meteor spectra and transform them to the orthographic projection.
The sum spectrum is stored as mdist_sum.fit (actually the image is averaged to avoid overflow of the image intensity). This is a low noise 2-d spectrum, unfortunately the background is quite non-uniform.
Next go to the registration tab and load the image with “Load Radd”
Adding a suitable number of rows in this image also adds this background.
A better result is obtained by subtracting a number of rows above and below the actual spectrum. A checkbox “correct background” has been added in the add rows window in the registration tab



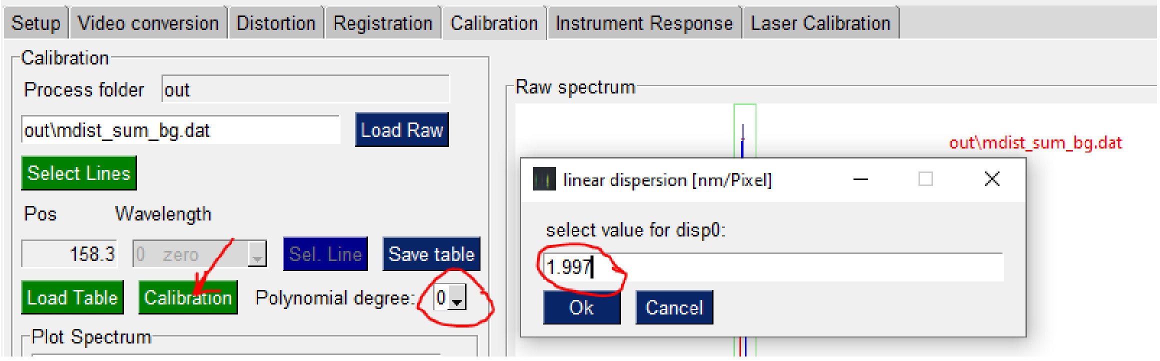
With the “correct background” checked two additional ranges of rows (green) in addition to the range selection (red) are marked. Adjust tilt if necessary. With OK two 1-d spectra are created:



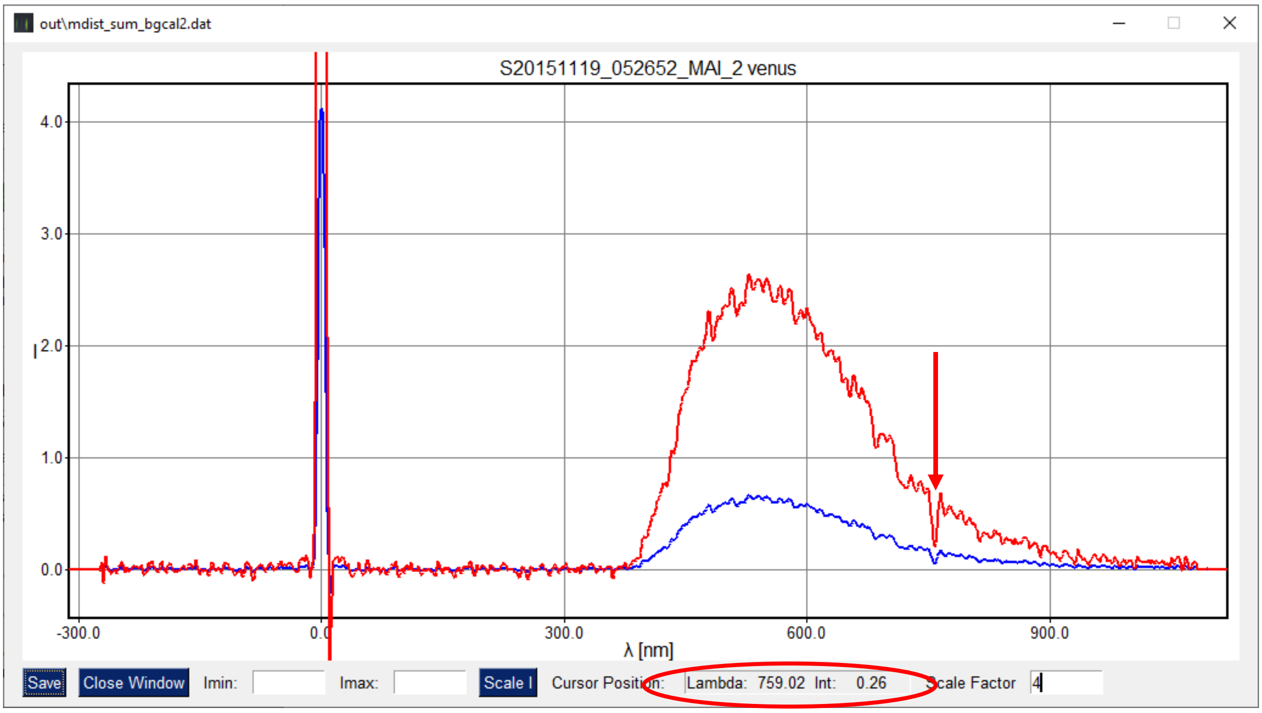
The plot was created with Plot spectrum …, right click, compare with spectrum …
Outside the zero order before the start of the spectrum around pixel 350 the level should be equal to zero. Whereas the background of the uncorrected spectrum is almost as large as the spectrum intensity (red spectrum), the background is removed with the background correction (blue spectrum). This is very important for a good instrument response correction!
This spectrum has to be wavelength calibrated. Since only the zero order is known, a single line calibration has to be done. Follow the steps:

- With “Load Raw” load the spectrum mdist_sum_bg.dat (default is mdist_sum.dat)
- “Select Lines” – mark zero order in graph – “select wavelength” 0 zero – “Sel. Line” – “Save table”.
- Select polynomial degree 0 (single line calibration).

For this the linear dispersion of the setup must be known. This is obtained from a calibrated meteor spectrum. For this camera setup the dispersion is 1.997 nm/pixel.
(Check the ini-file. If it not already laoded, load “m_set_watec.ini” in the Setup)



Plot the calibrated spectrum.
As a check you may see if the prominent Fraunhofer A line at 759.4 nm (telluric absorption of O_2) is present at the correct wavelength.

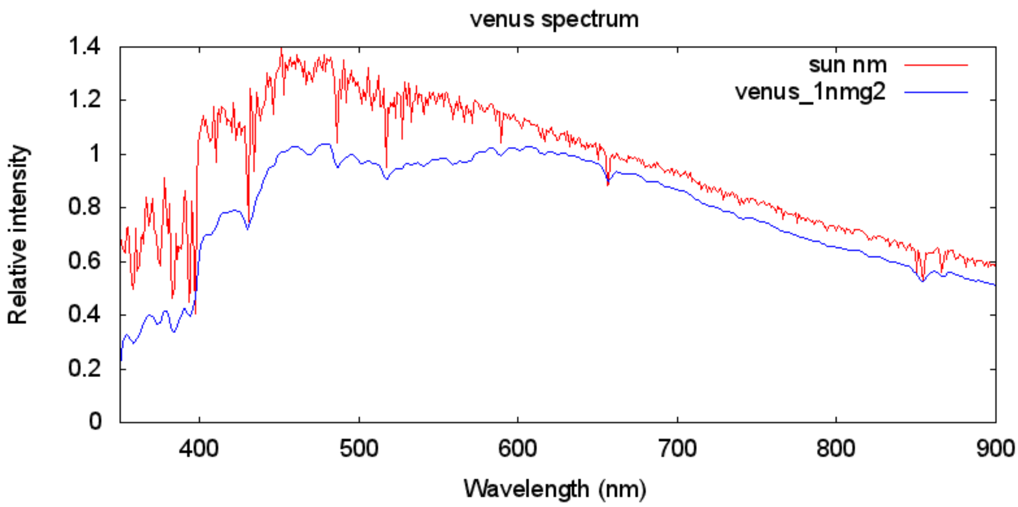


Calibration reference

The above spectrum was made of Venus. Venus reflects sunlight, but not by the same reflection factor for all wavelengths. A solar spectrum can be converted to a Venus spectrum, if the wavelength dependent albedo is known, by multiplying the solar spectrum I(λ) with the albedo R(λ)

$I_{venus}(\lambda) = I_{sun}(\lambda) * R_{venus}(\lambda)$.

It is advisable to smooth the resulting spectrum with a Gaussian function with the same resolution as the meteor spectra resolution. The details follow in the appendix.



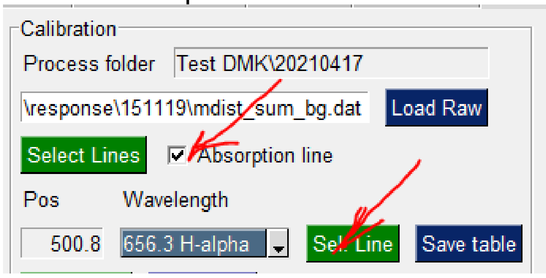
Solar spectrum with original (high) resolution and venus spectrum with Gaussian filter width 2nm.

For the present calculation we use a venus reference with a Gaussian width of 3 nm

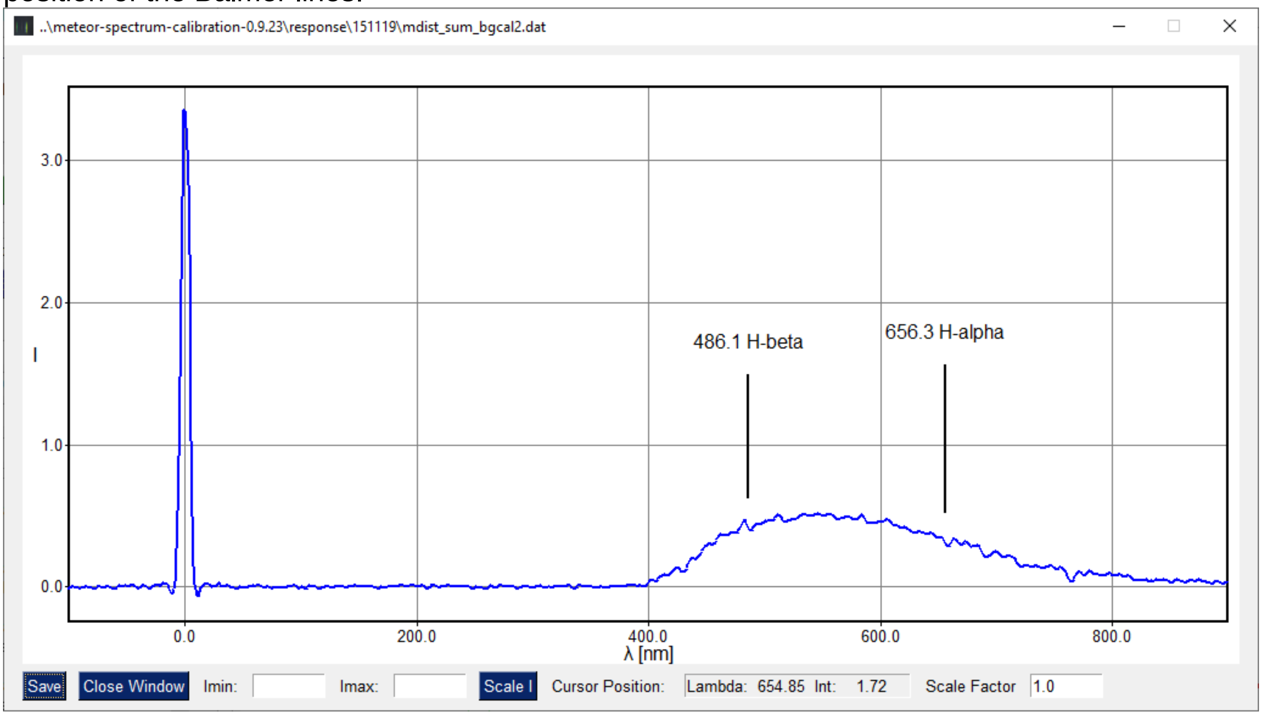
Calibration with absorption lines

For the calibration of meteor spectra, emission lines (Na, Mg, O etc.) are used. In stellar spectra absorption lines are usually present. For calculation of the response function, stars of spectral class B and A are particularly useful. They show a smooth continuum with a few Balmer lines (H-alpha, H –beta etc.) present. These can also be used for the calibration, if they are properly identified. Therefore they have been included in m_linelist.txt:

…
388.9 H-zeta
397.0 H-eps
410.2 H-delta
434.0 H-gamma
486.1 H-beta
656.3 H-alpha
Since m_spec does not know that these are absorption lines, you have to tell it by checking the box Absorption line before Select line:



With Absorption line checked, the program looks for a **minimum** in the selected range. For the zero order the checkbox has to be unchecked. If you are not sure about the correct line identification, you can do a single line calibration with zero order and known dispersion only, plot the resulting spectrum and use the label function with a right click to check the correct position of the Balmer lines.



Once identified, redo the calibration with the identified Balmer lines added.
For the present spectrum with low S/N:

Pixel	lambda	fit	error
154.53	0.00	-0.13	-0.13
399.05	486.10	486.62	0.52
484.10	656.30	655.92	-0.38

polynom degree: 1
polynom for fit lambda c: [1.9906 -307.7444]
rms_x = 0.3782

Single line calibration
polynom for fit lambda c: [1.997, -308.59641]

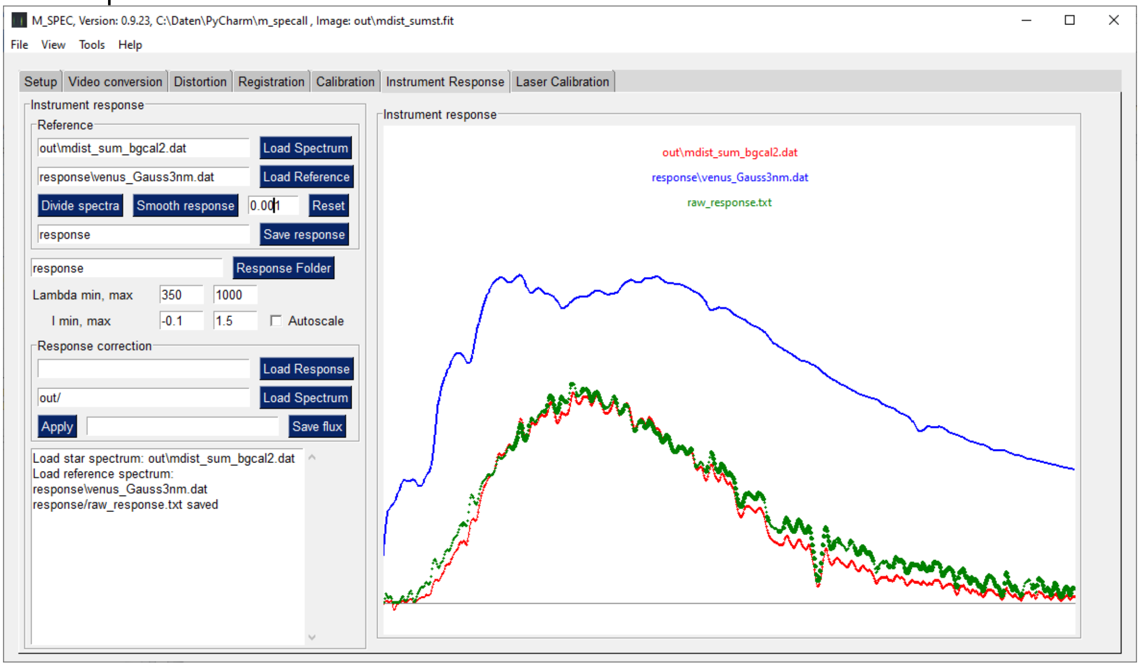
pixel	lambda	fit	error
154.53,	0.00,	0.00,	0.0000

rms_x = 0.0000

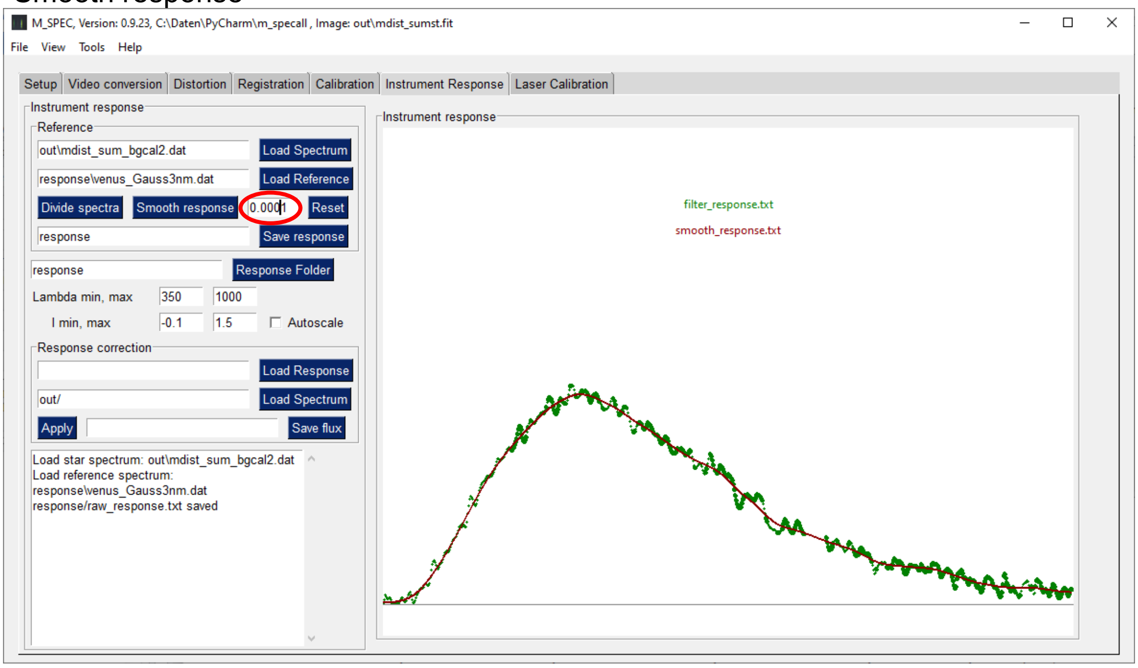
Which is close to the single line calibration at right

Calculate response:

- Go to the “Instrument Response” tab.
- Select a suitable wavelength range (350 – 800 nm is advisable, at shorter wavelength the signal is almost zero, at longer wavelengths the second order spectrum overlaps: You can always reduce the range later.
- Load the calibrated spectrum with *Load Spectrum”
- Load the reference from the library: venus_gauss3nm
- Divide spectra:



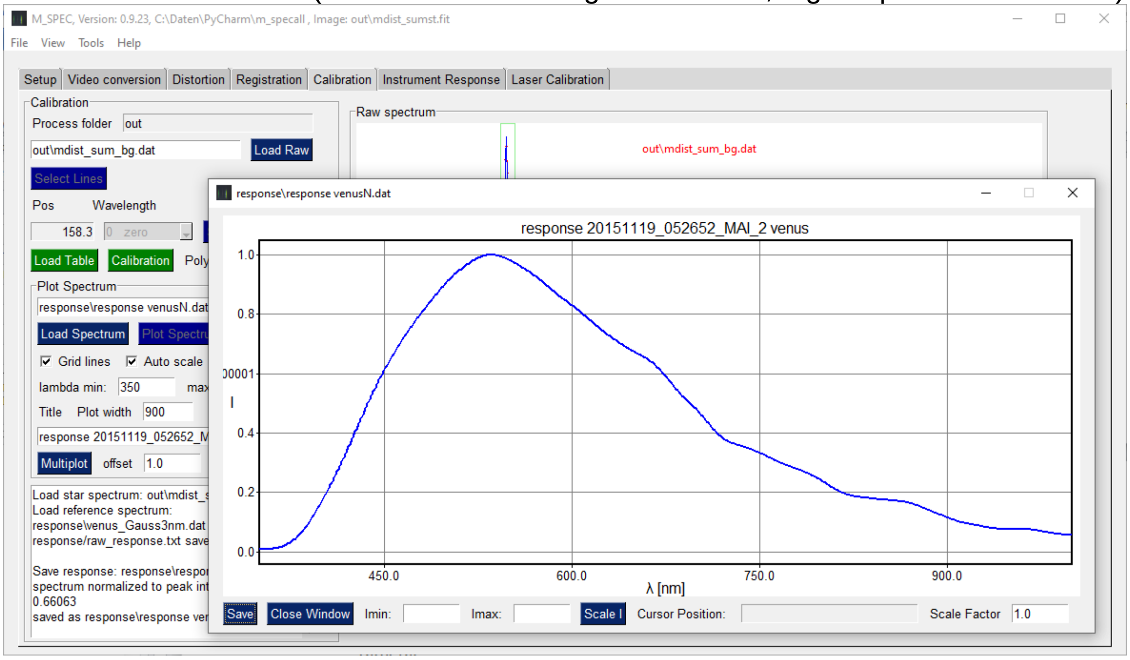
- Before smoothing the resulting spectrum remove the telluric line at 760 nm. Select a range with the mouse around this by dragging the mouse with left button pressed. You may repeat this for removing other artefacts (for a star reference you may remove the Balmer lines)
- This response has to be smoothed, preferable would be a less noisy spectrum. Adjust the agressiveness of smoothing by changing the smooth factor to the right of the button “Smooth response”



The smooth factor may vary between 0.0 and 1.0. Zero fits a straight line through the

points. One fits a curve through all the points. For the example a value of 0.0001 was used. By trying out different values, find a result which removes the noise but retains the shape of the response as closely as possible. With a noisy spectrum this is quite difficult.
For the interested reader the smoothing algorithm is described in detail here:
https://csaps.readthedocs.io/en/latest/formulation.html
It is based on an algorithm by: C. de Boor, A Practical Guide to Splines, Springer-Verlag, 1978 (link)
In my opinion it is better than the smoothing interpolation in scipy:
https://docs.scipy.org/doc/scipy/reference/tutorial/interpolate.html

- **Make sure the response does not cross the I = zero line (grey)!** If this happens applying the response to a meteor spectrum means big trouble (division by zero). Either limit the response to a smaller wavelength range or try a different smoothing. You can also edit the response file to eliminate or correct negative or very small values. For the example a useful range would be 400 – 800 nm, outside the values of the response are not reliable.
Save the response with a suitable name (date, object, elevation). Notice that this response also reflects the actual sky conditions (atmospheric absorption, dependent on elevation and air pollution)
- When you plot the spectrum you can normalize the spectrum to peak value = 1 (right click the spectrum plot and select “normalize to peak value” and plot with “Norm Scale” or “Auto scale” checked(N is added to the original filename, e.g. response venusN.dat):



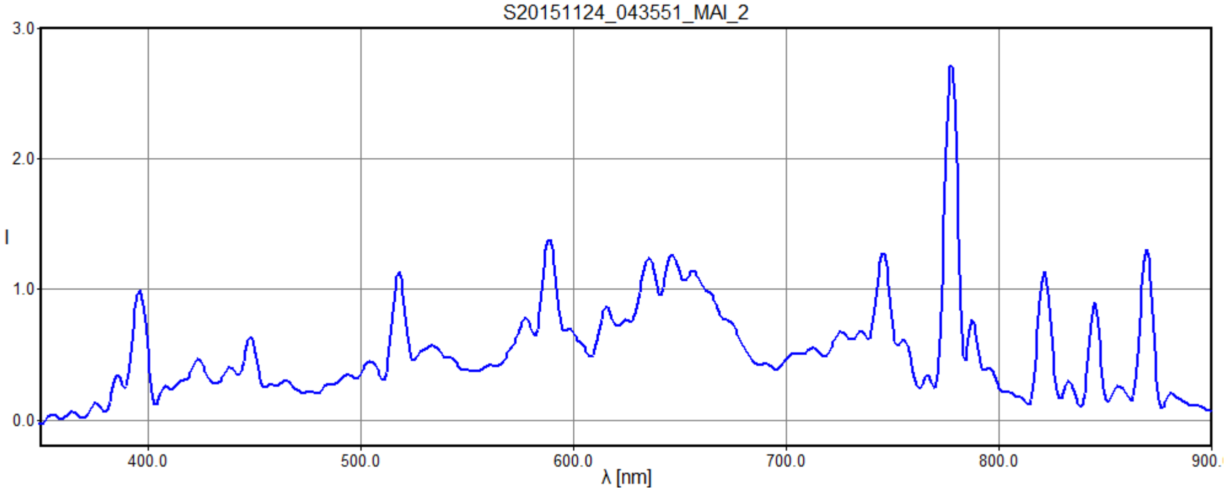
- Do not forget to calculate the elevation of the reference object at the time of acquisition for precise processing. From UFO Analyzer: 27.64°, from Carte de Ciel :27°53’ quite low over the horizon, but comparable to the elevation of the meteor M20151124_043551 at an elevation of 31.5°, to which this response was applied. See next.
- In order to get a better feeling try to make a response curve with different stars (Sirius, Vega, Deneb) at different elevations and compare the results. Ideally, the responsefunction should be independent of the object.

Apply response to measured spectrum

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

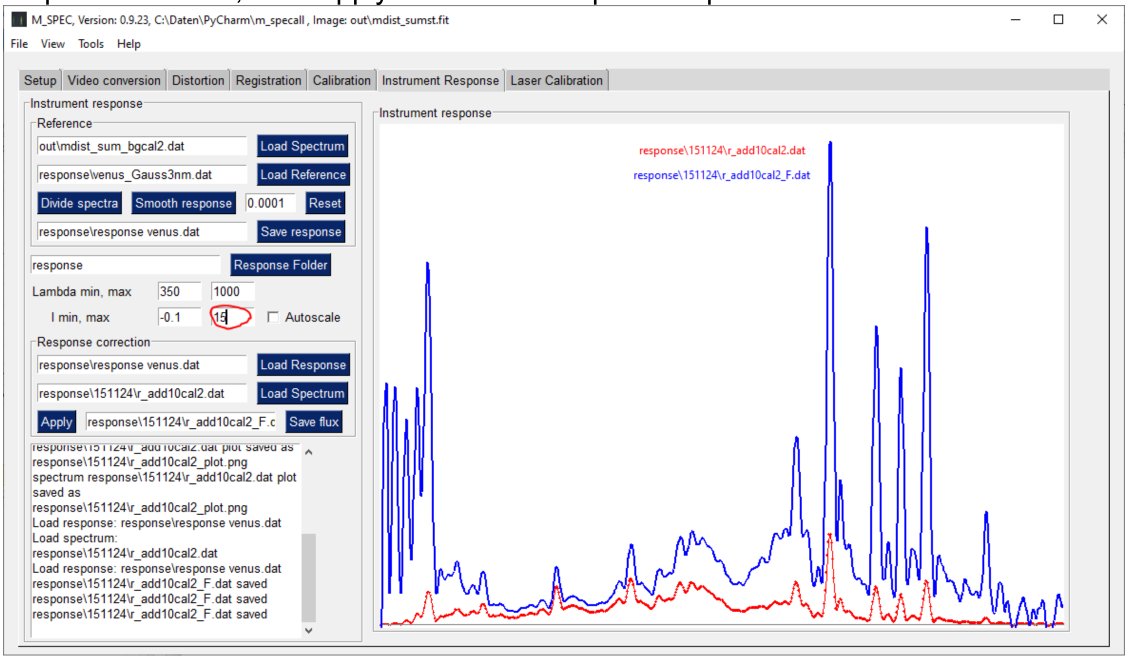
$S(\lambda) = I(\lambda) / R(\lambda)$
where $I(\lambda)$ is the measured spectrum and $S(\lambda)$ is calculated in relative units.
As an example I use the following spectrum:
response\151124\M20151124_043551_MAI_2.avi

Adding 10 processed frames and calibrating resulted in the following spectrum:

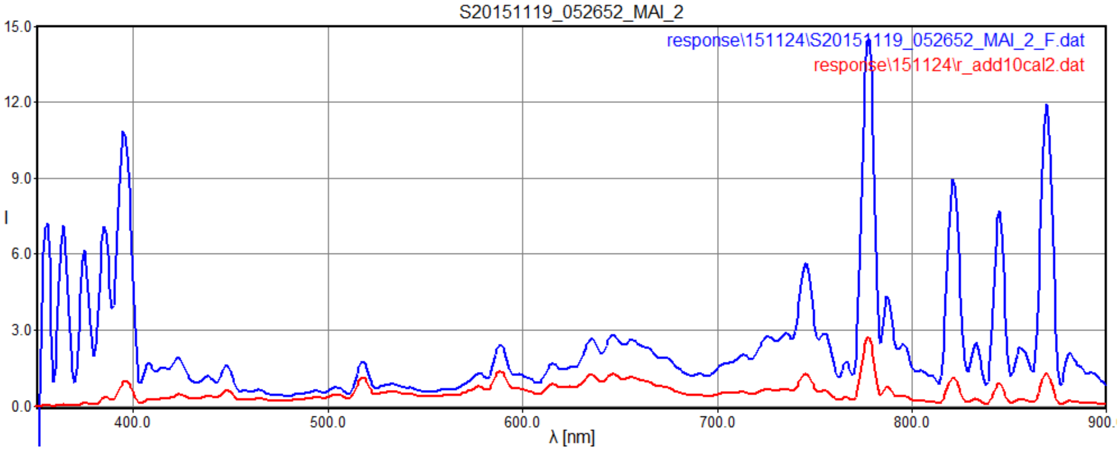


- Go to the “Instrument Response” tab
- The response correction is done at lower left
- Load the instrument response (the default is from the previous response calculation)
- Load the meteor spectrum 151124\r_add10cal2.dat
- Make the corrected spectrum 151124\r_add10cal2_F.dat (the appendix “_F” is added to the original file to show that this is a flux corrected file.
- Adjust the scale to fit the spectrum (the low value of the response at the end of the wavelength range means that the spectrum is amplified there, adjust the scale accordingly (autoscale only works for the original spectrum). This displays the

response function, use “Apply” to renew the spectrum plot:



- You can save the resulting spectrum with a meaningful name.
- You can plot the resulting spectrum in the calibration tab . With right click the plot and “compare with spectrum” you can add the original spectrum to the plot:



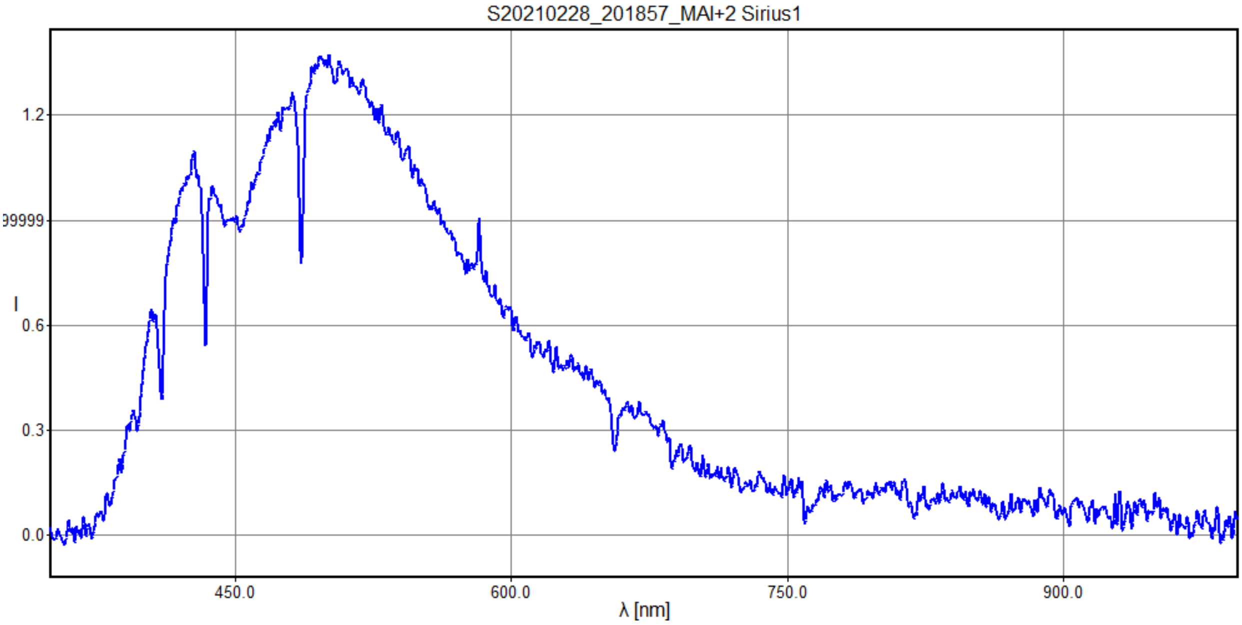
- Comparison of the two spectra:
  Red: response not corrected
  Blue: response corrected
- Above 750 nm notice the second order of the strong Fe and Ca lines around 400 nm. The lines below 400 nm are very noisy, because they are amplified by the low response.
- At this point the atmospheric transmission could 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) under similar sky conditions

Example with atmospheric correction, higher resolution

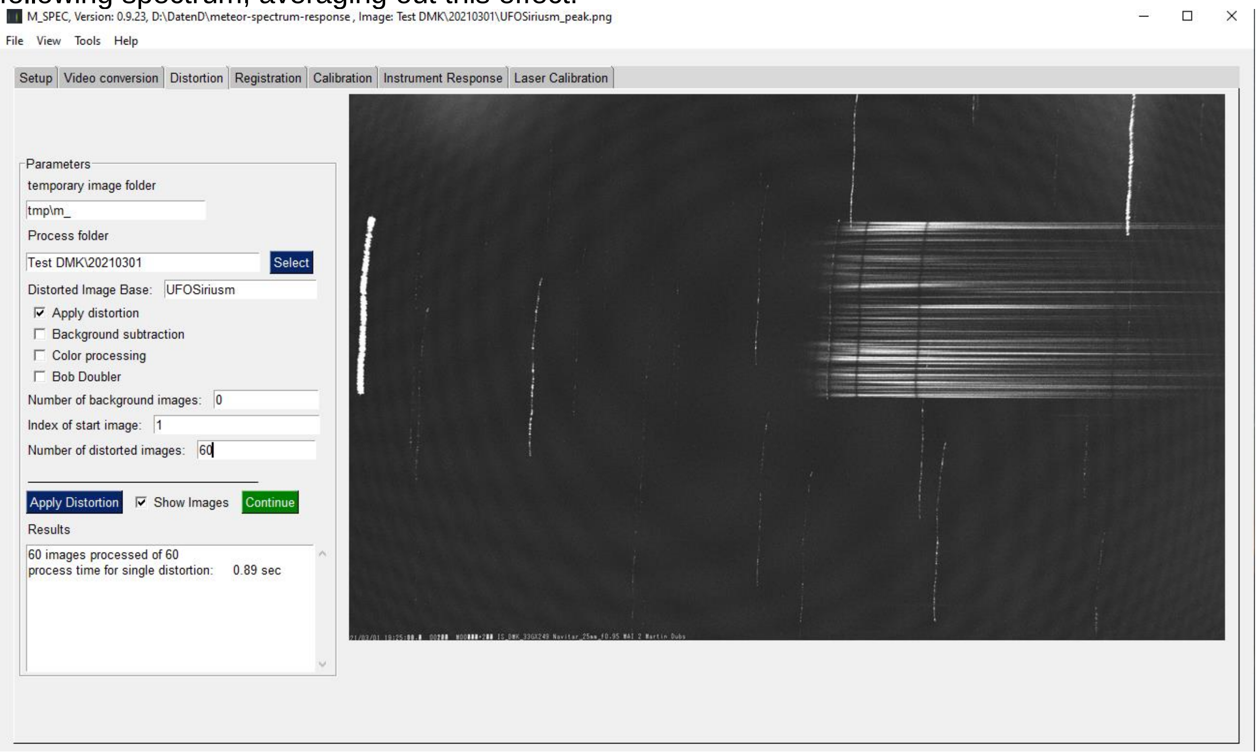
The previous example used spectrum of Venus, with quite low S/N-ratio. With standard recording, at 1/25sec exposure time, only the brightest stars produce useful spectra. The following example was recorded with a DMK 33GX249 from The Imaging Source, with a Navitar 25mm f/0.95 lens.

Dispersion with 600 L/mm grating: 0.40 nm/pixel

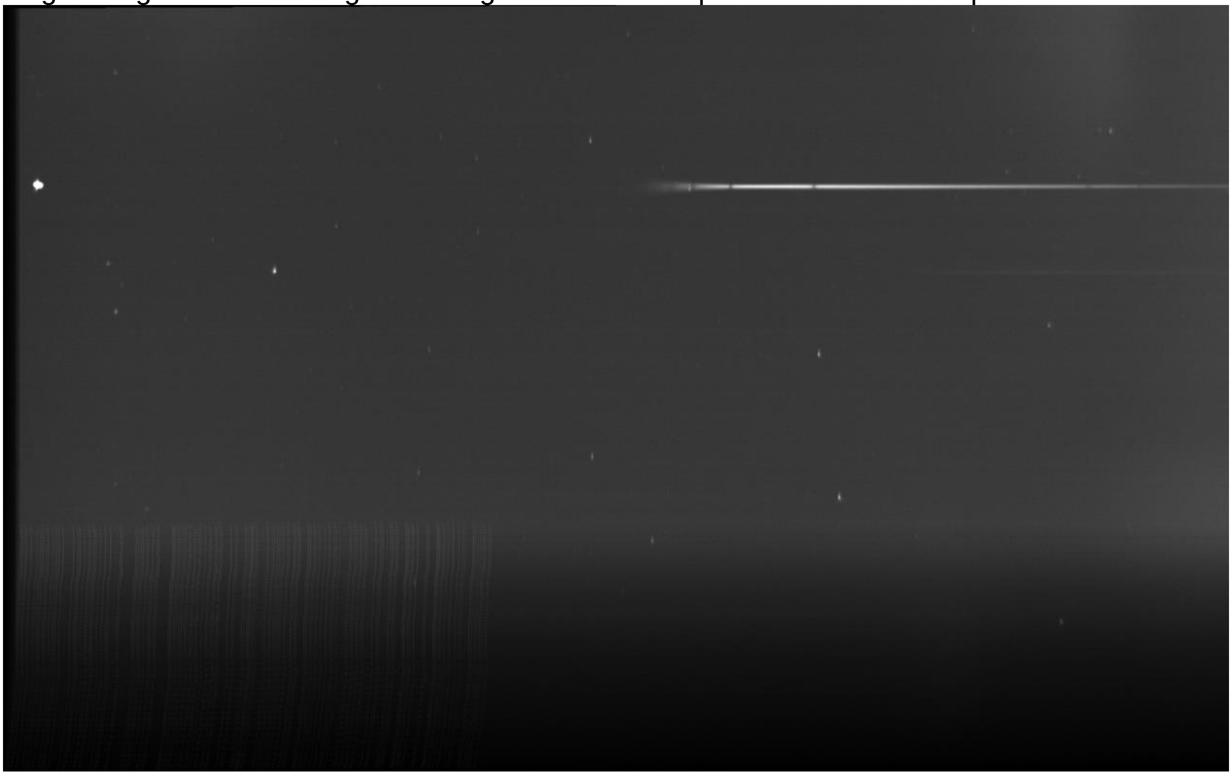
A first attempt with Sirius gave the following calibrated spectrum:



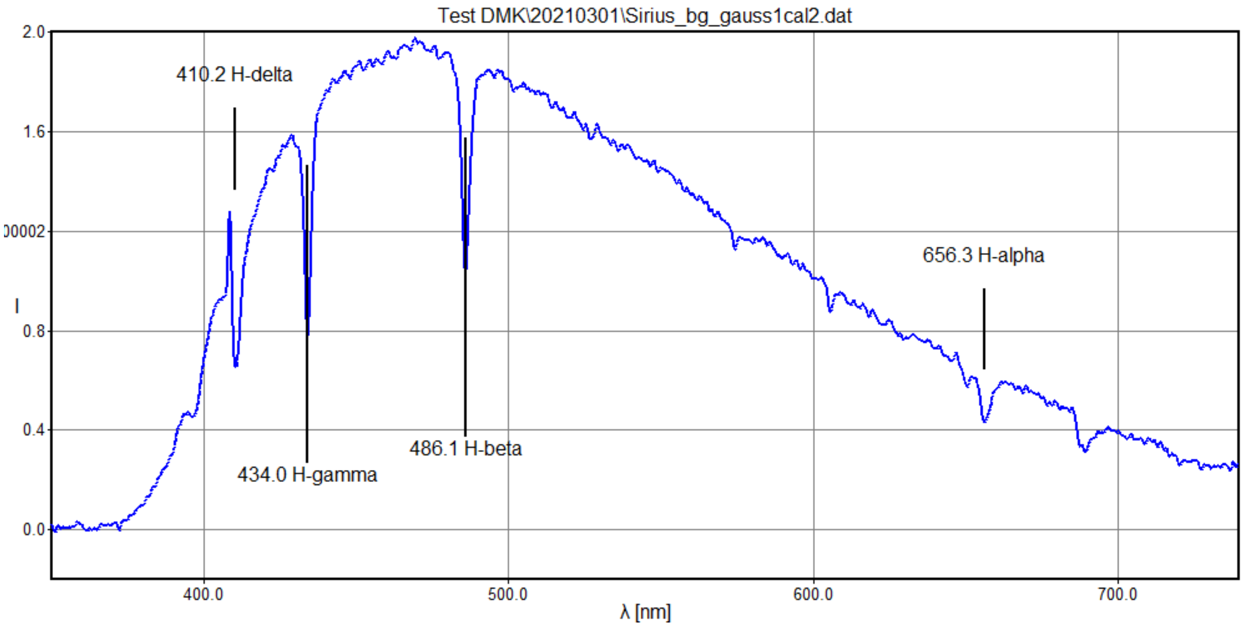
The Balmer lines are clearly shown, also the Fraunhofer A line at 759.4 nm (telluric absorption of O_2). The “emission line” near 580nm is actually the zero order of a background star coinciding with the spectrum. The broad dip around 450 nm varied in different spectra. It is caused by the narrow spectrum with a width close to one pixel. Depending on how the light is distributed among neighbouring pixels, local saturation may occur. This may lead to artefacts of this type. In order to eliminate these artefacts, the camera was moved vertically in the following spectrum, averaging out this effect:



One notices that individual exposures are affected by scintillation effects, varying widely in intensity and spectral profile.
Registering and subtracting the background however produces a smooth spectrum:



After some Gaussian smoothing of the uncalibrated spectrum with sigma = 1 pixel:

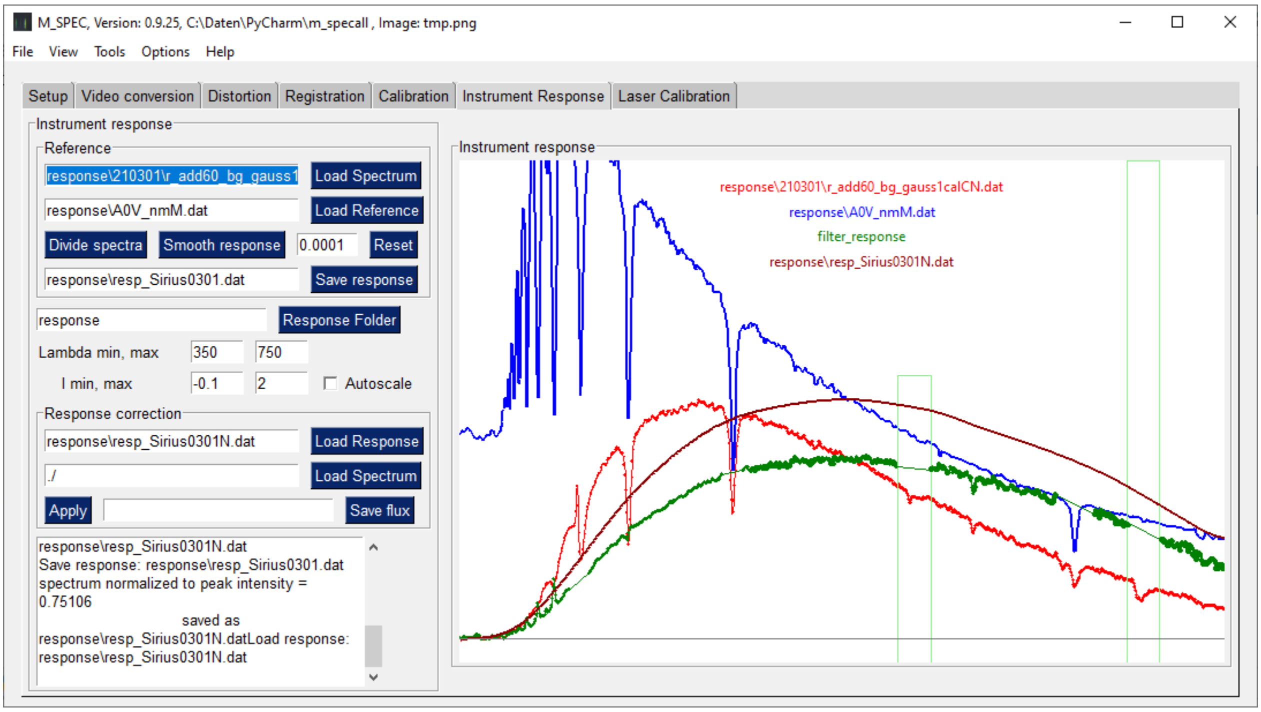


A background star close to the H-delta Balmer line can be eliminated during the response calculation.
Additional Information:
Sirius: M20210301_192505_MAI+2cut
Elevation above horizon: 26°16’, required for atmosphere transmission correction
spectral type A1V

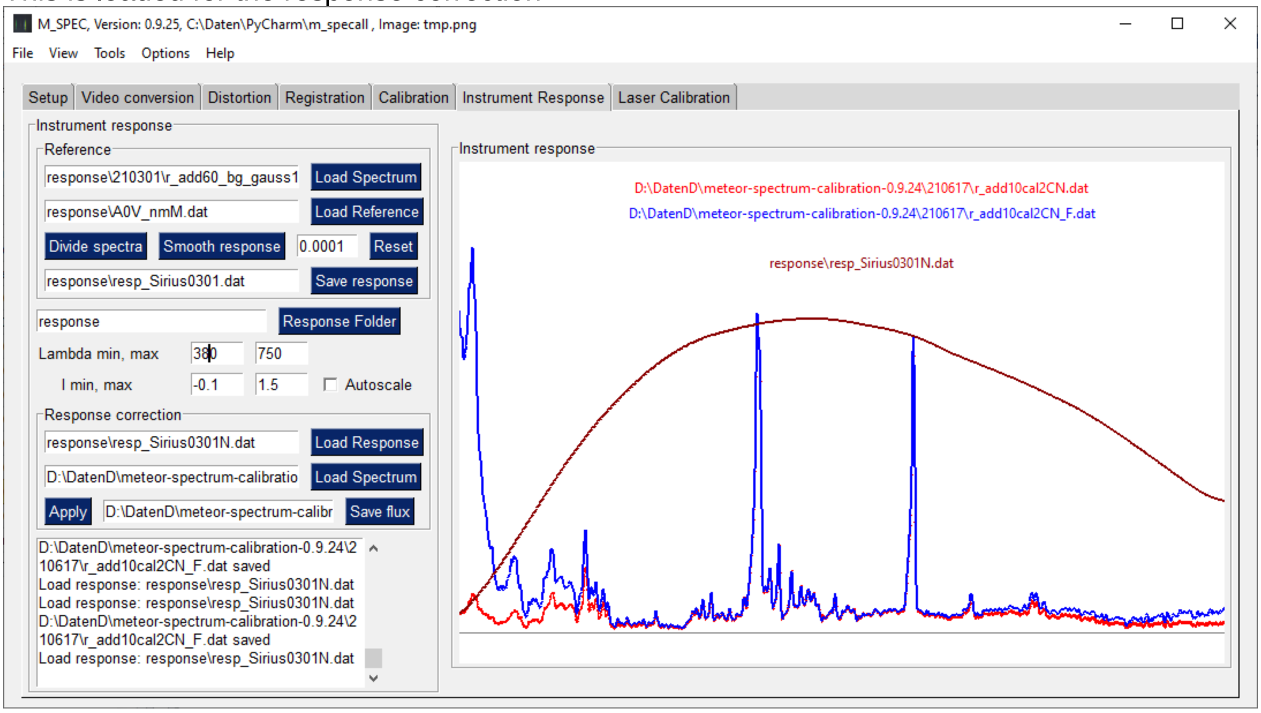
Calculation of response with spectrum of Sirius

The spectrum above can be used for the calculation of the instrument response. As a reference spectrum a spectrum from the ISIS database is used, spectral type A0V is closest to

the spectral type of Sirius (A1V). It is converted to nm with Tools – Gaussian, wavelength tools and scaled to Intensity 1 at 500 nm by dividing by 2 (response\A0V_nmM.dat).
From the raw response the Balmer lines are eliminated as well as an atmospheric line at around 690 nm



The smoothed response is saved as resp_Sirius0301.dat.
In the calibration tab it is plotted and normalized to the peak value with: right click – Normalize to peak value (Short cut Alt T - N). It is saved automatically as resp_Sirius0301N.dat.
This is loaded for the response correction



Correction of atmospheric extinction

The spectra are influenced by the transmission of the terrestrial atmosphere. If the stellar reference for the response and the meteor spectrum are taken under similar condition and similar height above the horizon, the atmospheric transmission is similar for both spectra and a further correction is not necessary. However one has to keep in mind that in general, both response and meteor spectrum are affected by atmospheric transmission.

The following discussion of atmospheric extinction is based on the method of Christian Buil, described in http://www.astrosurf.com/aras/extinction/calcul.htm and used in ISIS spectroscopic software: http://www.astrosurf.com/buil/isis-software.html, as described in the theory section at the beginning. Before proceeding, study this chapter Atmospheric transmittance again.

Let us start with the instrument response.

The overall response including atmospheric extinction is calculated by dividing the measured stellar intensity by the reference flux for this object, taken from a catalogue of reference spectra

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

From this the true instrument response can be calculated using

$R(\lambda) = IR(\lambda) * T_{atm}(\lambda, AOD, z)$

or

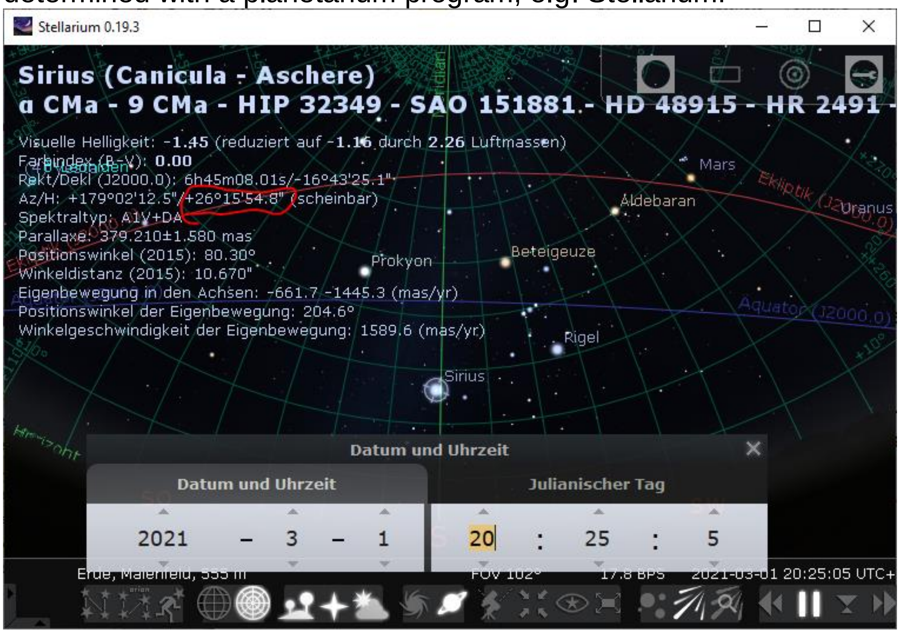
$IR(\lambda) = R(\lambda) / T_{atm}(\lambda, AOD, z)$

The atmospheric transmittance depends on the wavelength, the quality of the air and the zenith distance (90° - elevation) of the object or the corresponding air mass.

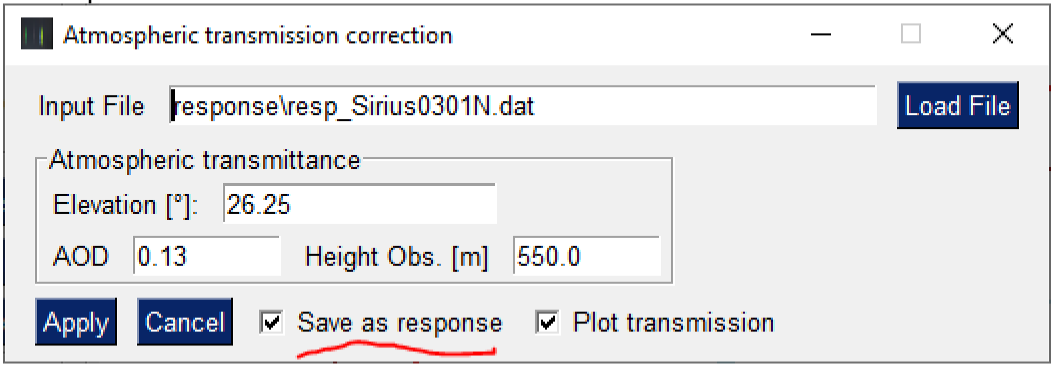
In the method of Buil the air quality is described by the parameter AOD (aerosol optical density). It can be determined by fitting observations of the same or different stars at different altitudes with a common AOD until the resulting instrument response is independent of the elevation. This is the best method, but rather time consuming and would have to be done every night, in order to account for night to night variability of the air quality.

A simpler method consists in making a guess of AOD (mean for France or Switzerland AOD = 0.13, varying from 0.07 in winter to 0.21 in summer for clear skies) and measuring the reference star at a similar elevation as the meteor, so that only the transmittance difference caused by the different elevation has to be corrected.

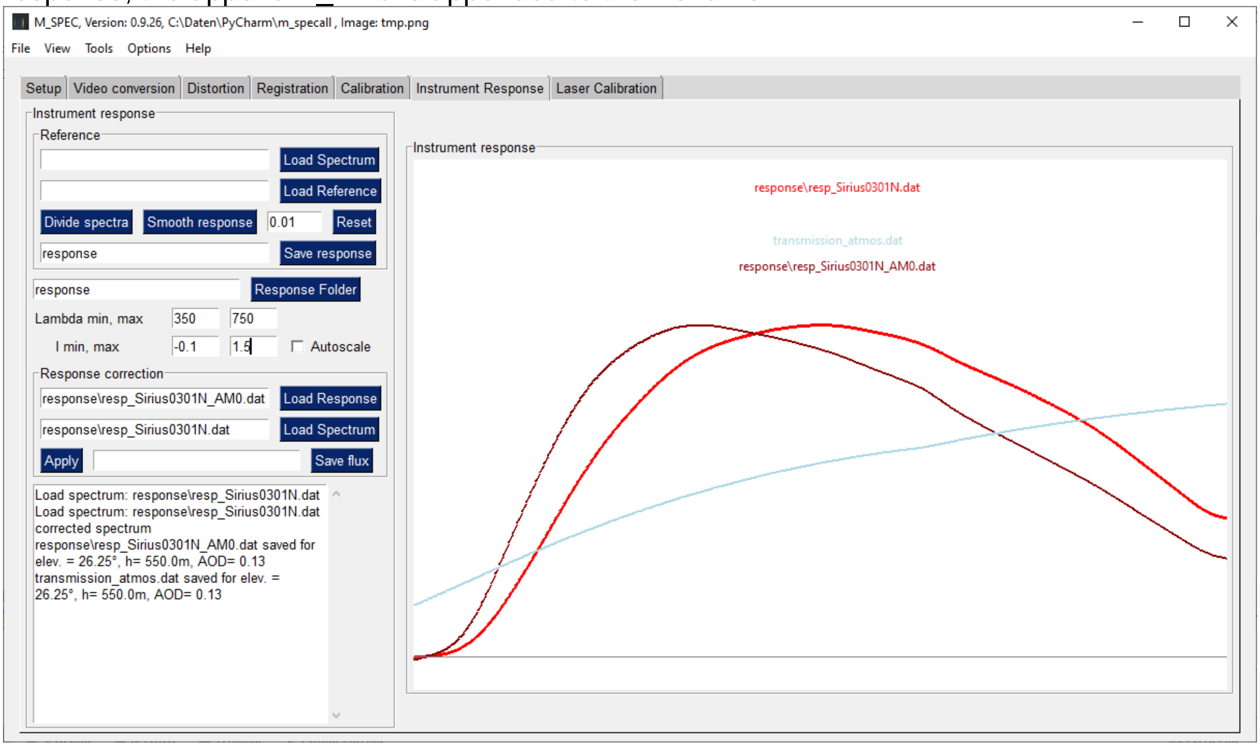
In addition to the AOD also the elevation or zenith distance of the object (reference star or meteor) has to be determined. This is most easily done in UFO Analyzer, for the date and rime of the observation. If this is not available, because the clip was not calibrated (as in the case of Sirius M20210301_192505_MAI+2, used in the example above, the elevation can be determined with a planetarium program, e.g. Stellarium:



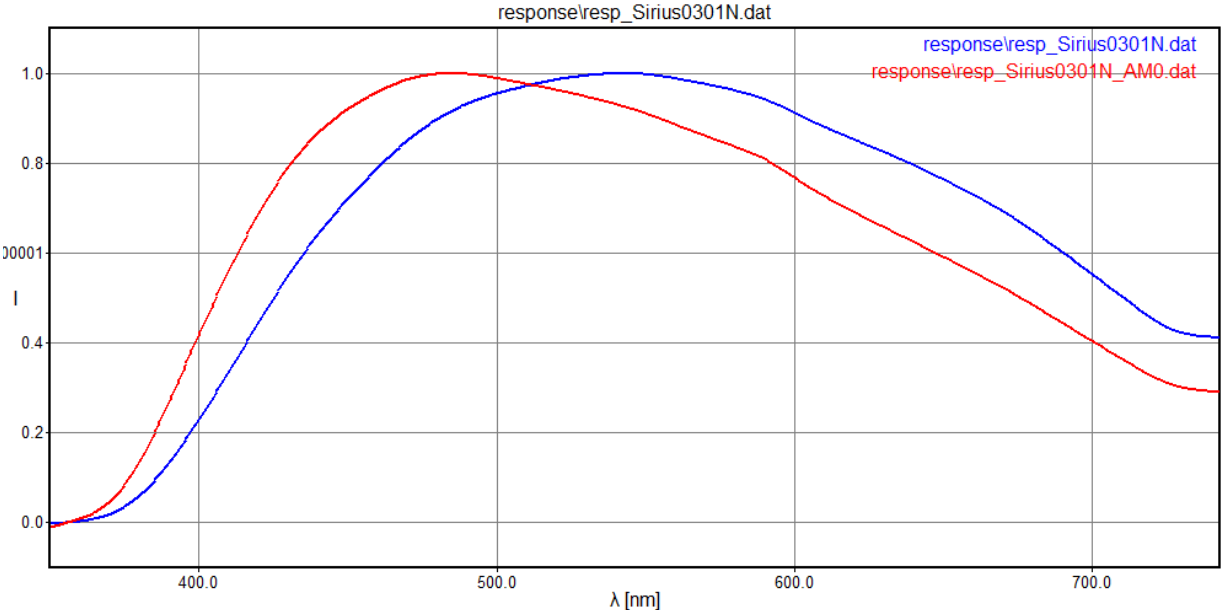
Do not forget to use the correct time zone or change the observation time (MEZ = UT + 1h) accordingly.
With the assumed AOD = 0.13 (checked with a second star Procyon at elevation 45°, details omitted here) we have the necessary information to apply the atmospheric correction to the instrument response.
For the division of the response by the atmospheric transmission select from the menu Tools – Atmospheric correction:



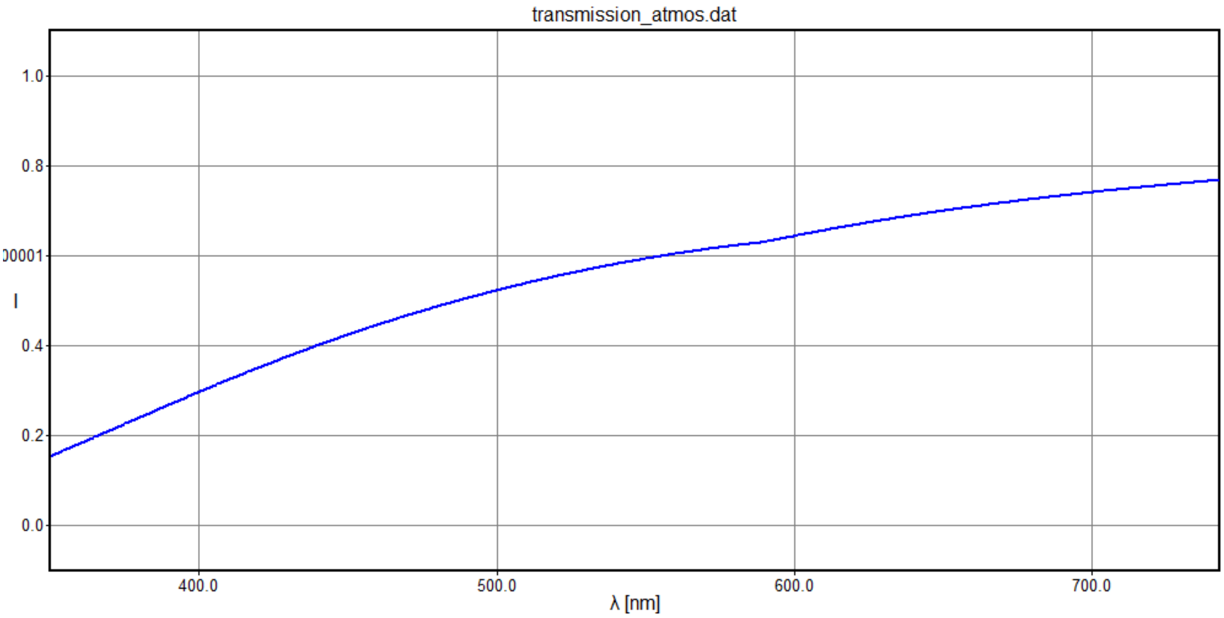
With Load File select the desired uncorrected response, fill I the elevation and AOD and the height above sealevel of the observation location. Check “Save as response”. This will put it in the correct field for the response correction. In order to distinguish it from the uncorrected response, the appendix _AM0 is appended to the filename:



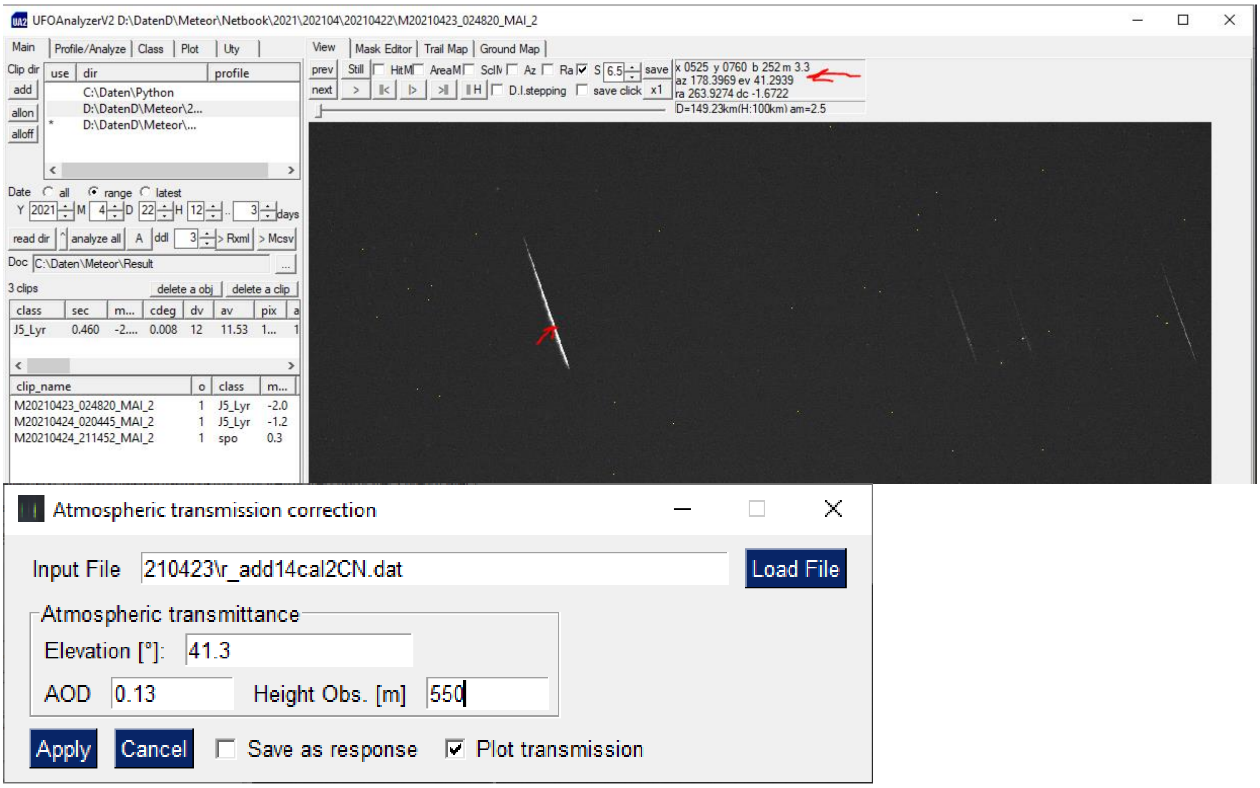
The respose was loaded first as spectrum, to show the difference between the raw response and the corrected response (both spectra are normalized to 1). The transmittance can also be shown. For a better graph go to Calibration, load the spectrum response\resp_Sirius0301N.dat, plot and compare with response\resp_Sirius0301N_AM0.dat:
The details of the calculation can be found in the logfile and the textbox at the bottom left
…
2021-08-31 00:13:39,056 20 1776 Load spectrum: response\resp_Sirius0301N.dat
2021-08-31 00:14:02,959 20 1933 corrected spectrum response\resp_Sirius0301N_AM0.dat saved for elev. = 26.25°, h= 550.0m, AOD= 0.13
transmission_atmos.dat saved for elev. = 26.25°, h= 550.0m, AOD= 0.13
…



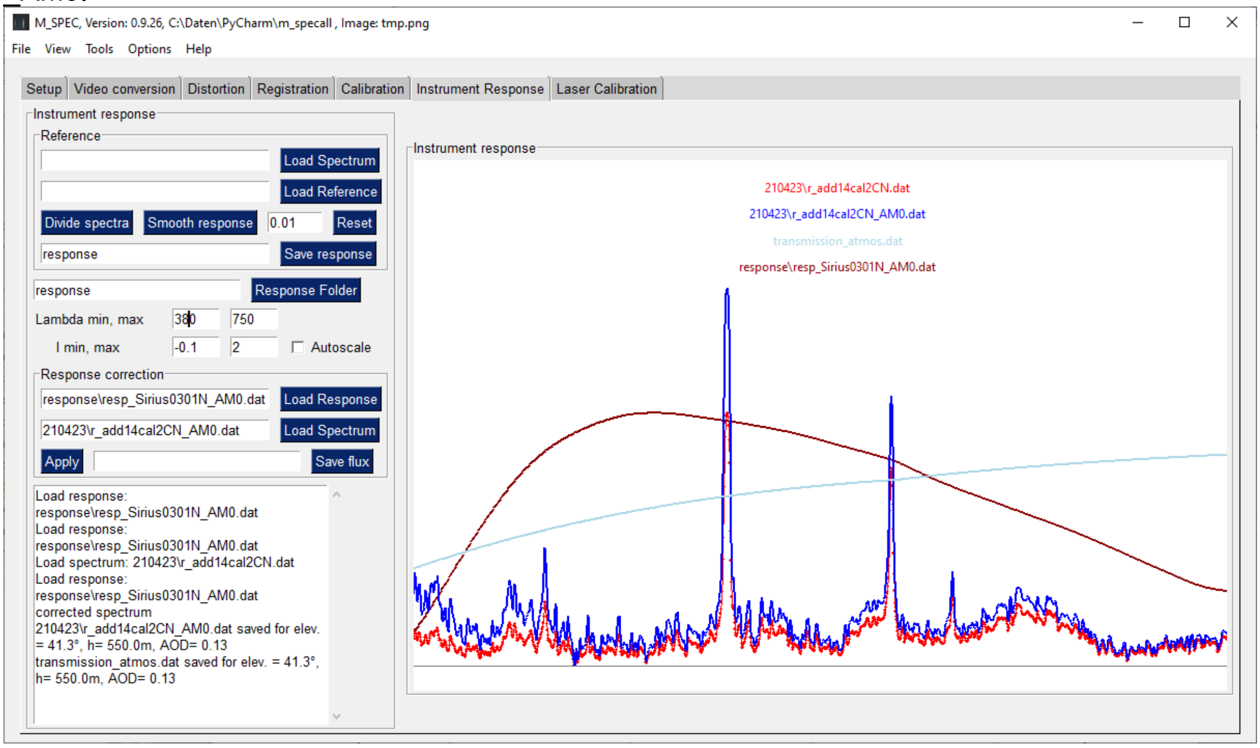
For the atmospheric transmission plot the file transmission_atmos.dat:



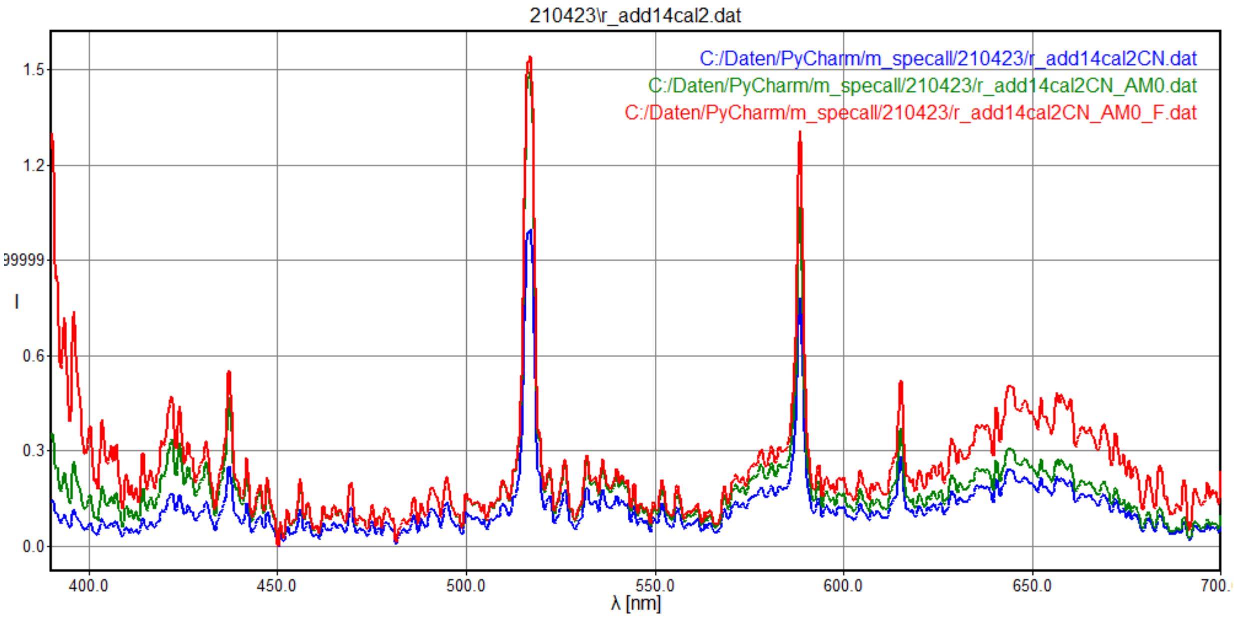
Note that the atmospheric transmission file is overwritten for every new calculation. Save it under a different name if you want to save it for further use (e.g. if you want to compare the transmission for different air mass).
Next we correct the meteor spectrum for atmospheric transmission:
We have to assume that atmospheric conditions are similar to the reference spectrum, otherwise a extinction correction is not meaningful. Get the average elevation of the meteor (zero order image, brightest part) from UFO Analyzer:
41.3°, same AOD = 0.13



Note that Save as response is **not checked**, the file is saved as spectrum with appendix _AM0.

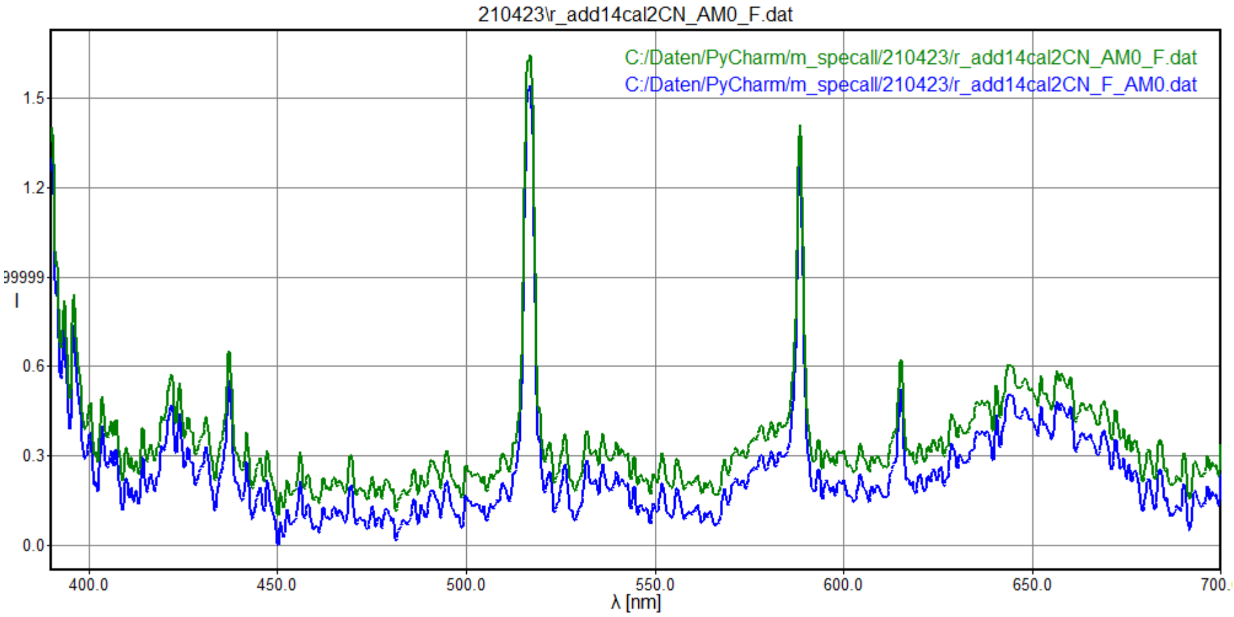


To this spectrum (r_add14cal2CN_AM0.dat.dat) the flux correction can be applied directly
The following graph shows the result, red: uncorrected meteor spectrum, green: atmospheric correction, blue: flux corrected and atmospheric correction applied



The high values in the short wavelength end are probably an artefact caused by a near zero value of the response at the short wavelength edge.

You may apply also the atmospheric correction to the flux corrected spectrum, with the same result as applying the flux correction to the atmospheric corrected meteor spectrum (curves displaced by 0.1 units)



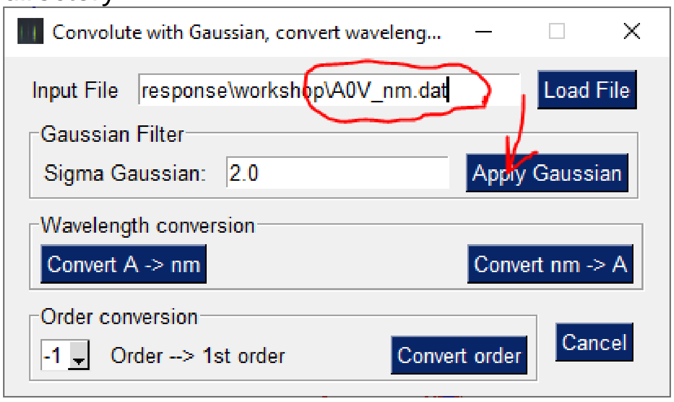
Tools used with instrument response

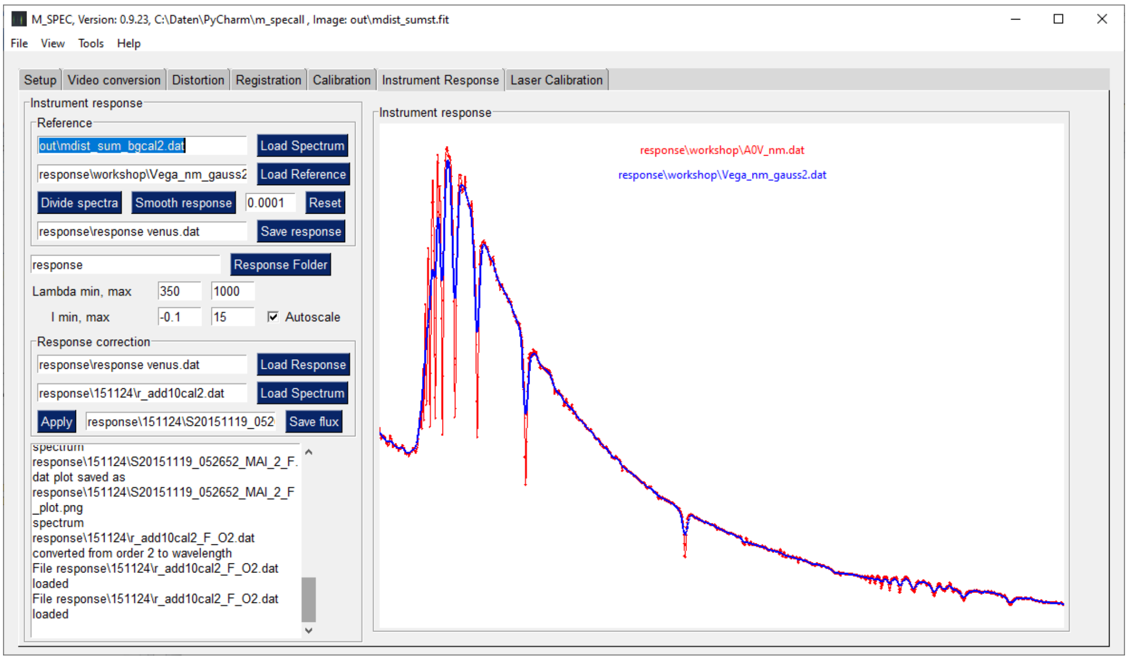
Some tools have been added, which are useful for calculating and applying the instrument response. They can be accessed from the “Instrument Response” tab in the menu “Tools” – “Gaussian, wavelength tools”.

Convolute with a Gaussian

This allows to smooth a spectrum by convolution with a Gaussian function of width sigma measured in wavelength units, nm for files calibrated in nm (sigma is about the half width at half maximum, FWHM = 2.355 * sigma). When you divide a spectrum by a calibration reference, both spectra should have a similar resolution, otherwise artefacts occur caused by digitization or sharp absorption features. Therefore the higher resolution spectrum can be reduced in resolution by convolution with a Gaussian function of width corresponding to the lower resolution spectrum.

- Load an input file, e.g. A0V_nm.dat
- Enter the desired sigma
- “Apply Gaussian”
- The resulting smoothed file with the appendix _gauss.dat will be created in the same directory





Convert Å ←→ nm

Spectra in the literature are often calibrated in Å, but m_spec works with spectra calibrated in nm. E.g. a database of reference spectra is contained in ISIS, which uses Å for wavelength units. ISIS uses both fit and dat format for spectra. Save the reference as *.dat in ISIS, usable for m_spec For the conversion to nm

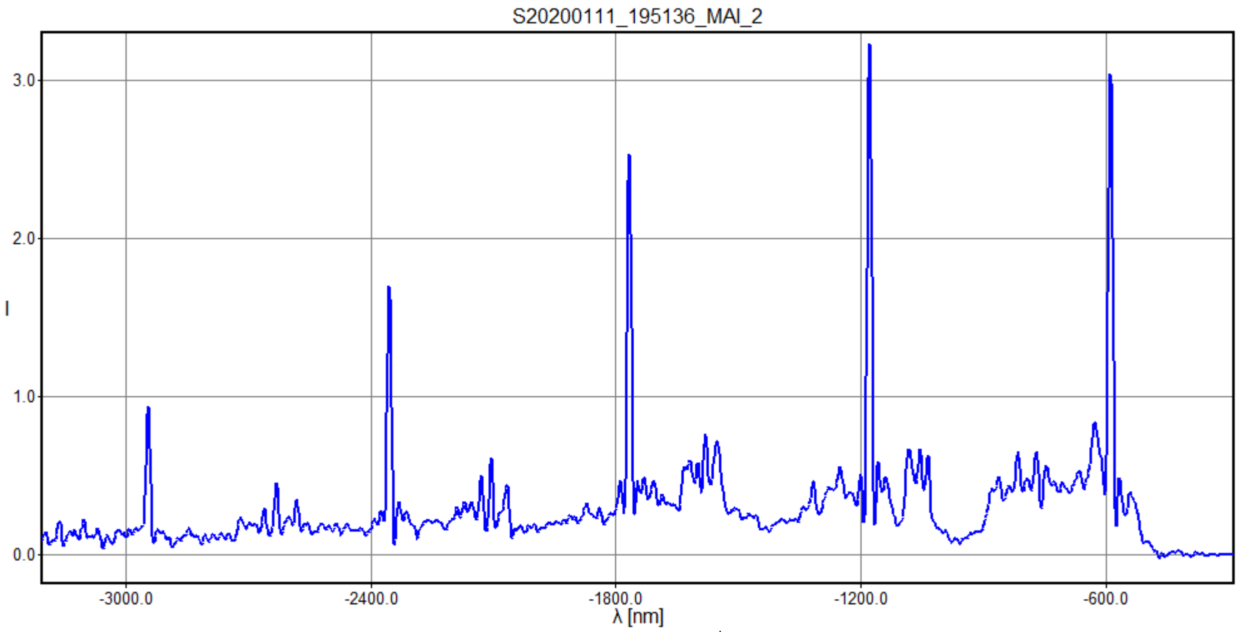
- Load an input file, e.g. A0V.dat
- "Convert A → nm"
- The resulting file calibrated in nm with the appendix _nm.dat will be created in the same directory (A0V_nm.dat)

Order conversion

The meteor spectra are calculated as intensity versus (order * wavelength). A second order spectral line cannot be distinguished from a line at twice the wavelength in first order. Spectra are created on both sides of the zero order. Those to the left are called negative orders. In order to convert wavelength * order to true wavelength, you have to divide the wavelength scale by the order:

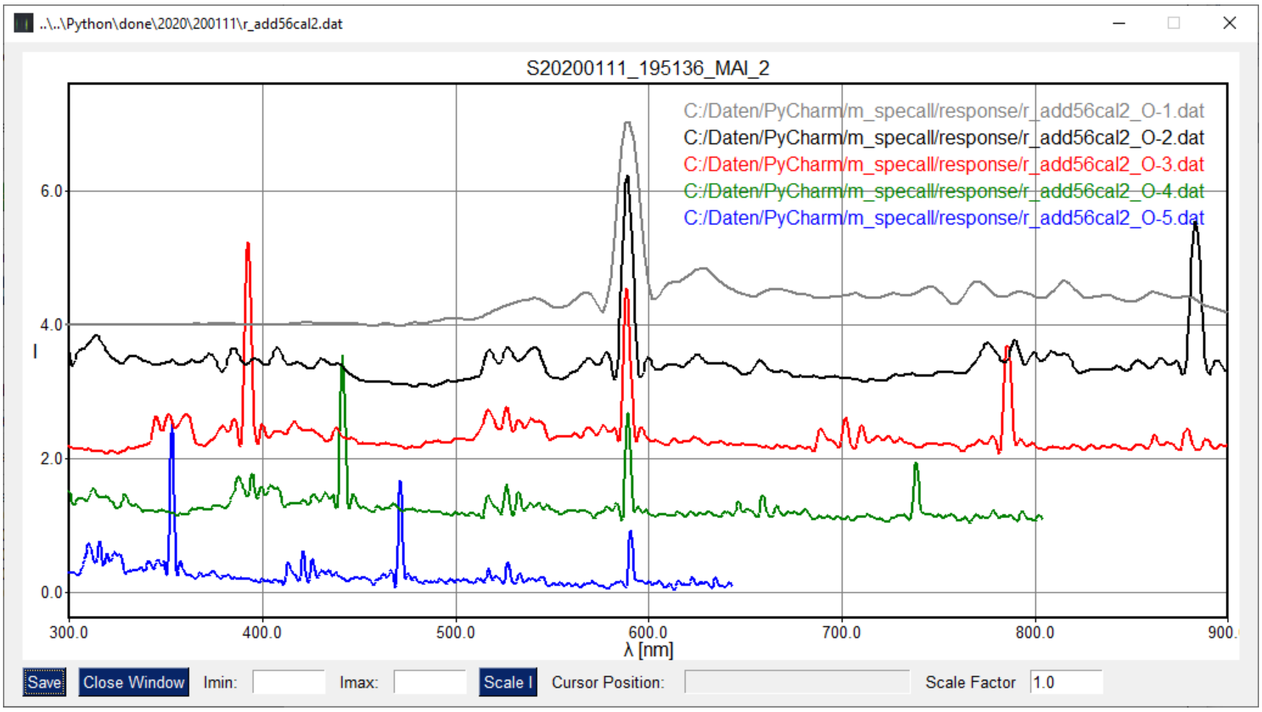
- Load a meteor spectrum
- Select the order x
- "Convert order"
- The resulting file calibrated in wavelength with the appendix _Ox.dat will be created in the same directory

It is up to the user to select the wavelength range which contains spectrum uncontaminated by higher or lower orders. Plotting the different orders in the same plot may help with the identification. The following meteor spectrum shows multiple orders, characterized by the strong Na-D line at 589 nm:



Only negative orders were observed. Changing from -1st order to wavelength flips the spectrum.

The camera is sensitive from about 350 to 900 nm, therefore the wavelength scale is chosen accordingly. The 517.5 Mg I line was outside the field of view in -1st order, but well visible in higher orders. In addition it can be seen that resolution increases with higher orders.



Venus reference spectrum

A spectrum of the albedo of Venus http://articles.adsabs.harvard.edu/pdf/1974IAUS...65..185F (E.W.Feigelson, 1974) was digitized with Tracer and resampled in ISIS https://sites.google.com/site/kalypsosimulation/Home/data-analysis-software-1

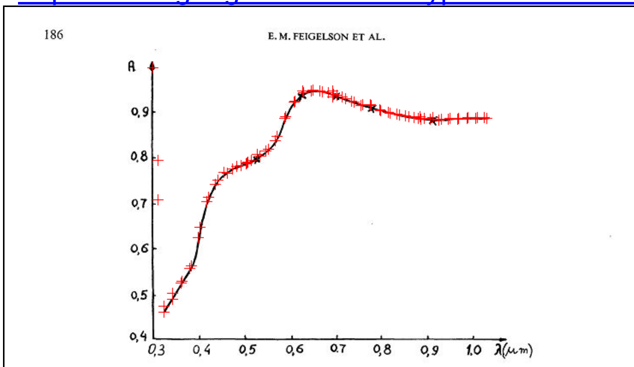
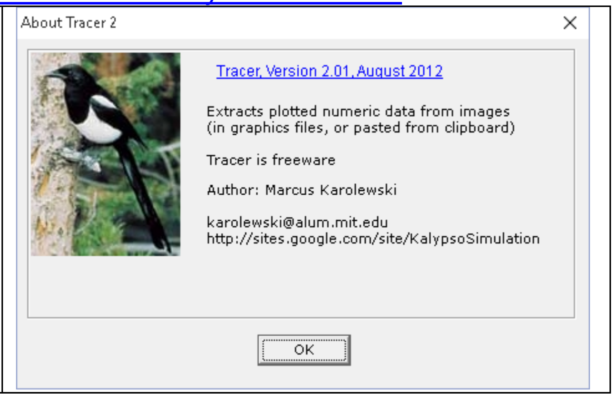
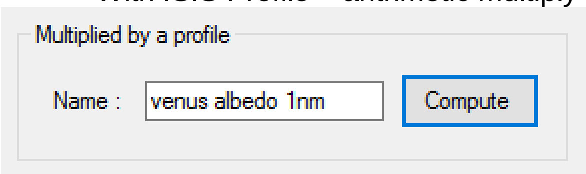


Fig. 1. The measured (full line) and the calculated (crosses) albedo of Venus for $\tau = 60$.

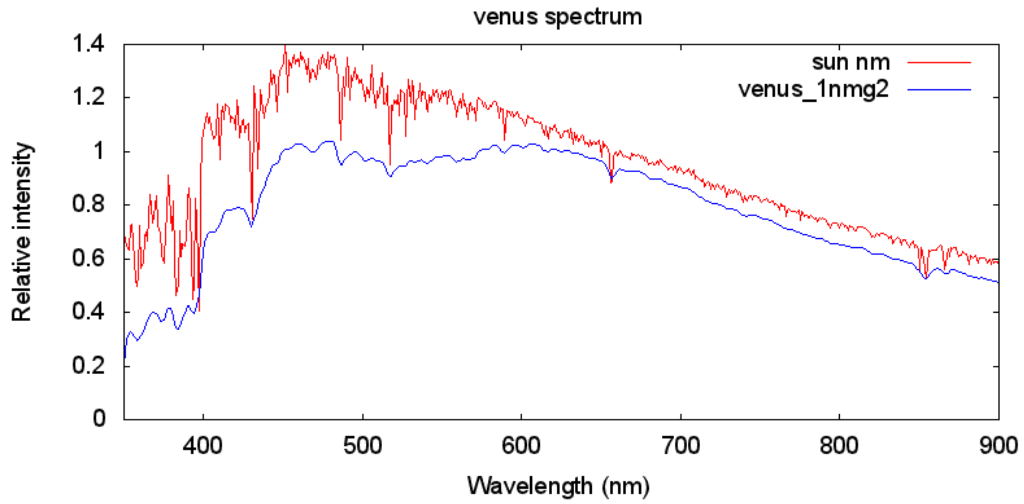


This was multiplied with a sun spectrum (from ISIS database, saved as *.dat)

- Load sun spectrum
- With ISIS 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

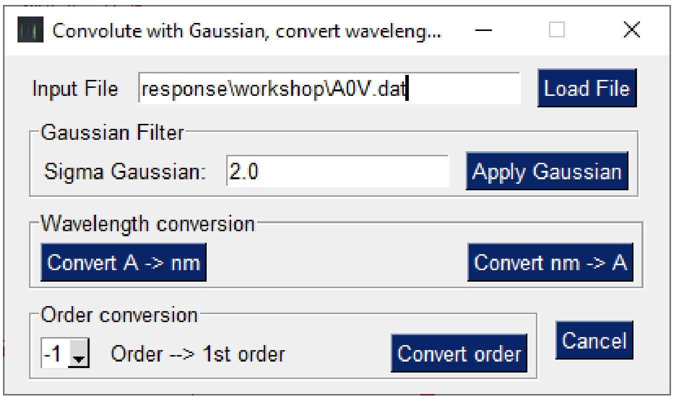


In the future, multiplication of two spectra will be implemented in m_spec as well, so ISIS would not be needed anymore

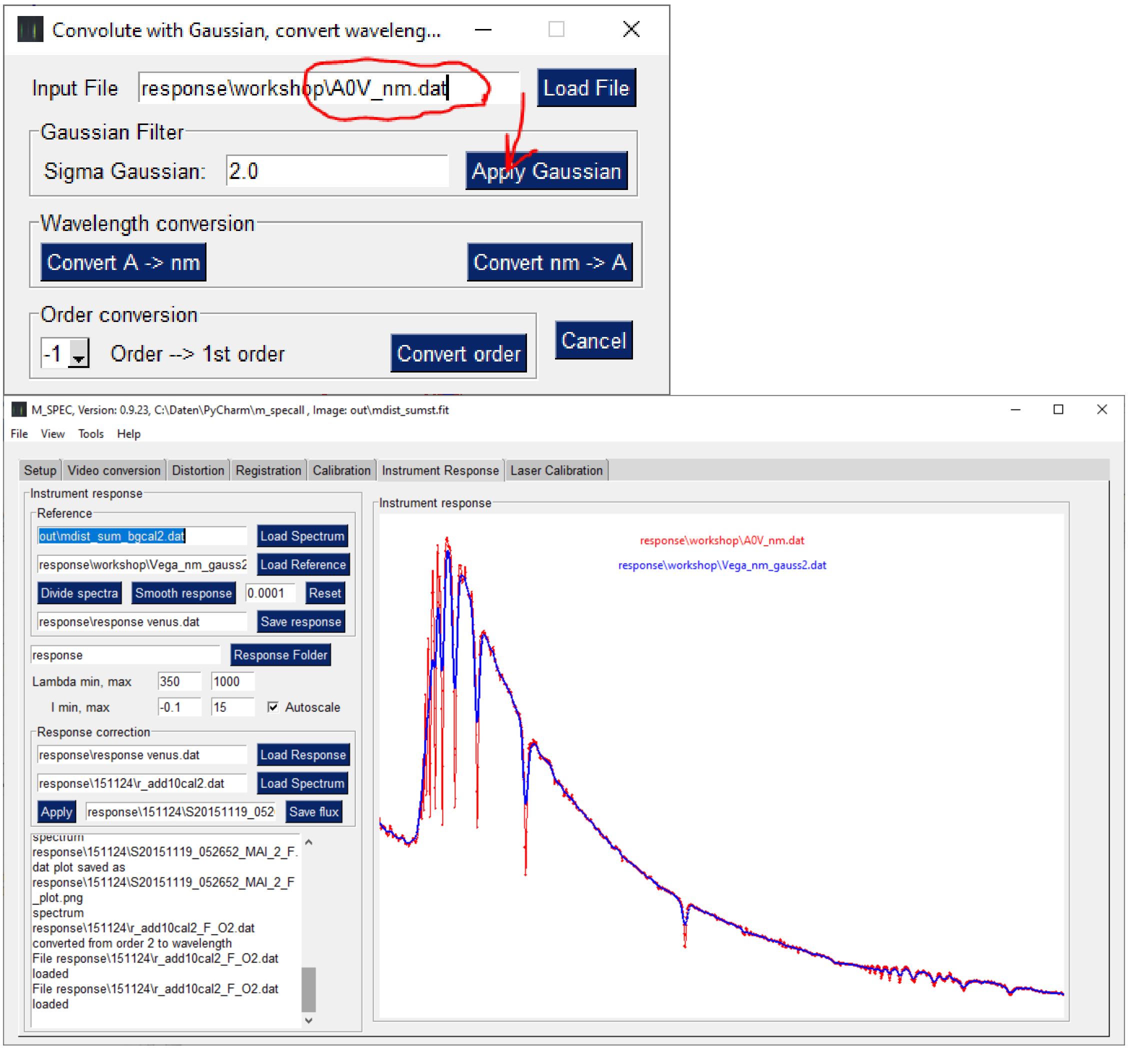
Wavelength conversion

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

- 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. Sirius is spectral class A1V, so use either A0V or A2V
- Save as *.dat in ISIS
- Go to m_spec, "Instrument response" tab
- In the menu Tools select "Gaussian, wavelength tools"
- Load ISIS spectrum calibrated in A with "Load file" in the Reference section
- "Convert Å → nm"



- Use the tool again, load the spectrum calibrated in nm.
- Smooth with Gaussian, width 2nm or what you need and save as A0V_nm_gauss2 or Vega_ref



Content of the Github folders

All example files corresponding to the present manual are contained in the folder response, in particular the calculated response function
response venusN.dat
In addition, several reference calibration files extracted from the ISIS database, calibrated in A and nm (*_nm.dat).

151119

The folder 151119 contains a Venus spectrum mdist_sum.fit, which was used to calculate the Response function:
response venus.dat, normalized to : response venusN.dat

151124

This folder contains a meteor spectrum and some derived files

210423

A meteor spectrum with applied atmospheric and flux correction

response\210301

a folder containing a Sirius spectrum at higher resolution and the corresponding response function

Index