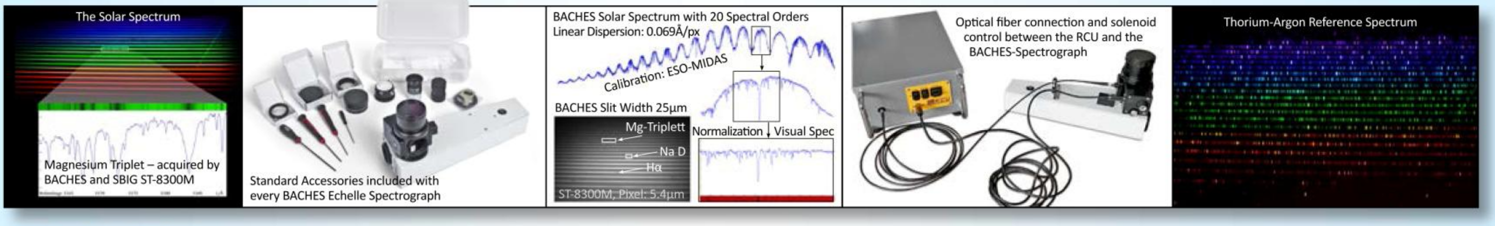
Calibration of BACHES Echelle Spectra with ESO-MIDAS



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1 Introduction

The BACHES echelle spectrograph is a research-grade tool for high-resolution investigations of stellar spectra. Unlike a conventional grating spectrograph, the entire spectrum from about 392nm to 800nm can be detected with a single shot. However, the covered wavelength range depends on the sensor size, which should be a minimum of 14mm x 9mm for a (semi-) automatic calibration with MIDAS.

The advantages of BACHES are obvious: no time-consuming search for a particular spectral range, no moving of the grating, high mechanical stability with torsion deformation below 9µm at 180° rotation, and constant focus over a wide temperature range. Short time-scale tasks, such as the rapid expansion of a nova or supernova shell, can be detected simultaneously in the spectral lines of different elements.

Capturing a stellar spectrum with the BACHES echelle spectrograph is much easier as compared to a conventional grating spectrograph. Light coming from the RCU's Thorium-Argon reference lamp and halogen flatfield lamp are easily introduced into BACHES via a fiber optic cable. BACHES is designed for fully remote control.

You probably have experience with the calibration of stellar spectra obtained from a conventional grating spectrograph. Echelle spectra are calibrated in the same manner in single sections, called "orders". The special feature of the presented MIDAS scripts is that a specified number of calibrated orders can be merged semi-automatically to a complete and fully calibrated spectral profile. This is achieved by simply marking two selected pairs of spectral lines.

Carlos Guirao, one of the designers of the BACHES Echelle spectrograph and author of the BACHES-MIDAS scripts, has written an informative video tutorial for calibration of BACHES echelle spectra. We recommend viewing this video first, and then entering the calibration process.

http://www.baader-planetarium.de/baches/kalibrierung/BACHES Tutorial Carlos Guirao geschnitten/baches_midas_data_reduction.htm

The following calibration steps are performed on solar spectra (daylight spectra) obtained simply "on the desktop" without a telescope. They serve to familiarize you with BACHES, its spectra and the calibration process. Right from the beginning, you should ensure that the spectra are recorded in a proper orientation with regard of the camera. Care has been taken to align the CCD camera exactly parallel to the spectral orders. This can be done with the aid of the flatfield spectrum of the halogen lamp. Otherwise, the MIDAS scripts cannot analyze the spectra. The ThAr spectrum can be used for precise focusing.

The spectra used below were obtained with MaxIm DL[1] software and saved as 16-bit monochrome Fits images. A dark frame ("Auto Dark") was subtracted from each light frame. The flatfield images obtained with the RCU will be used during the calibration process. Note: These ASCII format BACHES scripts must be adapted to the observational requirements (more about this later on in this guide). Important: make a backup of these scripts before changing them. Fig. 20 provides information on the location of the scripts. Also, understanding the course of calibration is helped by having a printout of the scripts always at hand.

[1] www.cyanogen.com

2 How to Cature a BACHES Echelle Spectrum

2.1 Capturing Daylight and Calibration Spectra

Becoming acquainted with BACHES and capturing the first solar spectra should happen in daylight, but without using a telescope. Place all parts on a desktop (Fig. 1). Then connect the camera to BACHES, and the motor control cable and fiber optic cable to BACHES and RCU. Insertions of the reference light source are carried out manually at the RCU. Now connect the camera to your computer and open your favorite capturing software, like MaxIm DL.

BACHES has been optimized for a sensor with a pixel size of 9µm square. Very well suited is a camera with the highly efficient KAF-1603ME sensor, as used in SBIG ST-1603ME or STT-1603ME[2].

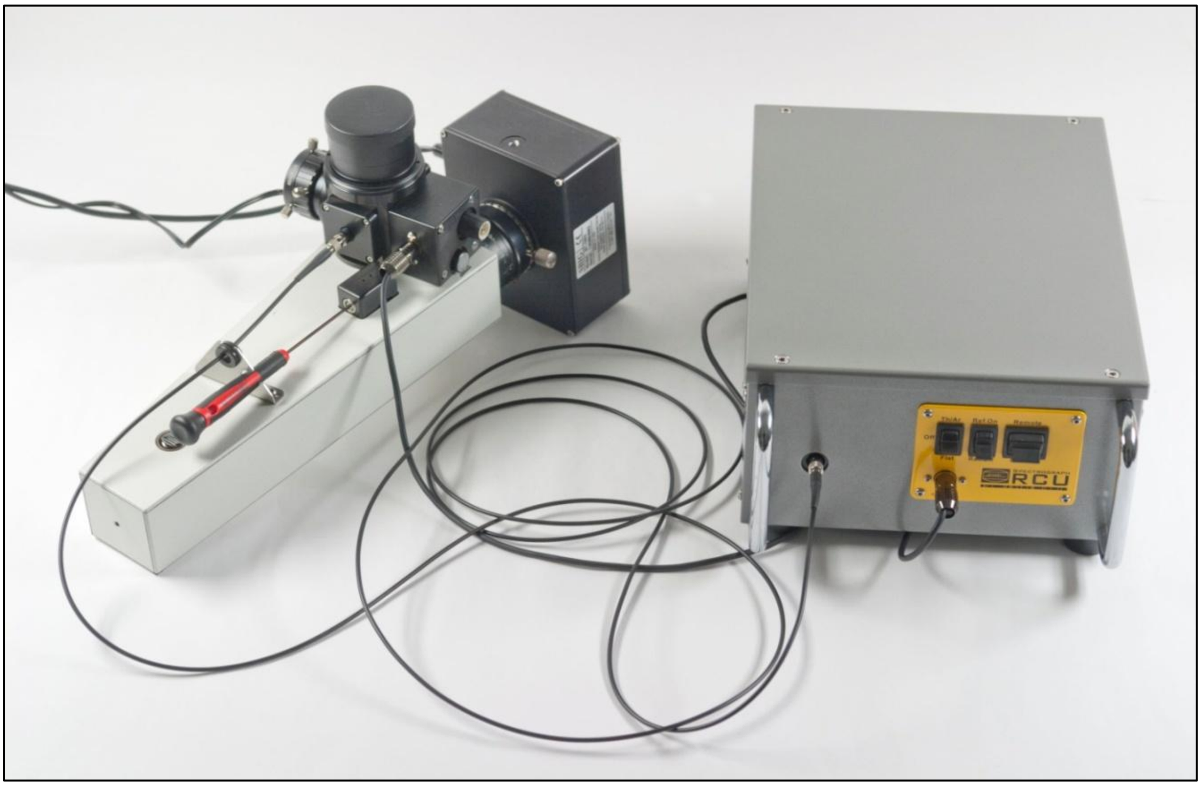

Fig. 1: SBIG ST-1603ME CCD camera attached to BACHES, and Remote Calibration Unit RCU

Imaging CCD	Kodak KAF-1603ME
Imaging/Pixel Array	1530 x 1020 pixels
CCD Size	13.8 x 9.2 mm
Total Pixels	1.56 million
Pixel Size	9 x 9 microns
Full Well Capacity	~100,000 e-
Dark Current e/p/s at 0 C	1e-/pixel/sec at 0 deg.
Antiblooming	NABG Only
Peak QE	>80%

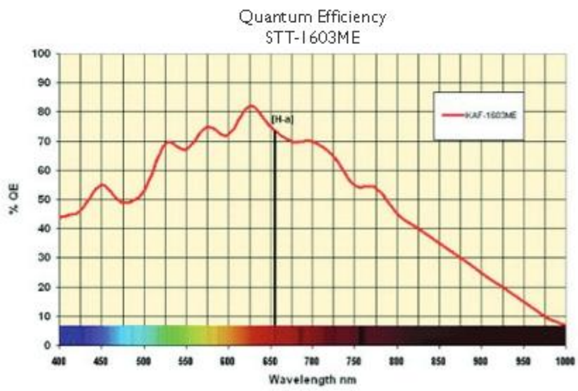

Fig. 2: Technical data and quantum efficiency of the KAF-1603ME

[2] https://www.sbig.com/products/cameras/st-compact/st-1603me/

2.2 How to Align the Camera to the BACHES Echelle Spectrograph

To achieve a precise calibration in MIDAS[3], the CCD camera, in this example the SBIG ST-1603ME, must be aligned with BACHES in a specific way. The "camera-bottom" with photo tripod mount must be pointing upwards, as shown in Fig. 1. All spectra should be calibrated with an (averaged) Dark Frame, using the "Auto Dark" option, for instance. In continuous operation mode at 1s intervals, the brighter lines will be easily visible.

The fine alignment of the spectrum on the sensor is done in two steps:

1. Rotate the camera by means of the BAADER T2 Quick Change System in the exact horizontal position. Using a cross-hair is advisable. The spectral orders are inclined to each other only very slightly (Fig. 3).

2. The selected spectral section in accordance with Fig. 3 can be set using the adjusting screws on BACHES. With the ST-1603ME camera, up to 25 orders can be displayed and later detectd by MIDAS. To achieve this, you need to move the spectrum to exactly match the position shown in Fig. 3. You can find instructions for setting the spectrum in the BACHES Manual on page 24 (Fig. 4). Familiarize yourself with the marked spectral line group in the second and the third line from the bottom, which is later used for calibration.

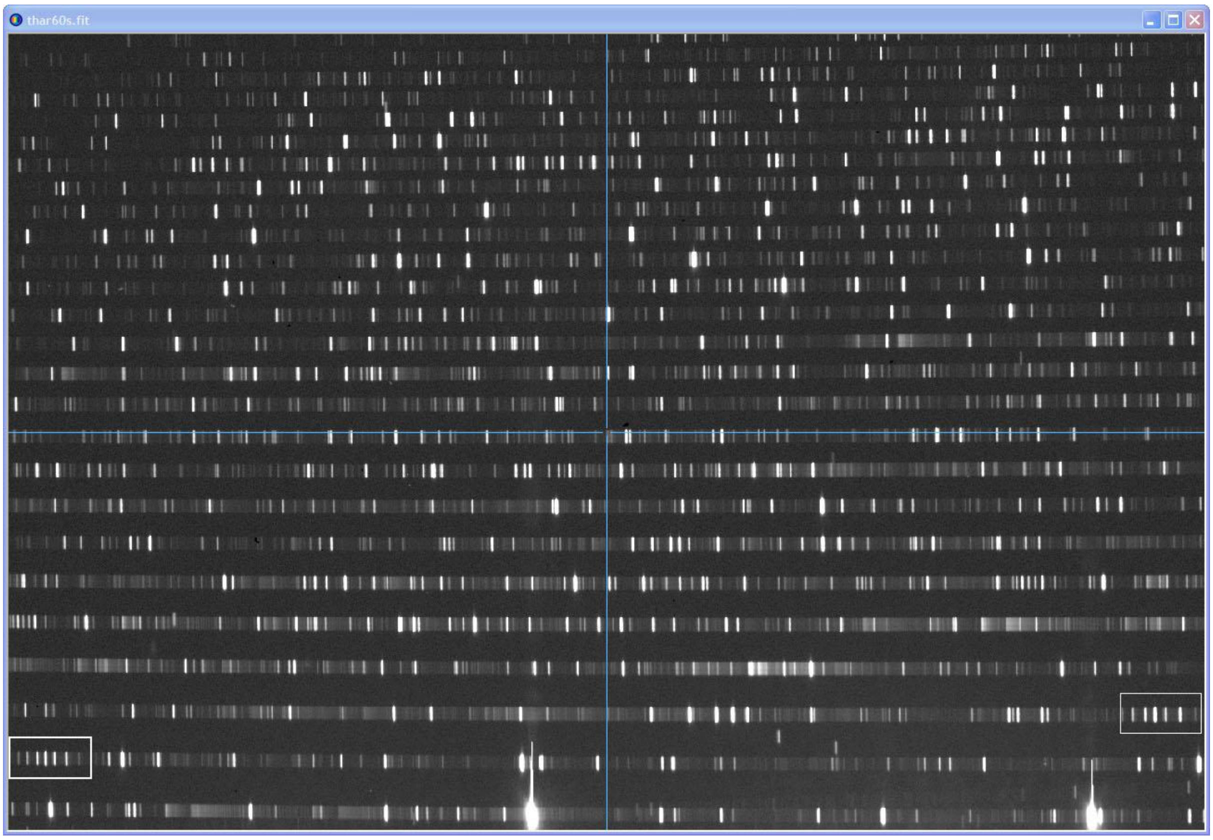

Fig. 3: 25 orders fit into the field of the KAF-1603ME sensor. The ThAr spectrum exposure was 60s. Top left: Ultraviolet, ca. 392nm. Bottom right: Infrared, ca. 710nm

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[3] https://www.eso.org/sci/software/esomidas/

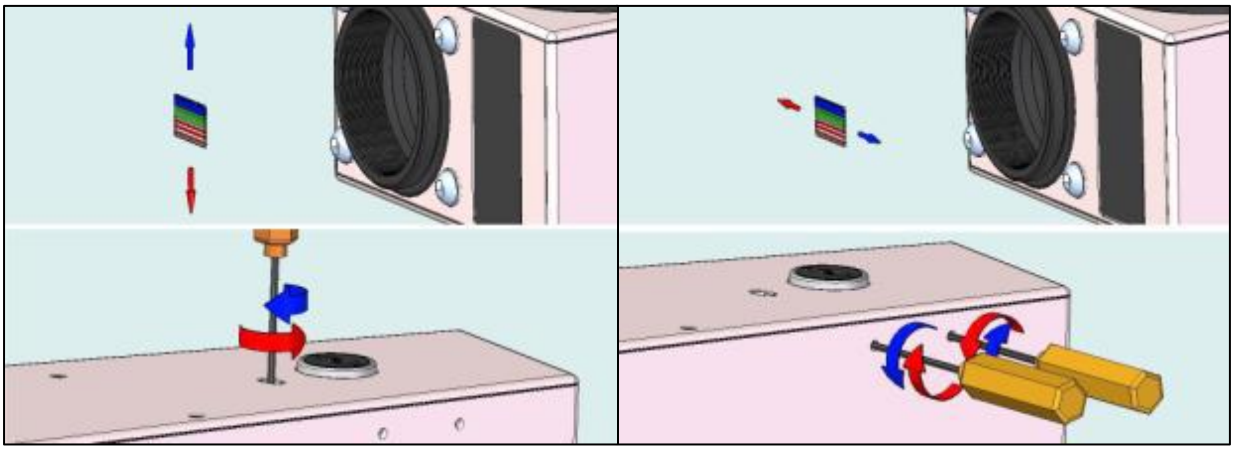


Fig. 4: Vertical and lateral displacement of the spectrum

2.3 Spectrum focusing

Careful focusing is mandatory for a high spectral resolution. If you are looking for the highest possible resolution at a selected spectral line, for example Hα, you should focus on a ThAr line located nearby. On the other hand, a very high average resolution across the entire range is achieved by focusing on a line in the green spectral range, as chosen in Fig. 5.

To focus the spectral line, the small window will be read out in continuous mode every second (Fig. 6).

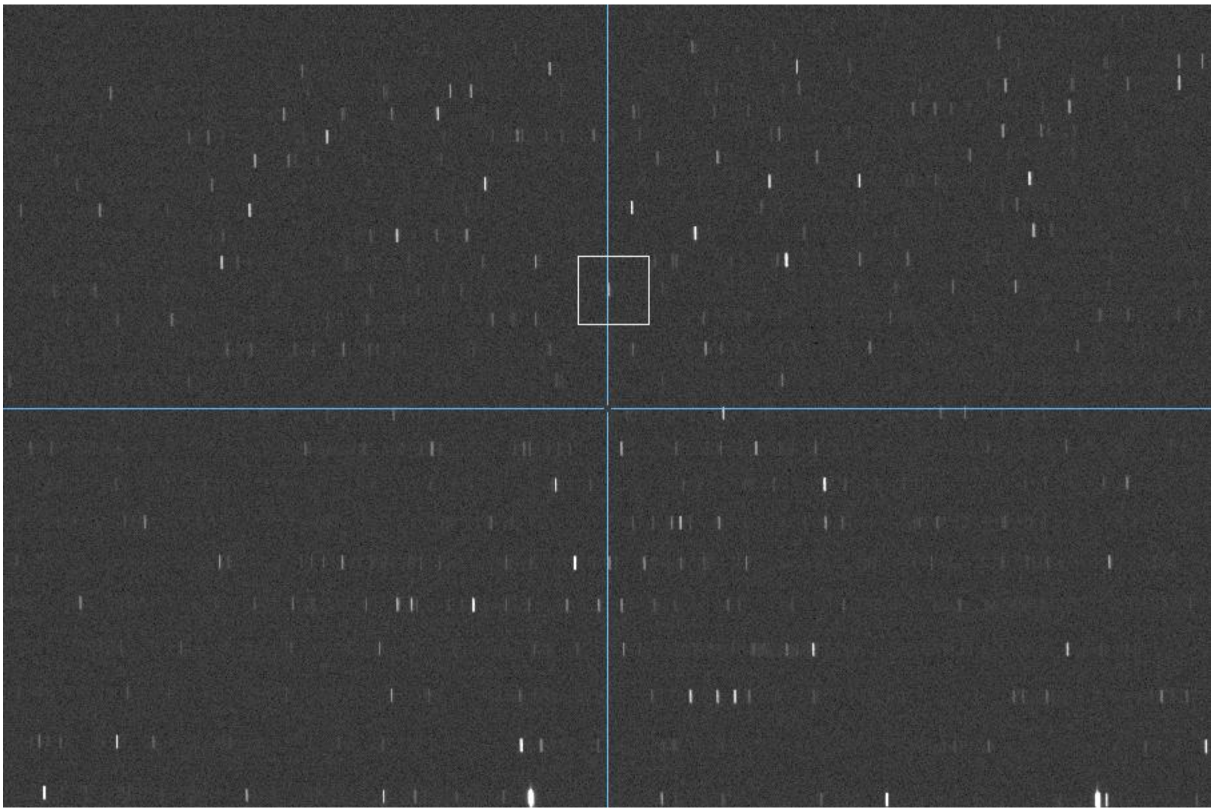


Fig. 5: Focusing on a green spectral line of the ThAr spectrum ensures a high spectral resolution across the field

MaxIm DL enables a horizontal intensity scan across the spectral line while focusing. A sharp line yields the highest peak intensity. This will be accomplished, when the line is 3 pixels wide with a 9 micron camera (Fig. 6, right).

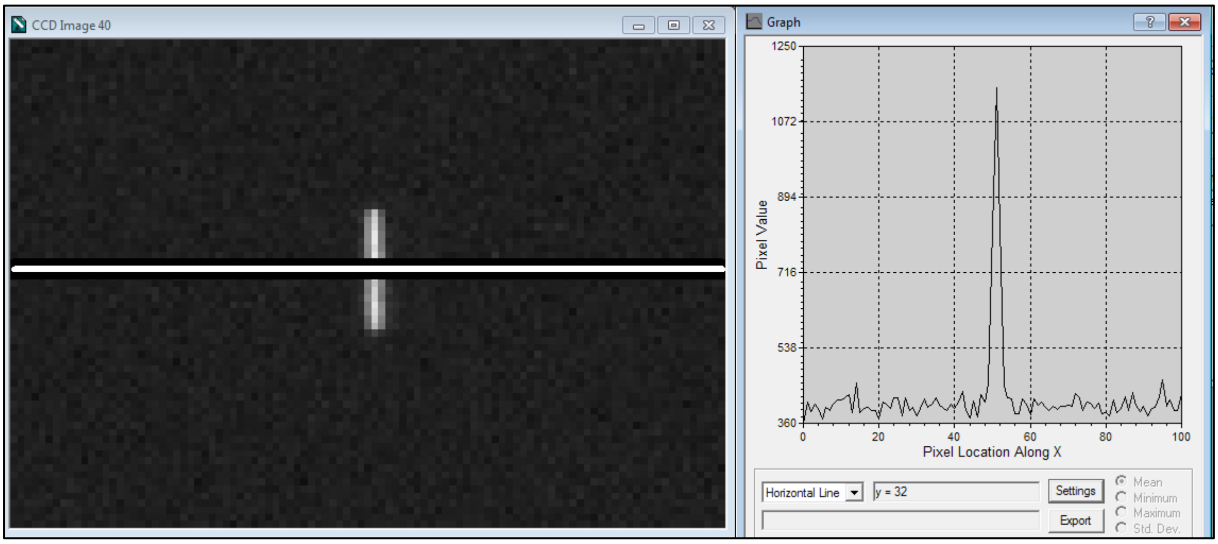


Fig. 6: Maximum peak intensity of a spectral line at about FWHM = 3 pixel

Focusing will be accomplished with an Allen key© (Fig. 7).

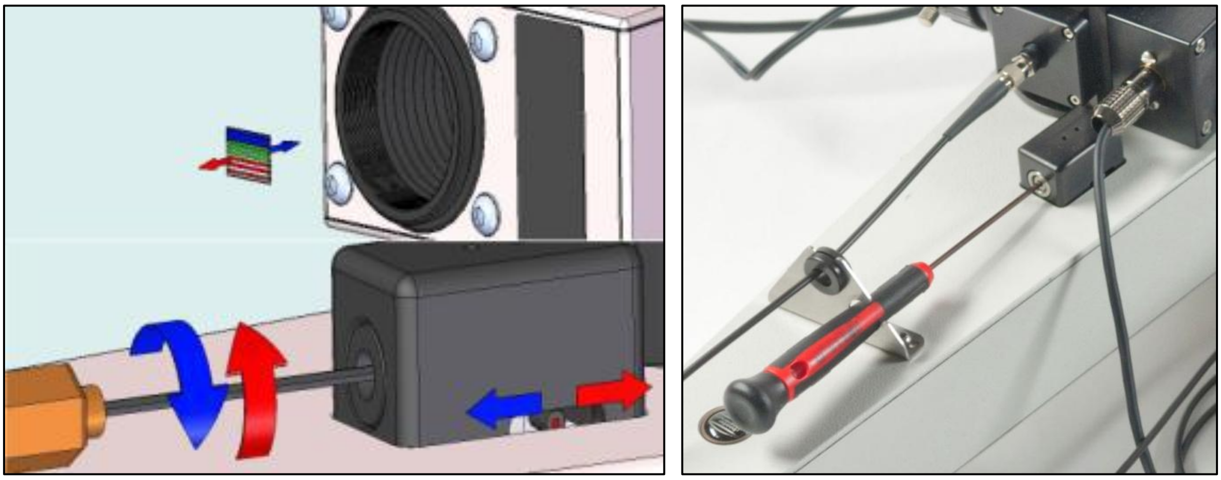


Fig. 7: Focusing the spectrum.

2.4 Taking Daylight and Calibration Spectra without a Telescope

1. Place BACHES with attached camera on a solid table close to a window with a view of the daytime sky.
2. Do not move the BACHES once positionede.
3. Launch the camera software and cool down the sensor.
4. Cover BACHES ports with black caps.
5. Switch on the ThAr lamp.
6. In continuous mode align the ThAr spectrum (Fig. 3).
7. In continuous mode focus the ThAr spectrum (Fig. 6).
8. Take an image of the ThAr spectrum with an exposure time below the saturation level of the spectral lines, except the very bright infrared lines, which are allowed to be saturated and blooming. ST-1603ME: Exposure time about 60s. Subtract an averaged dark frame or enable “Auto Dark” .
9. Switch off the ThAr lamp.
10. Switch on the halogen flatfield lamp.
11. Take an image of the halogen flatfield spectrum with an exposure time well below the saturation level. Watch intensity in a vertical scan (Fig. 10). ST-1603ME: 150s, with dark frames.
12. Switch off the halogen lamp.
13. Remove the black cap from BACHES input.
14. Take a daylight spectrum. Try different exposure times, depending on the sky brightness. Keep exposure time below the saturation level of the spectral lines, don’t forget the darkframes.
15. Check if the spectrum is well focused from the UV to the IR.
16. If not, return to item 7.
17. Check all spectra again, and then copy these FITS images to the folder “Shared” for calibration with ESO-MIDAS.

Exercise files for calibration with ESO-MIDAS. Darkframes have been subtracted.
Camera: SBIG ST-1603ME

ff150s.fit: Flatfield, 150s exposure.
thar60s.fit: ThAr reference spectrum, 60s exposure.
sun240s.fit: Daylight spectrum, 240s exposure.
Slit width: 25µm

2.5 Orientation of BACHES Echelle Spectrograph to the Telescope

There is no compelling reason to set the echelle spectrograph in a particular orientation to the telescope. In case of a well polar aligned equatorial telescope mount, it is advisable, however, to align the slit with the Right Ascension or Declination axes. Because many mounts suffer from severe play in DEC, making it difficult to precisely track a star across the slit using the DEC controls, we suggest orienting the slit parallel to the DEC axis and using RA for guiding across the slit. The second reason to align the slit in this way is that BACHES could touch the pillar, when shooting at the zenith for example. Have a look at Figure 8: The CCD camera, in this example the SBIG ST-8300M, is oriented in a way that the tip of BACHES points toward the ground while the telescope points south.

Note on the camera: The BACHES echelle spectrograph has been optimized for a CCD pixel size of 9µm, like that of the KAF-1603 sensor. The SBIG ST-8300M in this example oversamples with an actual 5.4µm pixel size. In 2x2 binning mode, the 10.8µm pixel size result in a somewhat lower spectral resolution, although fainter stars are within reach. Depending on the scientific application, one must choose a suitable camera binning. For the measurement of stellar flux only – the key figure is the Equivalent Width EW[4] - a 2x2 camera binning with 10.8µm pixel size is sufficient. For measuring Doppler shifts precisely, one may choose 1x1 binning, however, only for brighter stars.

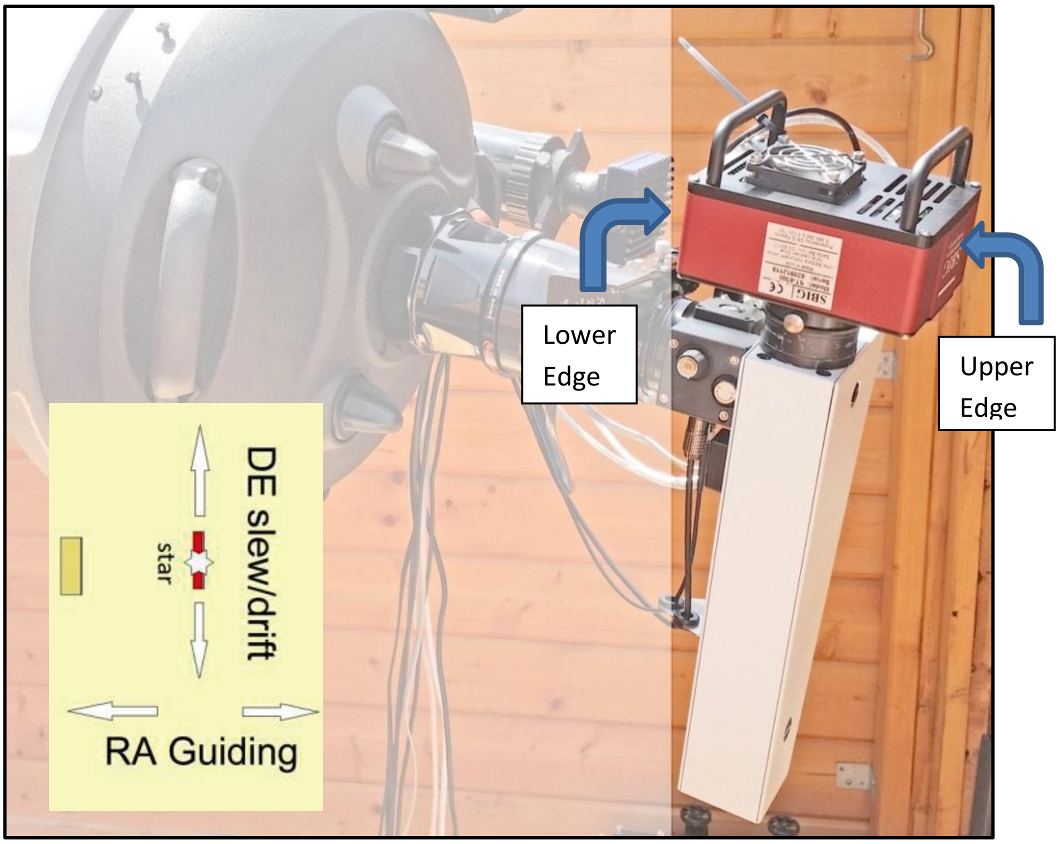


Fig. 8: The body of the BACHES echelle spectrograph is attached to the C14 Edge HD in north/south direction. The lower edge of the ST-8300M faces to the telescope.

[4] The „Equivalent Width“ (EW) is a measure for the stellar flux of an absorption or emission line.

2.6 The Flatfield Spectrum of the Halogen Lamp

The flatfield spectrum (**ff150s.fit**) recorded with the halogen lamp provides two features. First, it corrects for dust. Second, it is required for a semi-automatic wavelength calibration with MIDAS. MIDAS detects the position of the orders by the Flatfield spectrum and transfers the local information to the ThAr reference spectrum, and then to the object spectrum (Fig. 9, 10).

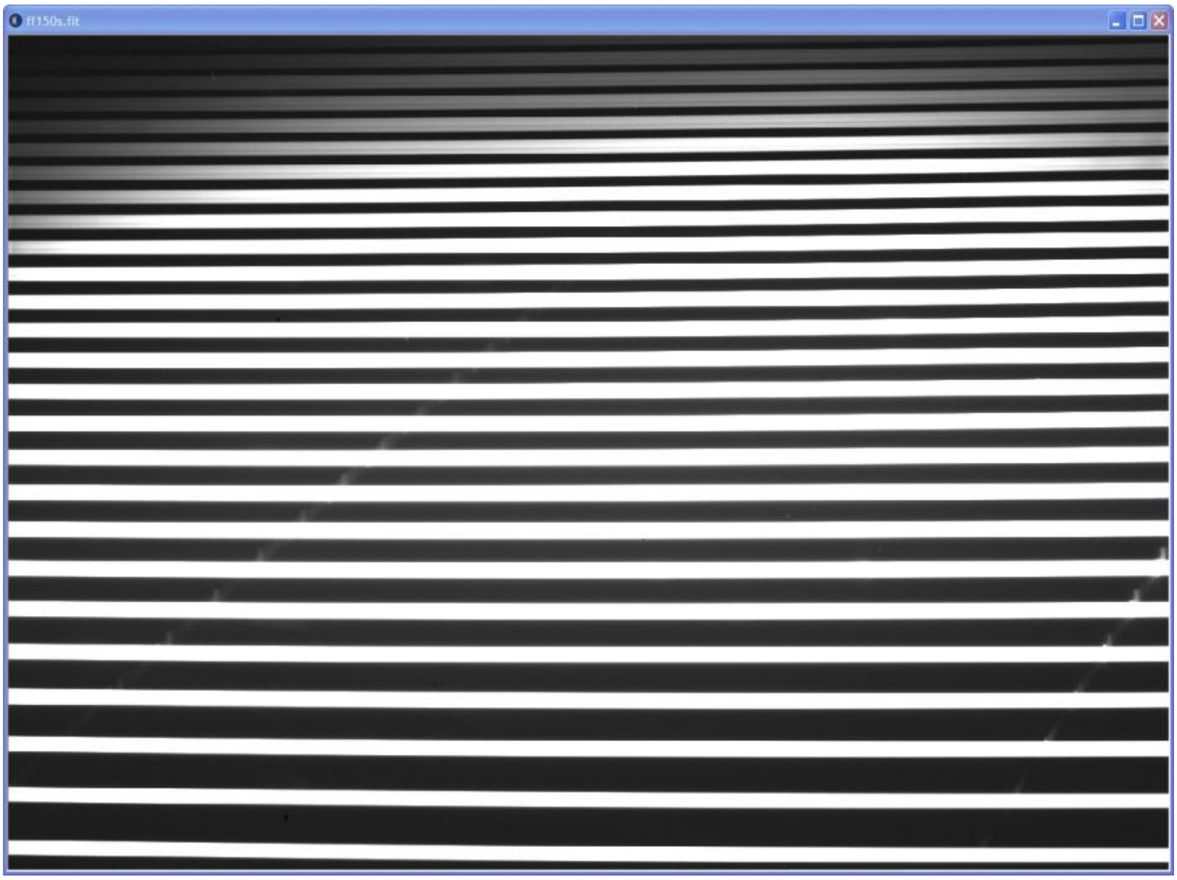


Fig. 9: Contrast enhanced flatfield spectrum: The 25 orders must be aligned in the field of the KAF-1603-Sensor exactly in this way to be detectd by MIDAS.

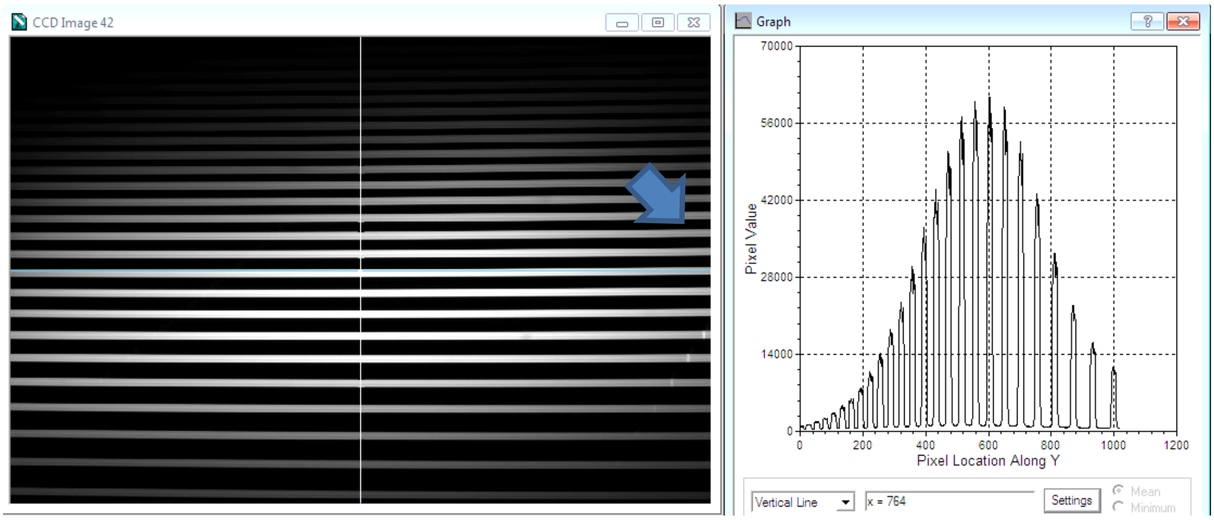


Fig. 10: Flatfield spectrum obtained with the RCU halogen lamp, 150s exposure with a SBIG ST-1603ME. Vertical scan across the spectrum. The maximum intensity is well below the saturation limit of 65535 ADU. 25 orders are recorded, as well as a dust spot (circle). The blue arrow points to reflections within the spectrograph.

2.7 The Reference Spectrum of the ThAr Lamp

The alignment of the spectra in a precisely defined way is important during the calibration process with MIDAS. Otherwise MIDAS is not able to detect all orders. This can be accomplished with the well-documented ThAr spectrum[5], as demonstrated in this 60s exposure (**thar60s.fit**) obtained with the ST-1603ME (Fig. 9). It should be aligned from top left (blue) to bottom right (red) in this way. Based on the characteristic bright lines in the red/infrared (below) it is easily possible to find the correct orientation of the CCD camera (Fig. 11).

Sensors without an anti-blooming gate clearly show blooming of the bright lines in the near infrared. This can be avoided by shorter exposures, but with the loss of very faint ThAr lines and is not recommended. Test exposures with different exposure times showed that blooming of these two bright lines has no effect on the calibrated ThAr spectrum. However, if you notice some effect, please let us know and send us a sample spectrum.

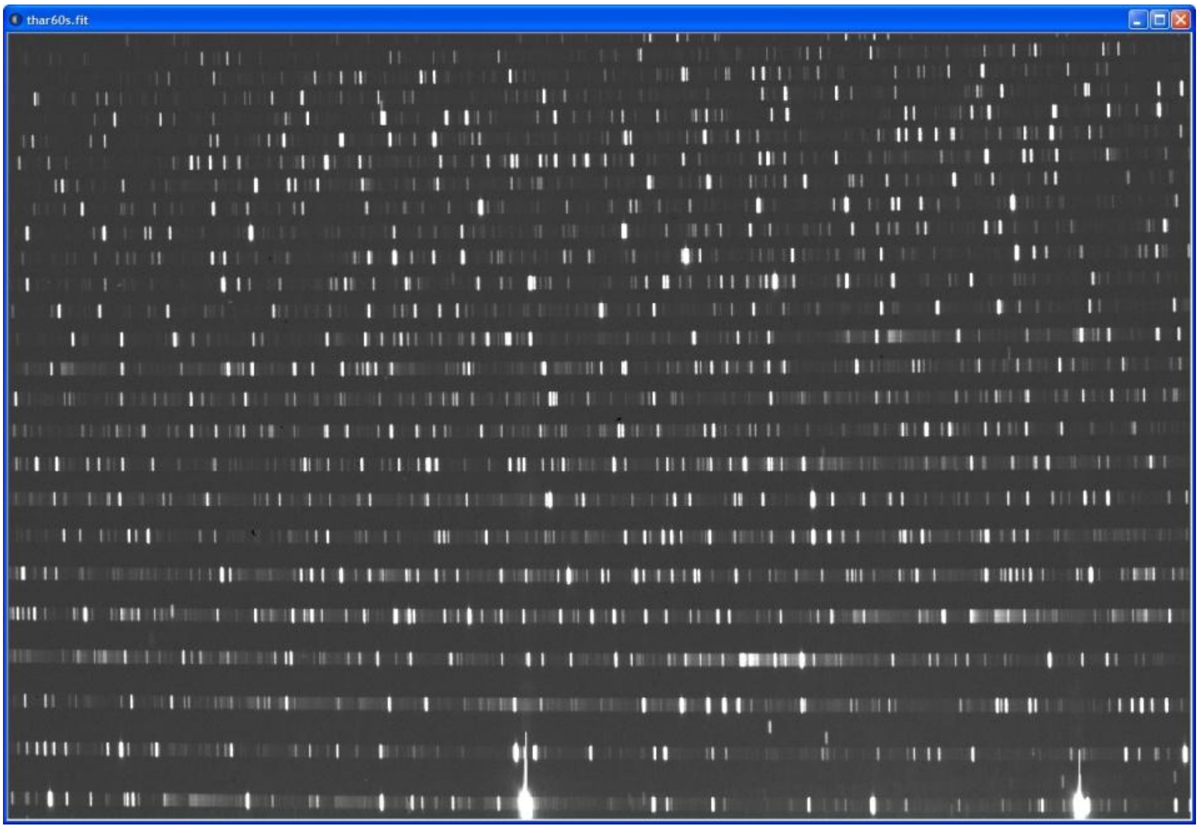


Fig. 11: : ThAr reference spectrum thar60s.fit, 60s exposed with a ST-1603ME. Spectrum from blue (upper left) to red (lower right). Blooming does not affect the calibration with ESO-MIDAS.

[5] http://spectroscopy.files.wordpress.com/2010/05/an_atlas_of_the_thorium-argon-spectrum-3900-9000.pdf

2.8 The Daylight Spectrum

The Sun, our nearest star, is the ideal object to learn the techniques of spectrum acquisition and calibration to be used in stellar spectroscopy. The Sun has a multi-line spectrum corresponding to a spectral class G2 V. The recording of the solar absorption spectrum can be done in the room without even using a telescope. Just point the spectrograph to a patch of the sky. It doesn't matter if the sky is clear or raining: The Earth's atmosphere scatters the sun light.

Fig. 12 shows a daylight spectrum (**sun240s.fit**) where the atmospheric water vapor and oxygen lines (Telluric Lines) are superimposed around and below the Hα order. Clearly visible are Hα, the Sodium doublet lines Na D1/D2, and the magnesium triplet. The typical G2 V spectrum starts in the UV upper left at the Ca II K line and ends up in the infrared at lower right at around 7100Å. The exposure time was chosen to limit the intensity in the green range of the spectrum to about 50,000 ADU to avoid saturation and to ensure a correct radiometric correction. Since all sensors are less sensitive in the UV, spectral lines may be weak in this spectral region. You should take this into consideration for the calculation of the total exposure of the spectrum which can be stacked from several partial exposures with different exposure times.

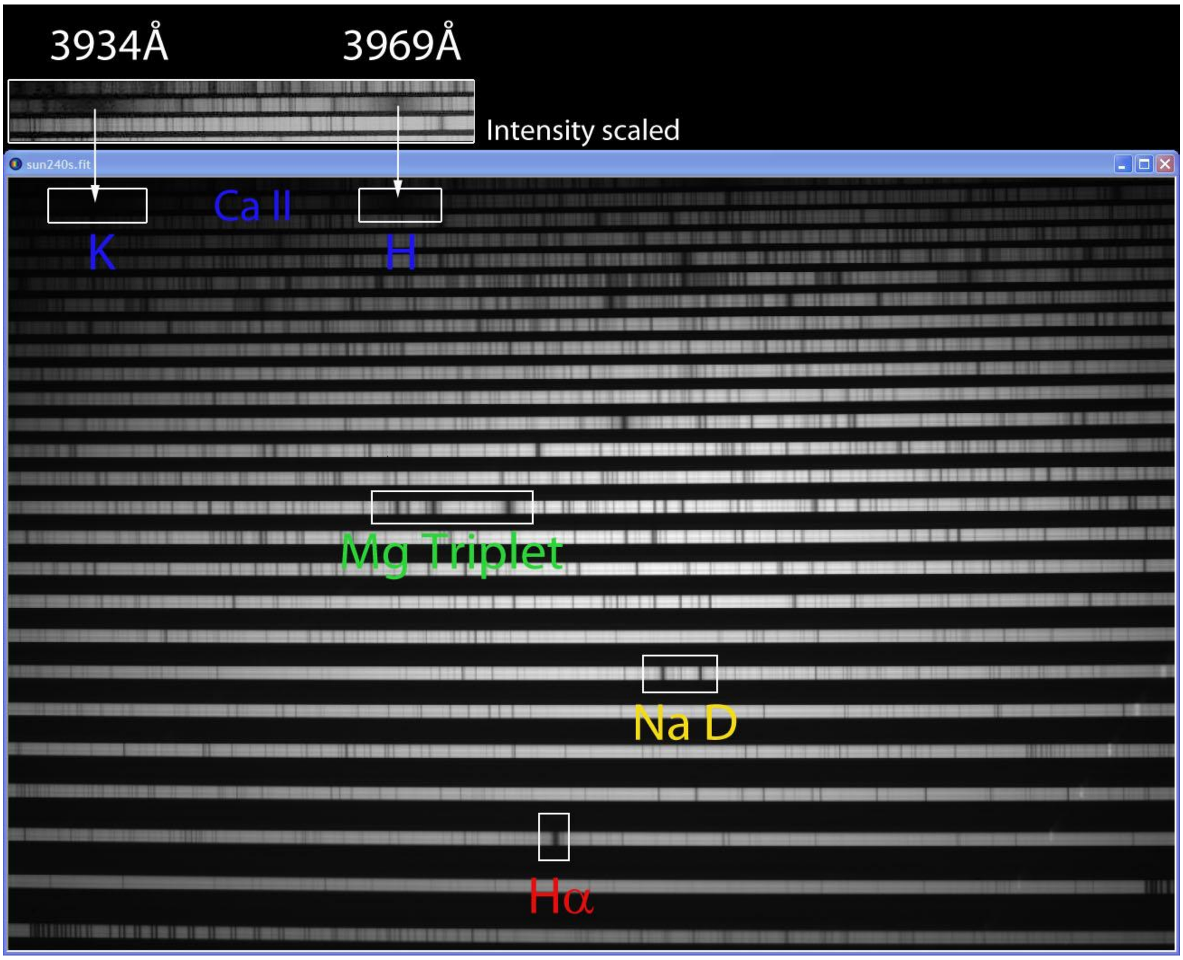


Fig. 12: Daylight spectrum (sun240s.fit), 240s exposed with a ST-1603ME CCD camera. Spectrum from blue (upper left) to red (lower right). The spectrum ranges from ca. 3925Å to ca. 7084Å; the important Ca II lines K and H are well recorded.

3 The LINUX Operating System in a Microsoft© Windows VirtualBox

The calibration of echelle spectra can be accomplished with the LINUX[6] based software ESO-MIDAS. Windows users are requested to install a VirtualBox, which runs on a Windows platform in a separate window. Data can be "shared" between the two systems by creating a common folder **`Shared`**

Start VirtualBox for Windows. If a login is requested, please enter:

User: user
Password: 1235813

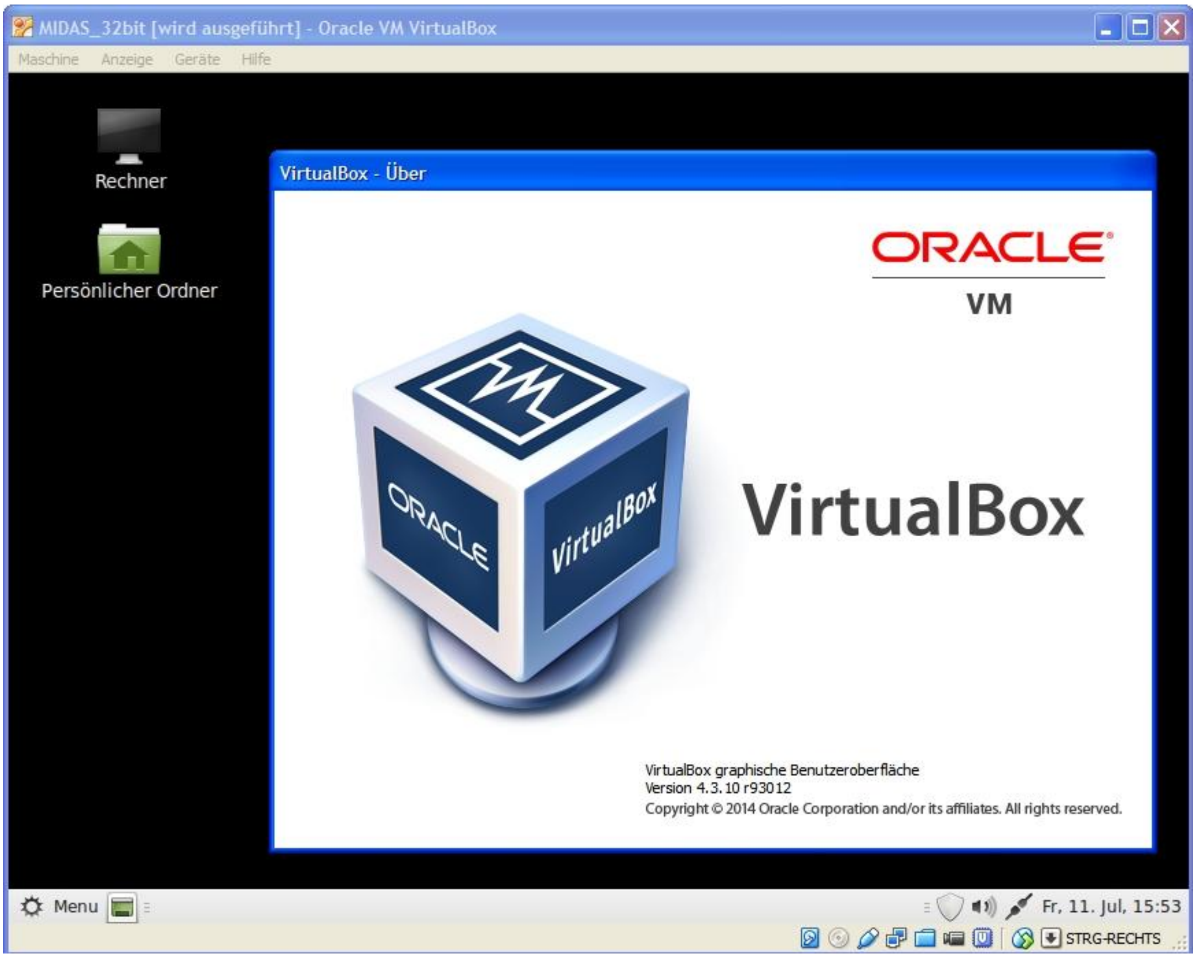
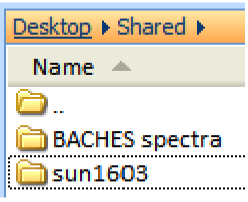


Fig. 13: Installation of a VirtualBox on Windows computers.

[6] http://ubuntuusers.de/

3.1 Sharing Files between LINUX and Microsoft© Windows

Exchange of files between both systems is accomplished by the common folder **`Shared`.**
It is mandatory to name this exchange folder exactly as "Shared".



Windows: Create a folder **Shared**. Copy the unzipped folder **sun1603** to this folder. The folder **sun1603** contains the files **sun240s.fit** (Daylight = solar spectrum, taken with the CCD Camera SBIG ST-1603ME, **thar60s.fit** (spectrum of the ThAr reference lamp), and **ff150s.fit** (spectrum of the halogen flatfield lamp). All three spectra were recorded in quick succession to minimize possible shifts in between.

Note: Some of the following LINUX screen shots are still in German, we apologize. They will be replaced with the corresponding English figures in the next english revision of this tutorial.

In LINUX, now create a path to the directory **Shared**:
"Gerate" -> "Gemeinsame Ordner" (common folder): "**Shared**"

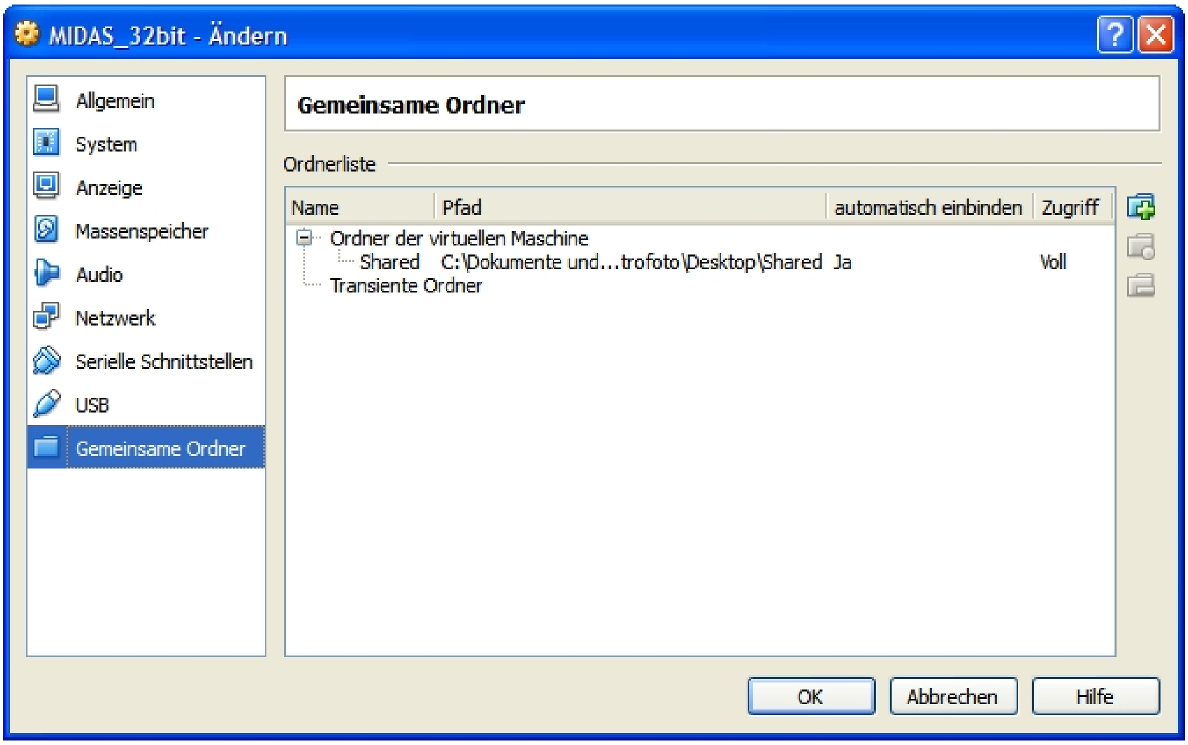


Fig. 14: Creating a path for the common folder "Shared".

In LINUX: Open “Persoenlicher Ordner“ -> “sf_Shared“. The directory **sun1603** is included.

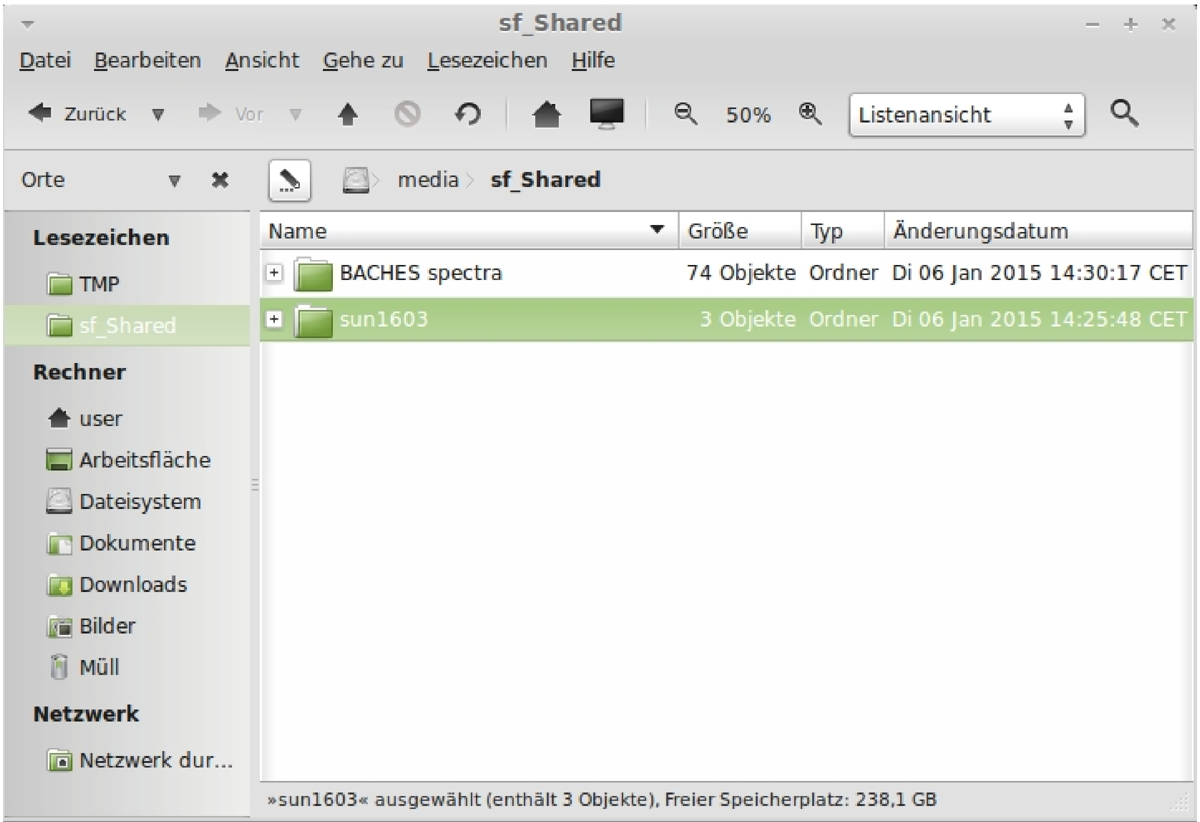


Fig. 15: Where the common folder "sf_shared" is located.

You can perform all operations in the **Shared** folder. Otherwise create the temporary folder **TMP** which can be used as working folder:

1. Copying the folder **sun1603**: “Copy“
2. Pasting to folder **TMP**: “Paste“

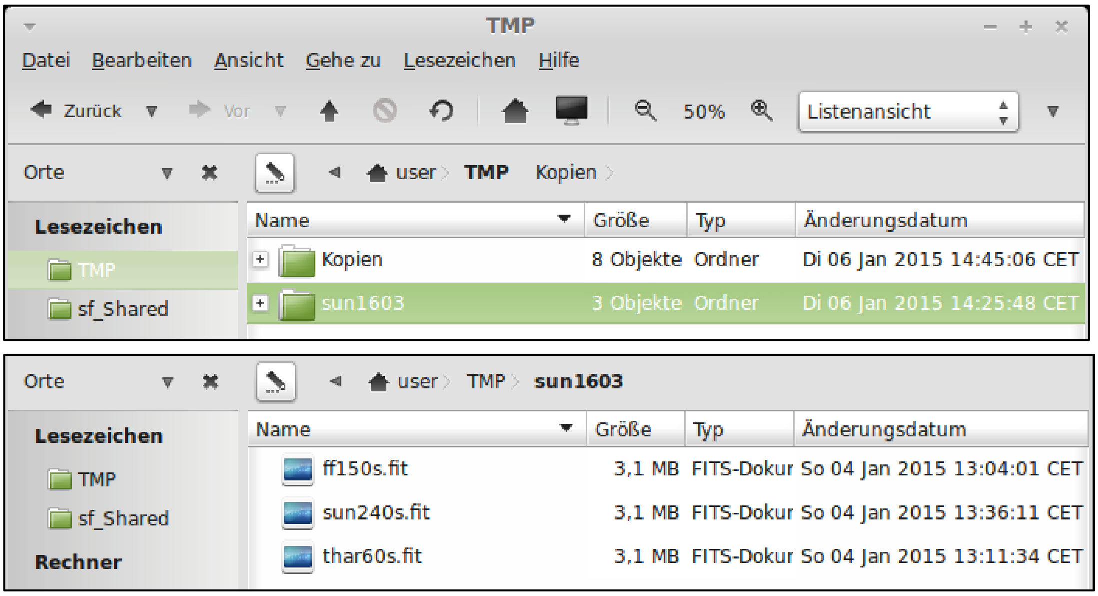


Fig. 16: The folder "sun1603" contains the daylight spectrum and two calibration files.

3.2 Verifying the Spectra

The folder **/TMP/sun1603** contains all spectra. Double-click on **thar60s.fit** will show the ThAr reference spectrum.

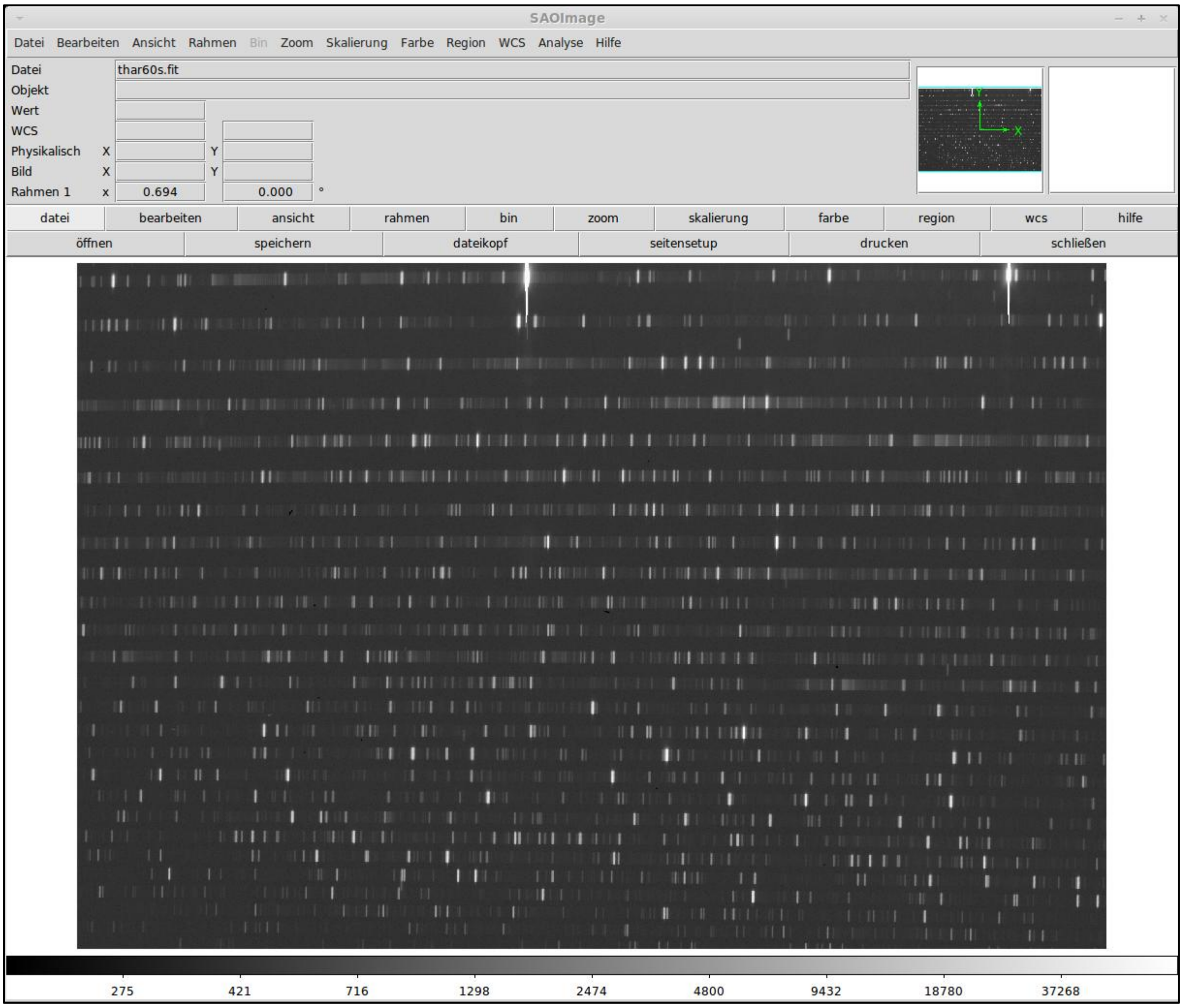


Fig. 17: The spectrum thar.fit appears mirrored vertically. This representation in SAOimage is absolutely correct!

Compare this with the view in Fig. 11. You will notice that the spectrum in Fig. 17 is vertically mirrored. **And that's absolutely correct. Only in this orientation is MIDAS able to detect the echelle orders and spectral lines!** Look at your spectrum: if the orientation of your ThAr spectrum is different, the spectrum has to be mirrored until it looks exactly this way.

The orientation of the spectra should be verified and changed if necessary in the right manner before copying to the folder **Shared.** If you forgot, you can do this later in MIDAS with the following command line. Omitting the "y" in the command line shown below yields in a horizontal mirroring (flip) only.

```
Midas > flip/image <spektrum.fit> y
```

4 Munich Image Data Analysis System (MIDAS)

4.1 Launching MIDAS

“Menu“ → “BACHES“ → “MIDAS“

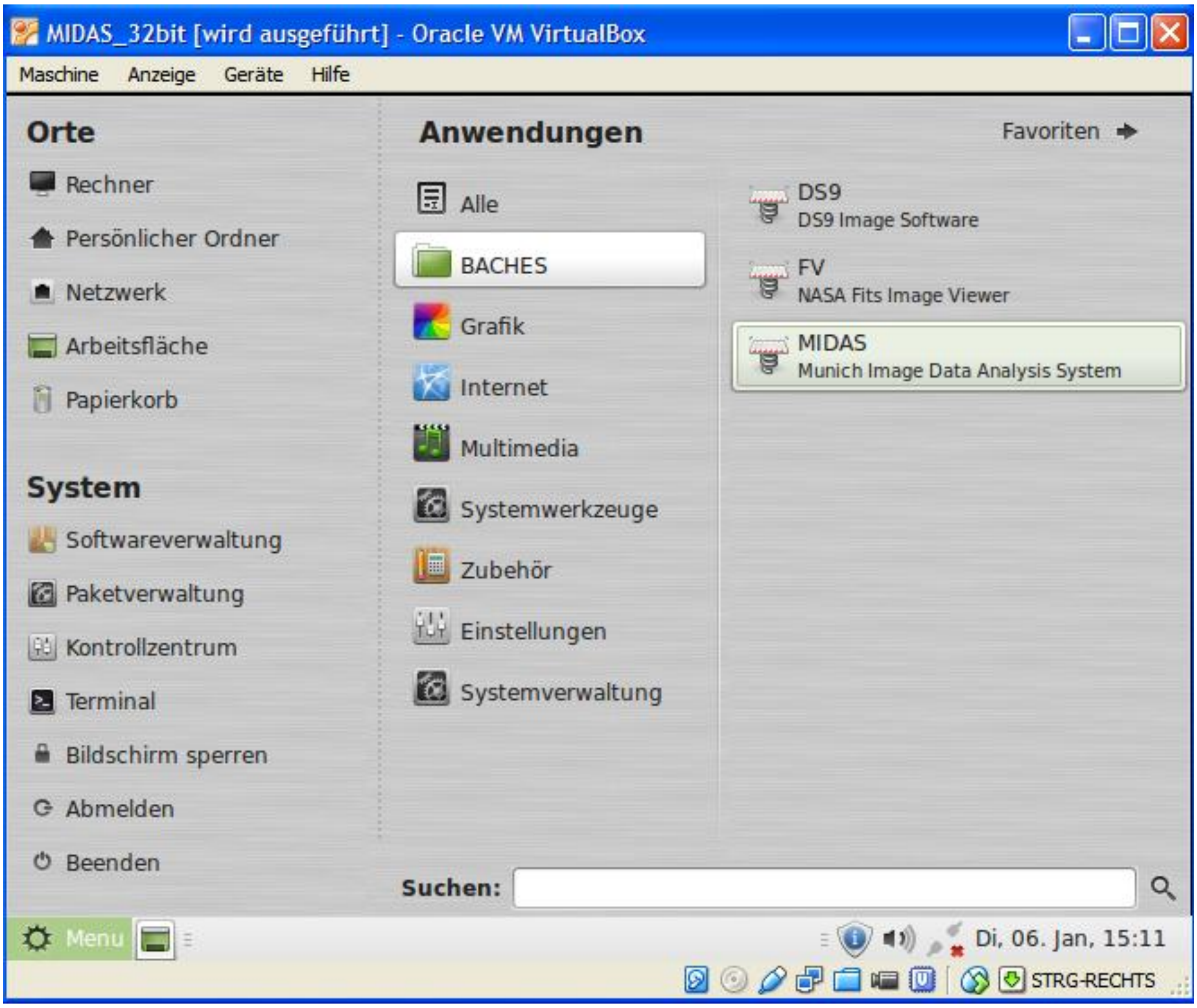


Fig. 18: LINUX Desktop: Launch of MIDAS

MIDAS starts in the terminal window (Fig. 19). MIDAS is a command line interpreter, and within the terminal window does not support the use of a mouse.

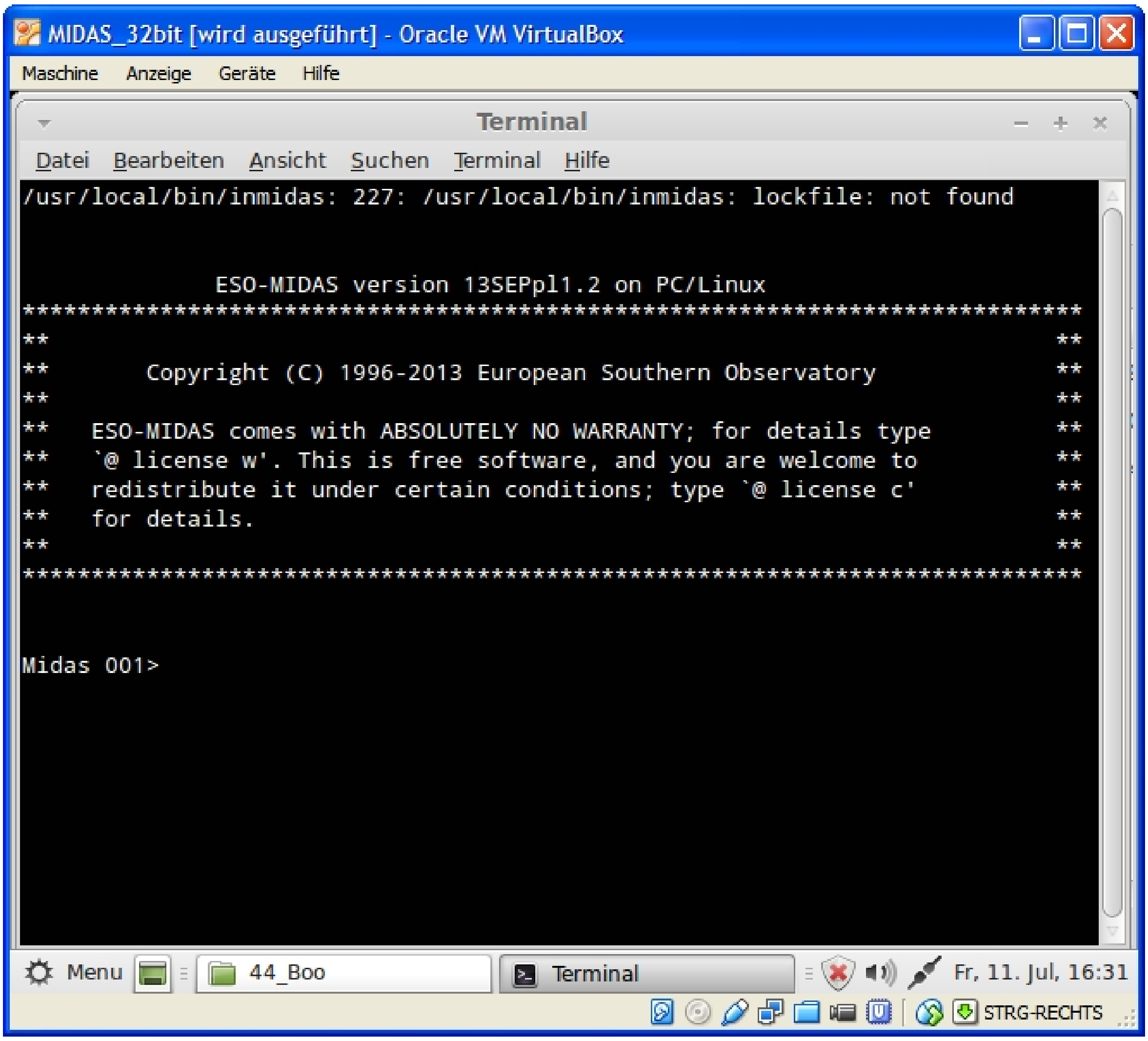


Fig. 19: This is the MIDAS terminal, where all commands must be manually entered and the results appear. It will not be saved automatically. Copy & Paste the contents frequently to a textfile for later inspection of the results.

The MIDAS commands are entered behind the prompt **`Midas 001>`**.

4.2 How to find the Folder “sun1603“ with the Spectra

`Midas > ch`

- ➔ Changes to the folder: **/home/user**

`Midas > ch TMP`

- ➔ Changes to the subfolder TMP: **/home/user/TMP**

`Midas > $ls`

- ➔ Creates a directory of the folder **TMP** -> **sun1603**

Midas > ch sun1603

➔ Changes to the folder: **/home/user/TMP/sun1603**

Midas > $ls

➔ Creates a directory of the folder **sun1603: ff150s.fit, sun240s.fit, thar60s.fit**

```
Midas 001> ch
current dir. now: /home/user
Midas 002> ch TMP
current dir. now: /home/user/TMP
Midas 003> $ls
Kopien  sun1603
Midas 004> ch sun1603
current dir. now: /home/user/TMP/sun1603
Midas 005> $ls
ff150s.fit  sun240s.fit  thar60s.fit
Midas 006> |
```

4.3 Loading the BACHES Scripts for Calibration

Midas > set/cont baches

Loads the BACHES Scripts (<name>.prg).

```
Midas 006> set/cont baches
******** TEMPLATE application package version 1.0 enabled **********
commands available:

CALIBRATE/BACHES executes baches_calib.prg
PIPELINE/BACHES executes baches_pipeline.prg
RESOLV/BACHES executes baches_resolving_power.prg
RECAL/BACHES executes baches_recalib.prg
CLEAN/BACHES executes baches_clean.prg
COMPUTE/BACHES executes baches_compute_fits.prg
FILE/BACHES executes baches_file_ext.prg
Midas 007> |
```

Important note: These scripts can be edited by the user. A few commands must be customized in regard of the camera or sensor used. Please save a security backup prior to changing the scripts. Fig. 20 reveals the path to the location of the scripts. Helpful in understanding the course of the calibration is to have a print-out always at hand. To edit the scripts, administrator rights are required.

4.4 Editing the BACHES Scripts

BACHES scripts are located in the folder **proc**, the path is **Dateisystem → usr → local → midas → 13SEPpl1.2 → contrib → baches.**

It is useful to copy the path to the folder **proc** in the left column below **Lesezeichen**.

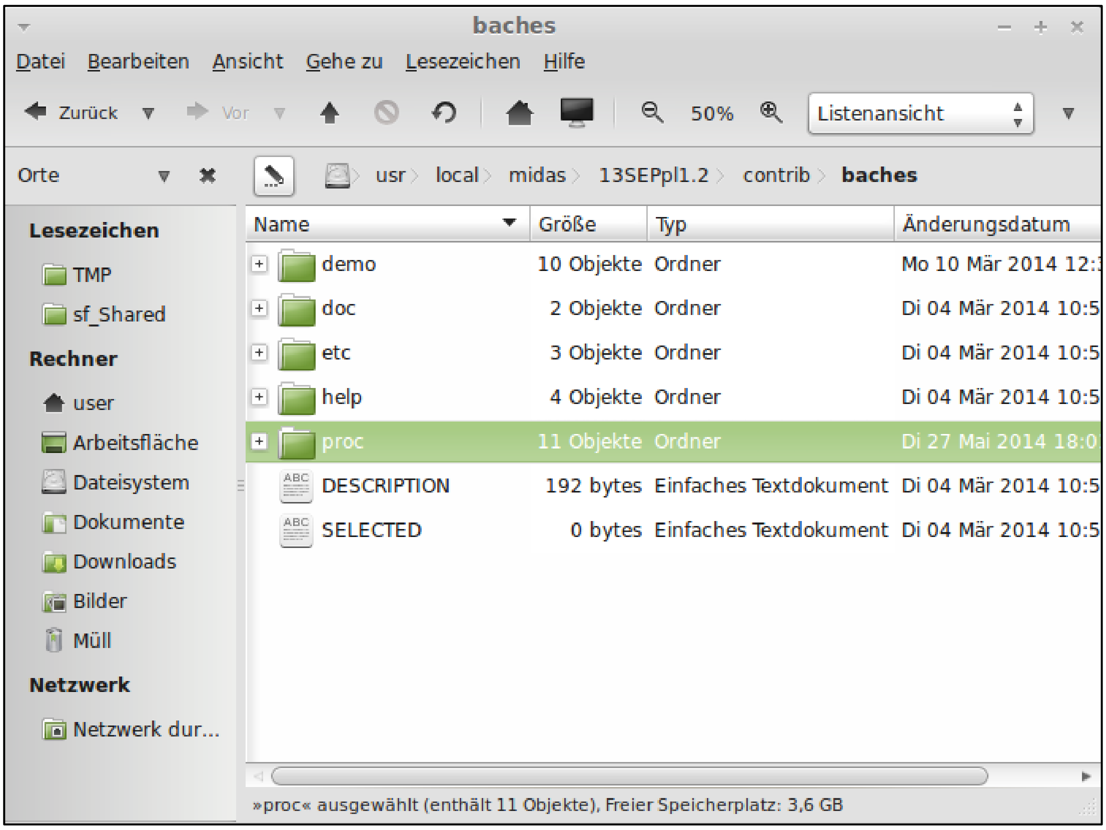


Fig. 20: Location of the BACHES scripts. The scripts can be edited. Safety rule: Don't forget to save a copy of the original file prior to editing. German file names will be changed to English in the next revision.

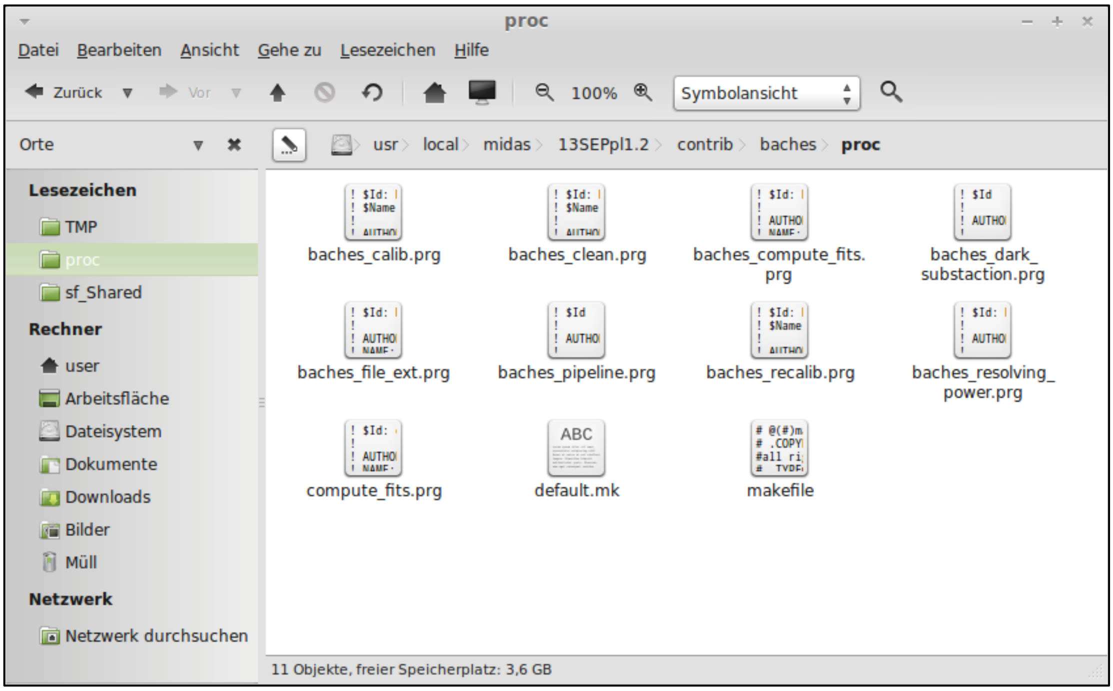


Fig. 21: These are the scripts which will be used by MIDAS to calibrate the BACHES spectra.

4.5 Customizing the Script “baches_calib.prg“ for the CCD Camera

1. Select “baches_calib.prg“
2. → “Öffne als Administrator“
3. Enter the Password: 1235813

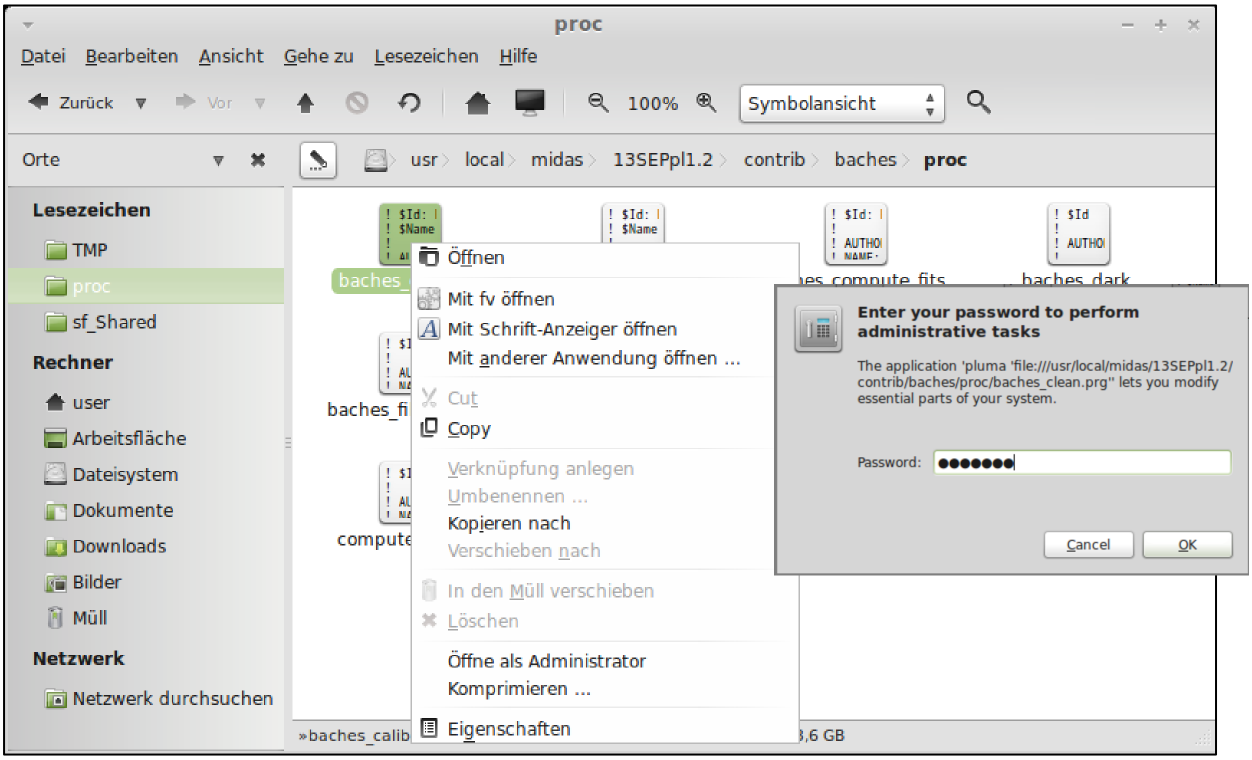


Fig. 22: You need administrator rights to edit and save a BACHES script. The Password is: 1235813

Important note: Save a copy of the original script under a different name prior to editing.

This is the editor window (Fig. 23), where scripts can be changed and commented.

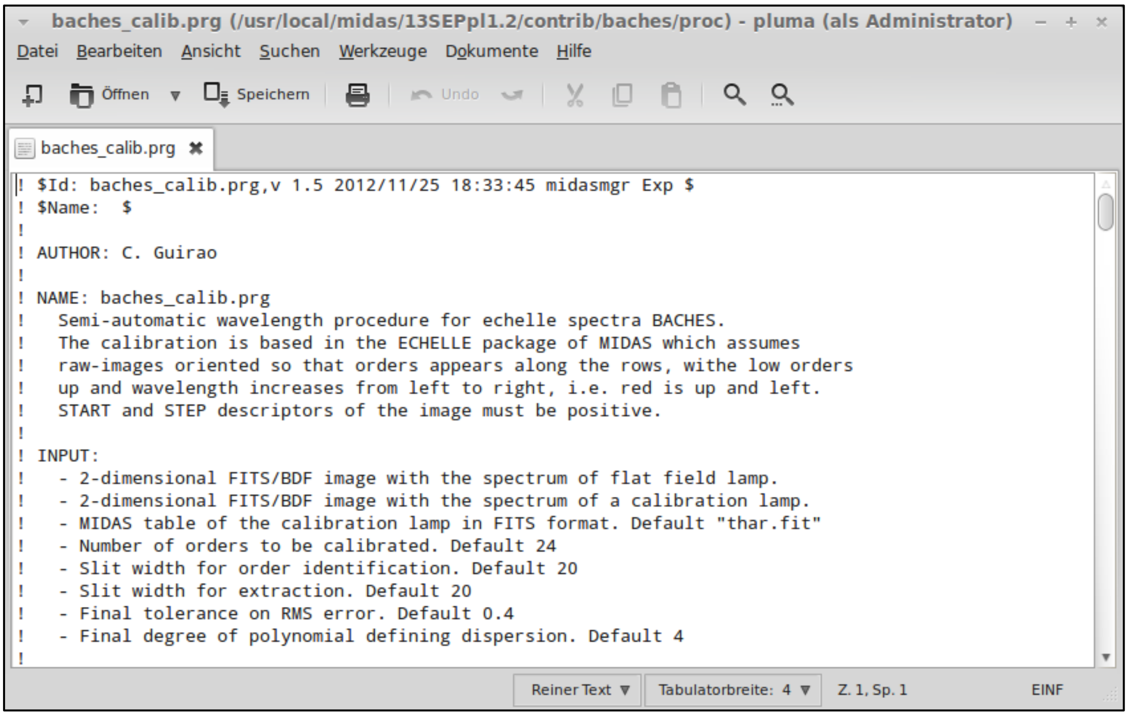


Fig. 23: Editing the script ”baches_calib.prg”

4.5.1 Edit “threshold“ (Line 84)

With BACHES, so far we have experience with only two typical sensors used in astrophotography. For every sensor the correct “threshold“ must be set. The threshold affects the detection of reference lines in the ThAr reference spectrum. If too few reference lines are used in the calibration process (less than 50% of all lines detected), the threshold value must be lowered. If more than 60% are used, nothing must be changed.

Edit line 84 as following:

For ST-1603ME (KAF-1603ME) use: DEFINE/LOCA threshold/i/1/1 10

For ST-8300M (KAF-8300) use: DEFINE/LOCA threshold/i/1/1 2

If you encounter problems in calibration, you may change these and/or other parameters and start again. Frequently use comment lines, beginning with an "!", which keep record of your edited program lines.

Do not forget to save backup copies before editing!

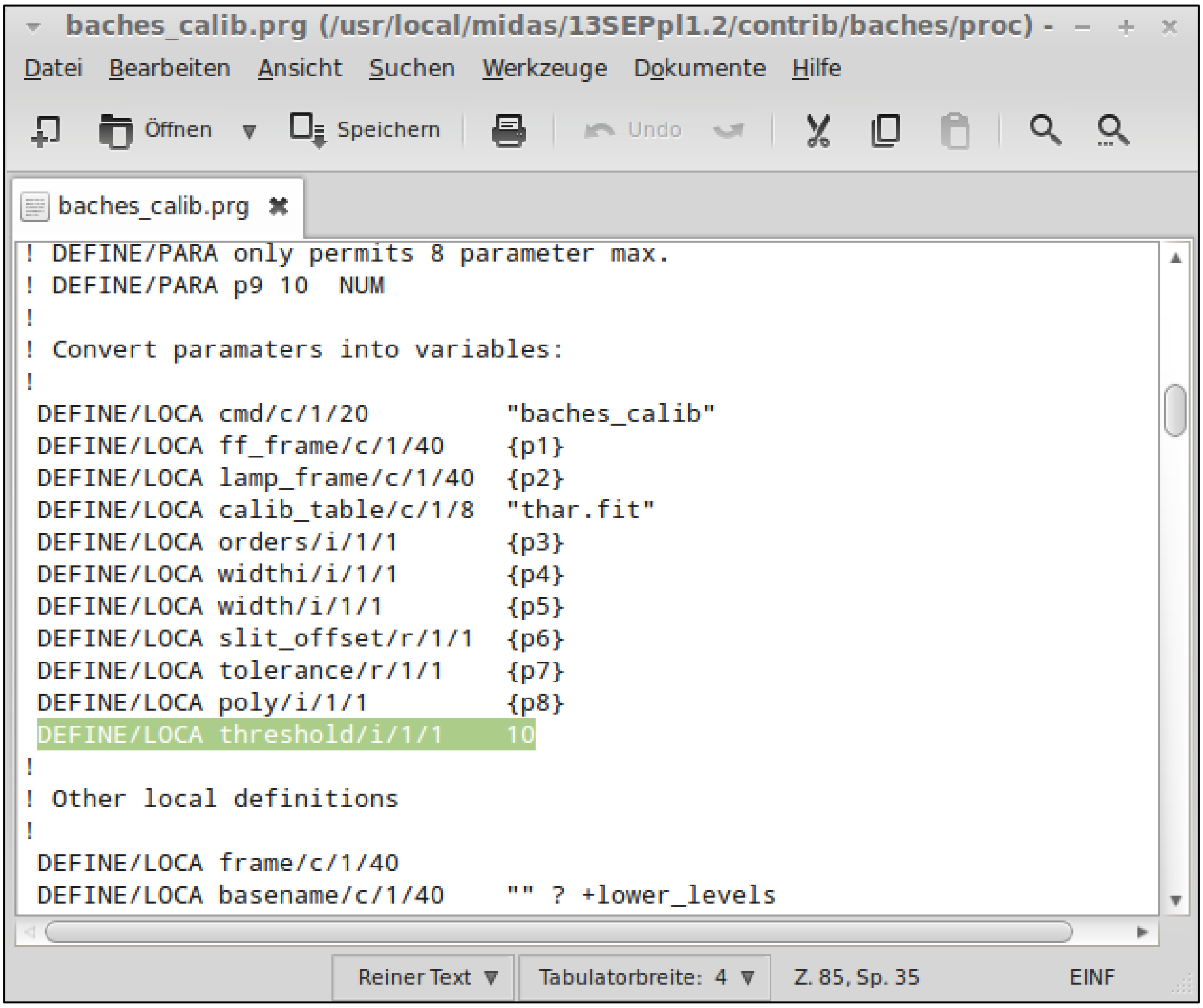


Fig. 24: The BACHES scripts are well commented by the author of the source code, Carlos Guirao. Thanks!

4.5.2 WRITE/OUT "threshold" (Line 115)

Remove the exclamation mark "!" in front of line 115, so that the preset threshold value, that is required to detect the lines in the ThAr spectrum, is displayed with all other parameters.

WRITE/OUT "Threshold = {threshold}"

Remember to save the script after each change you make.

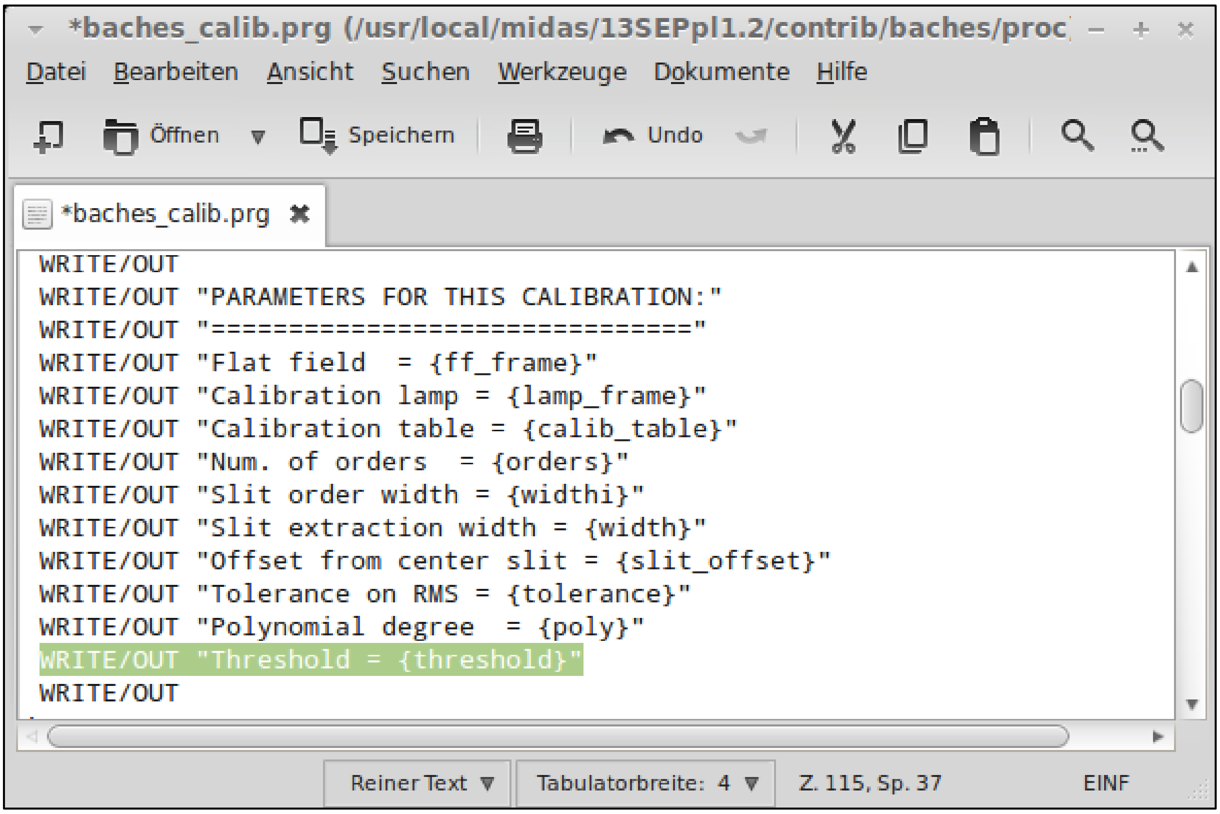


Fig. 25: The "Threshold" value should be included in the records.

4.5.3 Definition of the Spectrum Scan Area with the Cursor (Line 194)

This item deserves special consideration. MIDAS scans the flatfield spectrum and attempts to detect the successive orders. Depending on the size of the camera sensor, MIDAS sometimes detects too few orders or feels “disturbed” by overlapping higher UV orders while scanning the infrared region of the spectrum. To avoid this, you can manually force MIDAS to scan only a defined area for the detection of orders. You can pre-define this area, but it must be identical in every spectrum. For example: SCAN/ECHE {frame} 1, 1000.

In any case, you must activate the command SCAN / ECHE {frame} in line 190 first. As you may adjust the position of the spectrum more often, you should instead rely on the ability to define the scan area manually by using the cursor. This is done by deleting the exclamation point "!" in line 194.

SCAN/ECHE {frame} cursor

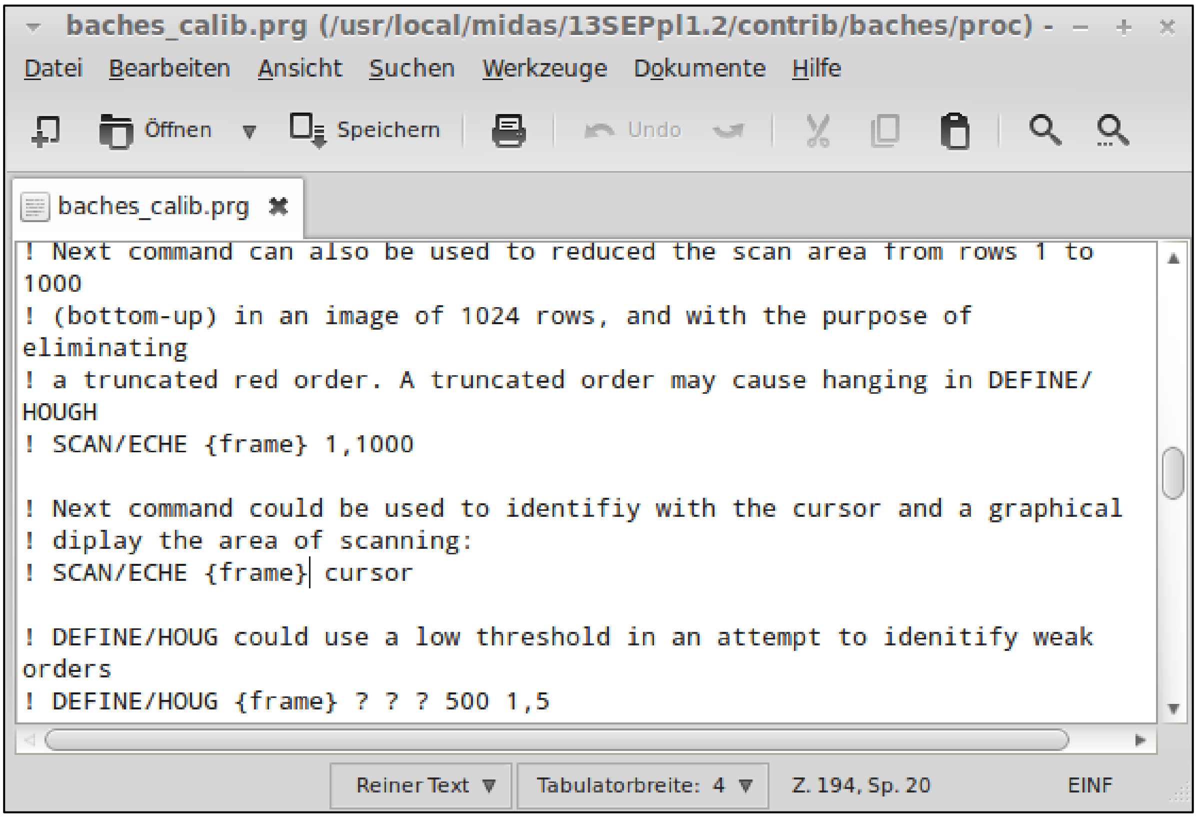


Fig. 26: Definition of the spectrum scan area in the flatfield by using the cursor manually.

4.6 Detection of the Spectral Orders and Wavelength calibration of the ThAr Spectrum

Now let's start the calibration process. First, the **Flatfield spectrum (ff150s.fit)** is loaded. The intention is to identify a specified number of orders, and align each order horizontally. **Without flatfield, a reliable detection of orders with MIDAS is impossible.** Thereafter, the **reference spectrum (thar60s.fit)** will be scanned for wavelength calibration. MIDAS will try to detect 25 orders.

`Midas > calib/baches ff150s.fit thar60s.fit 25`

```
PARAMETERS FOR THIS CALIBRATION:
================================
Flat field  = ff150s.fit
Calibration lamp = thar60s.fit
Calibration table = thar.fit
Num. of orders  = 0025
Slit order width = 0020
Slit extraction width = 0020
Offset from center slit = 0.00000E+00
Tolerance on RMS = 1.00000E+00
Polynomial degree  = 0004
Threshold = 0010

baches_calib: Do you want to continue [yn] (y)? |
```

Fig. 27: A fourth order polynomial is fitted to the data points (x-position on sensor vs. wavelength) by least-squares fit.

Advice: If in your own spectra the detection of 24 or more orders fails, gradually reduce the number of orders down to 20. This may happen for some reason. For example, please follow the instructions for proper alignment of the spectrum on the sensor.

Further guidance on the detection of up to 30 orders for cameras with large sensors can be found in the README file of Carlos Guirao: "**baches_midas_data_reduction.README**".

Here an excerpt:

```
<flat_field>.fit  Spectrum of a continuum lamp used to identified the orders.
                  You may need to combine several flats with differnt filters
                  in order to cover all the orders. The spectrum of a direct
                  halogen lamp is enough to cover 23 orders.
                  The spectrum of a halogen lamp with a blue filter (bg23) is
                  enough to cover upto 26 orders.
                  To cover more orders (28-30) you will need a composite of
                  flats with different filters and from UV lamps.
```

After confirmation with "y" MIDAS scans the flatfield spectrum **ff150s.fit** (Fig. 28) and provides a vertical intensity scan next to it (Fig. 29) across all 25 orders. More than 25 orders do not fit on the KAF-1603ME sensor!

The following figures reveal the distribution of the detected 25 orders:

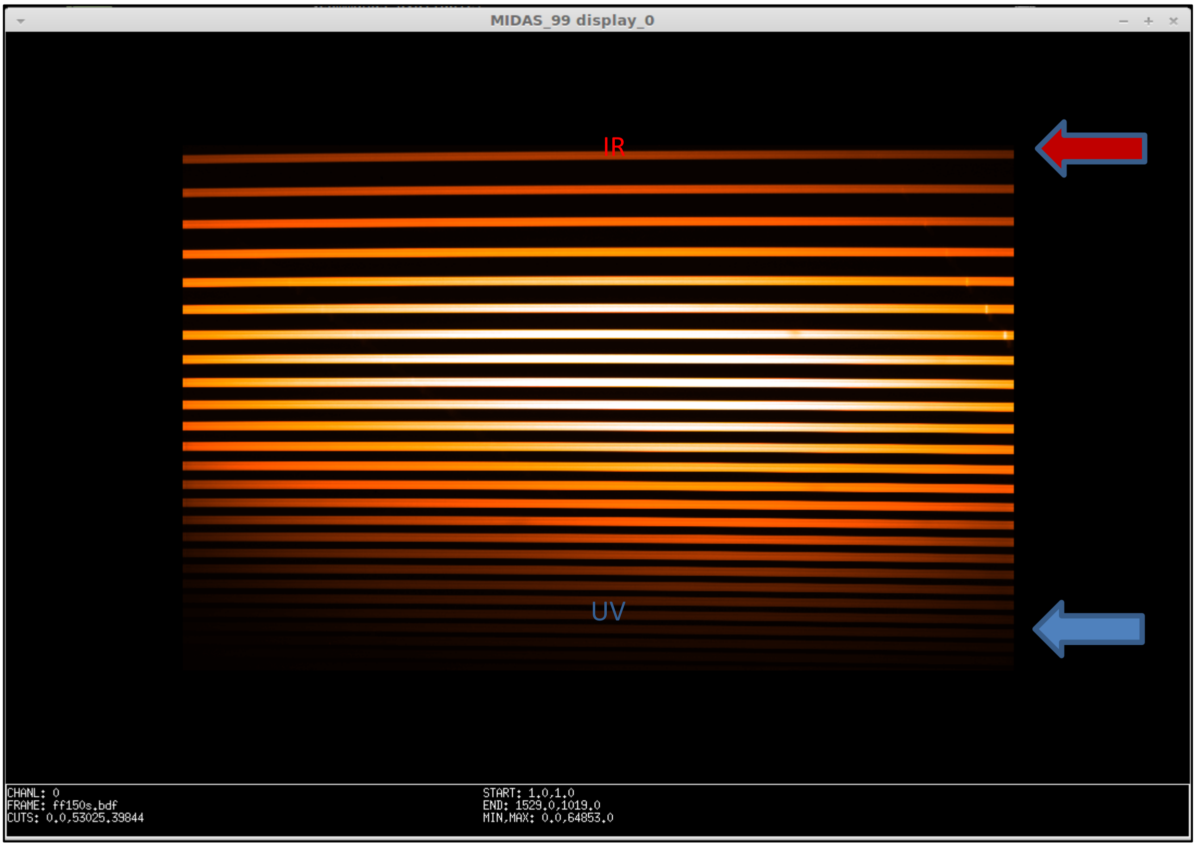


Fig. 28: Scan of the Flatfield spectrum ff150s.fit. Bottom: Ultraviolet UV, top: Infrared IR

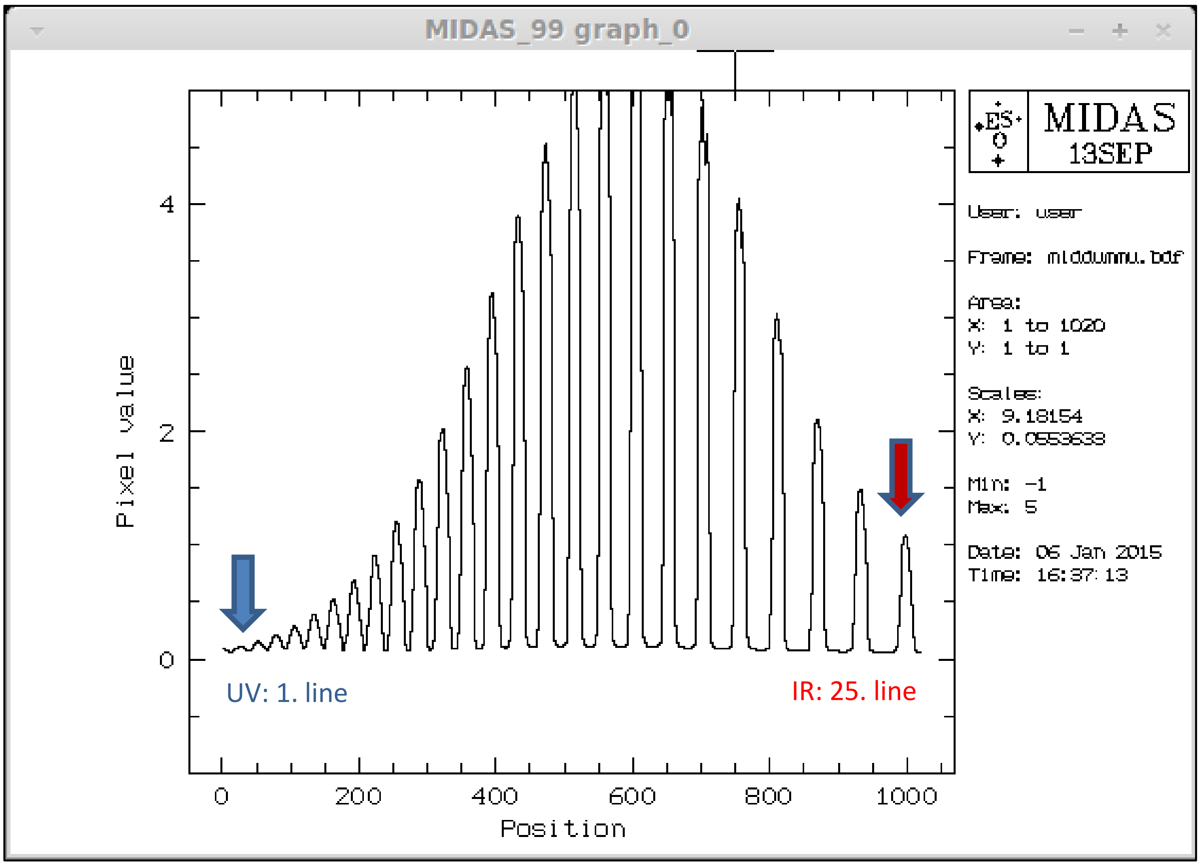


Fig. 29: Vertical scan through 25 orders.

Now place the first cross to the left of the first fully visible order (Fig. 30). This defines the lower edge of the scanning area in the UV. Then place the second cross right at the end of the order in the IR.

Advice: You must always click within the sensor field; otherwise it returns an error message.

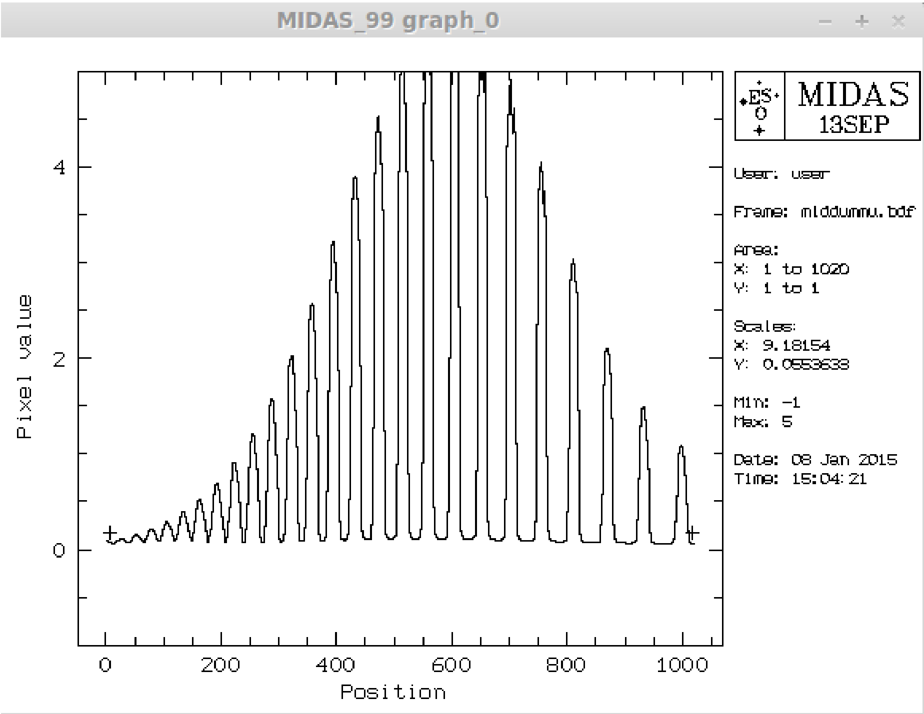


Fig. 30: The first cross must be set just left of the first completely detected order in the UV. The second cross at right limits the last order in the IR. Note: Never click outside the sensor field, which causes an error message.

Then MIDAS scans the defined area of the image and tries to detect the required 25 orders (Fig. 31).

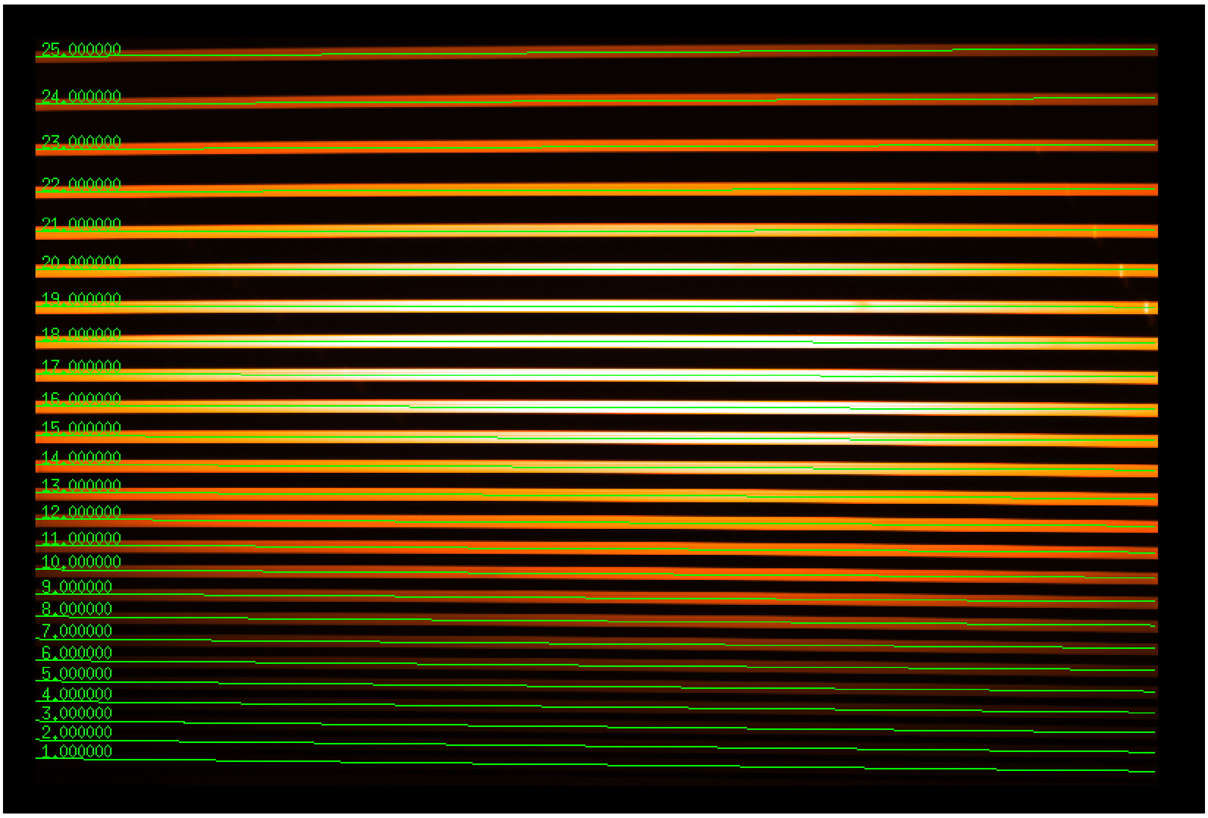


Fig. 31: Successful detection of 25 orders obtained with the ST-1603ME camera.

If the green lines slant on individual orders or between them, the detection is incorrect. Try again by either starting the detection with fewer than 25 orders, or redefining the scanning area. Here a little instinct is required. If you always acquire spectra in the same way, you can define the scan area by specifying the vertical positions of the upper and lower edge in the script.

By means of the detectd orders from the flatfield spectrum, the ThAr reference spectrum will be scanned. 25 orders will be processed.

```
--- (W) Wavelength Calibration ---
    Search Method (GRAVITY, GAUSSIAN) : SEAMTD  = GAUSSIAN
    Analysis window width             : WIDTH2  = 10.0
    Threshold above the background    : THRES2  = 0.0
    Wavelength calibr. meth.          : WLCMTD  = PAIR
" (Possible methods: PAIR, ANGLE, GUESS, LINEAR, ORDER, RESTART)
    Wavelength calibr. option (1D/2D) : WLCOPT  = 1D
    Regress. method (Standard,Robust) : WLCREG  = STANDARD
    Visualisation flag (Yes,No)       : WLCVISU = YES
    Arc frame                         : WLC     = +++
    Line Catalog                      : LINCAT  = MID_ARC:thar.tbl
    Polynomial Degree                 : DC      = 4
    Tolerance                         : TOL     = 0.2
NB: Parameter CCDBIN is also involved
    Mini, Maxi number of iterations   : WLCNITER = 3,20
    Iteration Loop parameters:
" WLCITER(1-3) = 1.0, 0.3, 20.0
    WLCITER(4-5) = 5.0, 4.0


baches_calib: Order identification finished
baches_calib: Do you want to continue [yn] (y)?
```

Proceed with the wavelength calibration by typing “y“.

Overall 1,946 spectral lines with Gaussian intensity profile are detected within a search window of 10 pixels (Fig. 32). More lines yield higher accuracy in the wavelength calibration.

```
search lines
------------
input image  : extwlc
output table : line.tbl
input parameters
      search window :  10 pixels
detection threshold :      10.00 DN
   centering method : gaussian fit
search for emission lines
seq.no.  detected lines
-------  -------------
      1         66
      2         69
      3         64
      4         59
      5         72
      6         77
      7         70
      8         70
      9         75
     10         77
     11         76
     12         75
     13         73
     14         91
     15         94
     16         87
     17         91
     18         75
     19         90
     20         93
     21         77
     22         90
     23         83
     24         78
     25         74
-----------------------
   no. of detections:     1946

baches_calib: line identification finished
baches_calib: if not enough lines, try changing threshold
baches_calib: Do you want to continue [yn] (y)?
```

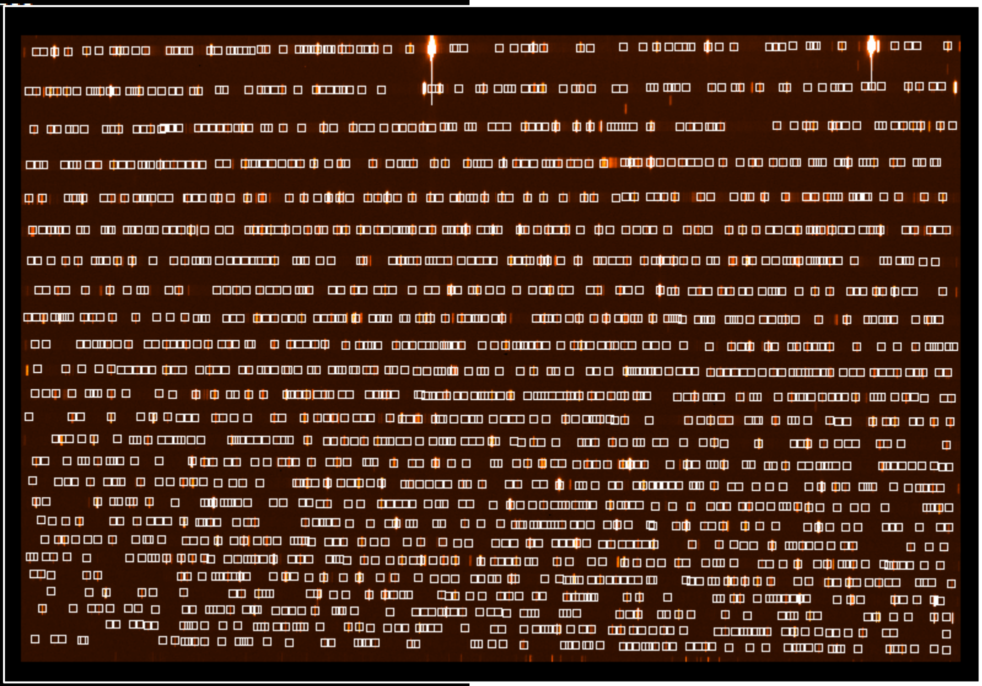


Fig. 32: Seq. no. 1 is the bottom line in above image, seq. no. 25 is the top line

Next, the assignment of the detected spectral lines with **known reference lines** in the ThAr spectrum is performed. Each of the 25 orders corresponds to a narrow spectral interval. The lower and upper limit will be listed in the terminal window.

After confirming with “y“, two windows open up: The window **thar_ref.bdf** (Fig. 33) contains predefined reference lines that need to be detectd and assigned in the acquired ThAr spectrum.

Two different spectral lines must be identified twice in adjacent, overlapping orders:
Two spectral lines, four mouse clicks (Fig. 34):

6662.268Å in order 33 (First click above left, second click above right)

4609.600Å in order 48 (Third click bottom left, fourth click bottom right)

Note: If the sensor is too small (smaller than the KAF-1603), it is possible that a line occurs only once. Then try other wavelength pairs according to the ThAr spectral atlas.

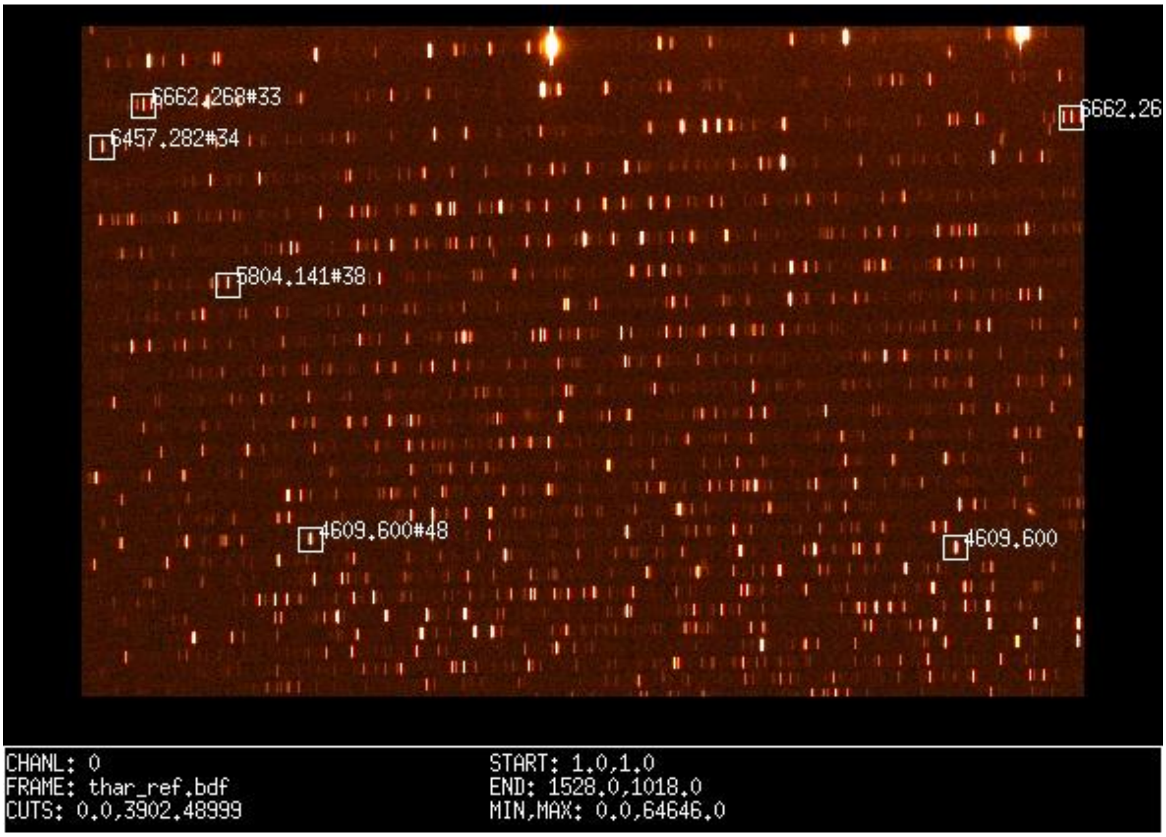


Fig. 33: thar_ref.bdf. Two pairs of the same wavelength must be clicked twice each.

Direct your attention to these two wavelength pairs (pair 1, 2) and (pair 3, 4). These must be identified and confirmed in your own spectrum by mouse clicks (Fig. 34, Fig. 35).

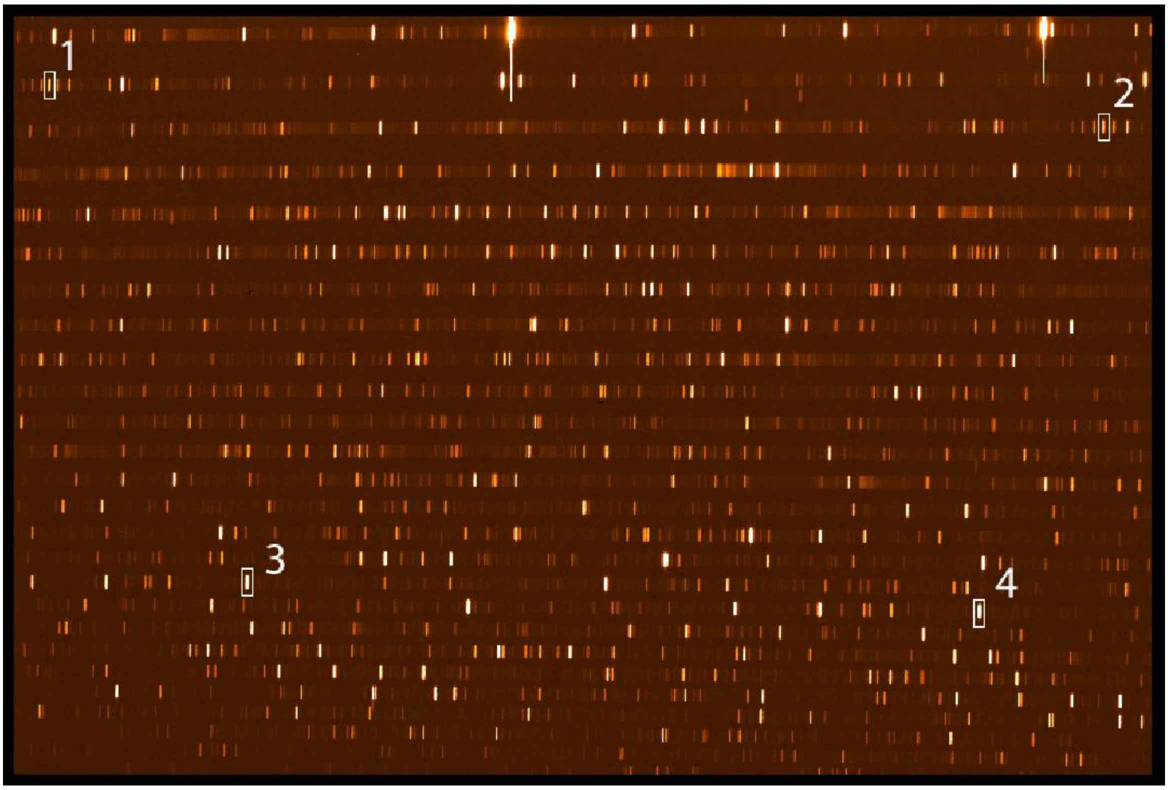
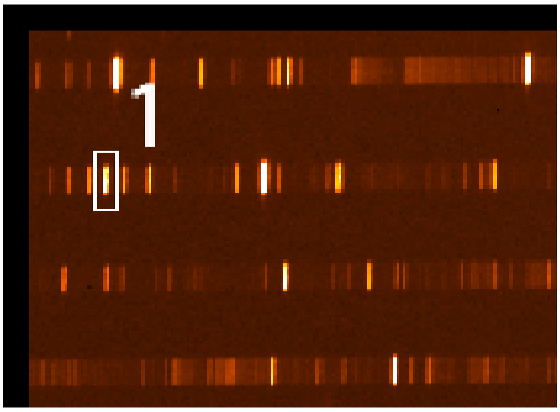
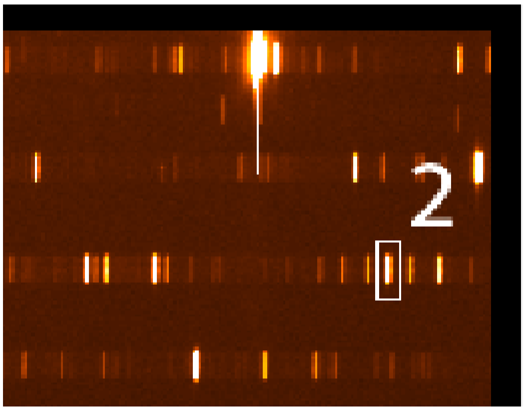


Fig. 34: Successively the lines #1 to #4 are clicked.

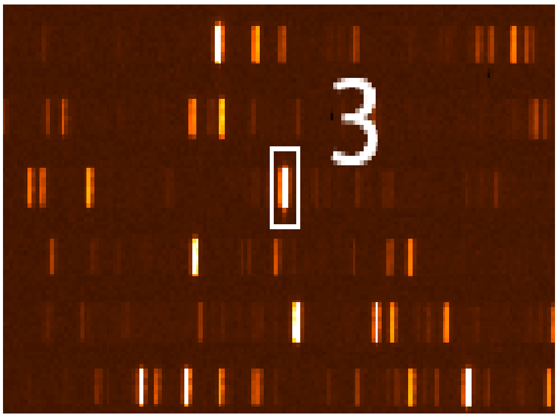
Details of Fig. 34. The coordinates of the four clicked lines are recorded in the terminal window.



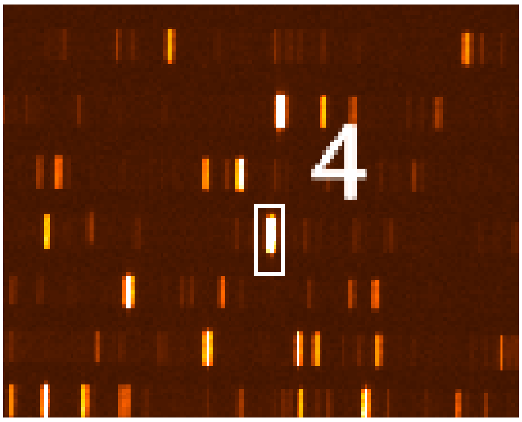
Step 1: Set the cursor on left spectral line 6662.268Å, then press the left mouse button.



Step 1: Set the cursor on right spectral line 6662.268Å, then press the left mouse button.



Step 3: Set the cursor on the left spectral line 4609.600Å, then press the left mouse button.



Step 4: Set the cursor on the right spectral line 4609.600Å, then press the left mouse button.

Step 5: A click on the right mouse button ends this input. The following window appears (Fig. 35):

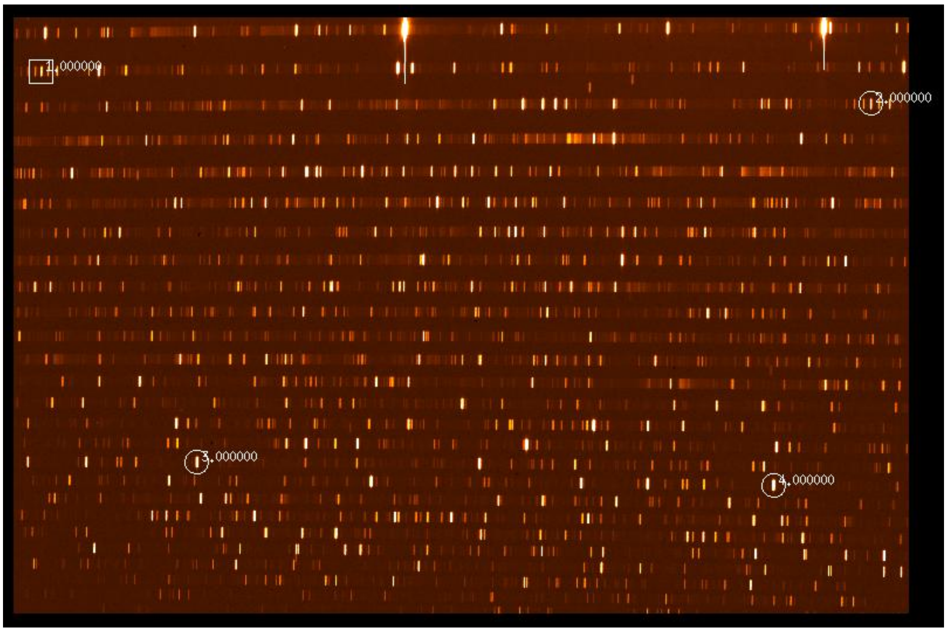


Fig. 35: MIDAS confirms the clicks after step 5.

Meanwhile, the (x,y)-center coordinates of the four identifications have been recorded in the terminal window:

```
Info: You must identify lines which are repeated in
      overlapped regions of two adjacent orders. You
      will do it two times.

With the cursor, select two lines that appear in two
different orders each. Click them in the following order :
   - First line: left-hand side, then right-side
   - Second line: left-hand-side, then right-side
For each line (for help, see CENTER/MOMENT with option CURSOR):
       - select approximate position with cursor
       - if necessary, optimize size of cursor rectangle
       - enter position by pressing Enter on keyboard
Exit by pressing Exit button
    xcenter     ycenter         xerr          yerr
                                   xfwhm         yfwhm      icent      ident
frame: thar60s.bdf  (data = uI2)
       plane_no 1 loaded
 47.910851      927.66968      0.85791E-01   0.48867
                                  1.9377       11.037       9493.0     ID0001

 1465.3567      871.70807      0.83085E-01   0.44585
                                  2.0706       11.111       10974.     ID0002

 313.80560      258.89569      0.94369E-01   0.46089
                                  2.3094       11.279       41382.     ID0003

 1298.8450      219.50665      0.89062E-01   0.42078
                                  2.3912       11.298       50464.     ID0004

Enter absolute order number of first pointed line (square mark) :
```

Step 6: Next the corresponding wavelengths and absolute orders are entered:

Enter absolute order number of first pointed line (square mark: → 33
Sequence no. 0001, Order no. 0033. Enter wavelength: → 6662.268
Sequence no. 0003, Order no. 0048. Enter wavelength: → 4609.6

With these settings, about 1,946 spectral lines of the orders #32 - #56 will now be identified and automatically assigned in an iterative process (Fig. 36).

Fig. 36: About 1,946 lines are detected. For accurate calibration, MIDAS must use as much lines as possible. At least 50%, in optimal circumstances 80%.

```
 COMPUTE DISPERSION COEFFICIENTS
 ------------------------------
 INPUT TABLE : line.tbl
 POLYNOMIAL DEGREE :   4
 SEQ.NO  SPECTRAL  NO.LINES  WL START    WL END  STD. DEV.
          ORDER                                  ANGSTROEM
 ------  --------  --------  --------    ------  ---------
      1        56        42   3923.68   4051.72    0.01140 *FROM 2D SOLUTION*
      2        55        50   3994.92   4125.36    0.01186 *FROM 2D SOLUTION*
      3        54        42   4068.81   4201.72    0.01224 *FROM 2D SOLUTION*
      4        53        47   4145.48   4280.95    0.01583 *FROM 2D SOLUTION*
      5        52        51   4225.10   4363.23    0.01570 *FROM 2D SOLUTION*
      6        51        52   4307.85   4448.72    0.01642 *FROM 2D SOLUTION*
      7        50        49   4393.92   4537.63    0.01331 *FROM 2D SOLUTION*
      8        49        47   4483.50   4630.17    0.01794 *FROM 2D SOLUTION*
      9        48        52   4576.81   4726.55    0.01682 *FROM 2D SOLUTION*
     10        47        53   4674.09   4827.03    0.01549 *FROM 2D SOLUTION*
     11        46        58   4775.61   4931.87    0.01307 *FROM 2D SOLUTION*
     12        45        48   4881.64   5041.37    0.01753 *FROM 2D SOLUTION*
     13        44        36   4992.50   5155.84    0.01674 *FROM 2D SOLUTION*
     14        43        48   5108.51   5275.63    0.01471 *FROM 2D SOLUTION*
     15        42        49   5230.04   5401.11    0.01587 *FROM 2D SOLUTION*
     16        41        54   5357.50   5532.71    0.01764 *FROM 2D SOLUTION*
     17        40        50   5491.33   5670.89    0.01551 *FROM 2D SOLUTION*
     18        39        41   5632.02   5816.14    0.01543 *FROM 2D SOLUTION*
     19        38        49   5780.10   5969.04    0.01159 *FROM 2D SOLUTION*
     20        37        56   5936.19   6130.19    0.01417 *FROM 2D SOLUTION*
     21        36        44   6100.94   6300.29    0.01044 *FROM 2D SOLUTION*
     22        35        41   6275.09   6480.10    0.01780 *FROM 2D SOLUTION*
     23        34        42   6459.48   6670.48    0.01488 *FROM 2D SOLUTION*
     24        33        40   6655.02   6872.39    0.02126 *FROM 2D SOLUTION*
     25        32        30   6862.76   7086.91    0.01021 *FROM 2D SOLUTION*
 -----------------------------------------------------------
                                        MEAN RMS:   0.01495
** TOTAL NUMBER OF LINES :    1171 **
***************************  Verification  ***********************************

1) Minimum number of selections per order : 6
   If the number of selections in any order (column NO.LINES above)
   is less or equal than the minimum, this order should be checked.

2) Percentage of identifications among the half brighter lines : 61 %
   This percentage must be as high as possible (above 50%). Low values
   indicate an uncertain calibration.
```

In total, MIDAS used 1,171 of 1,946 lines for calibration, corresponding to a good ratio of 61%. For every order from #32 (line 1) to #56 (line 25) the wavelength interval is calculated. The residual RMS error for the calibration from 3923Å to 7086Å is 0.01495Å, a nearly perfect result.

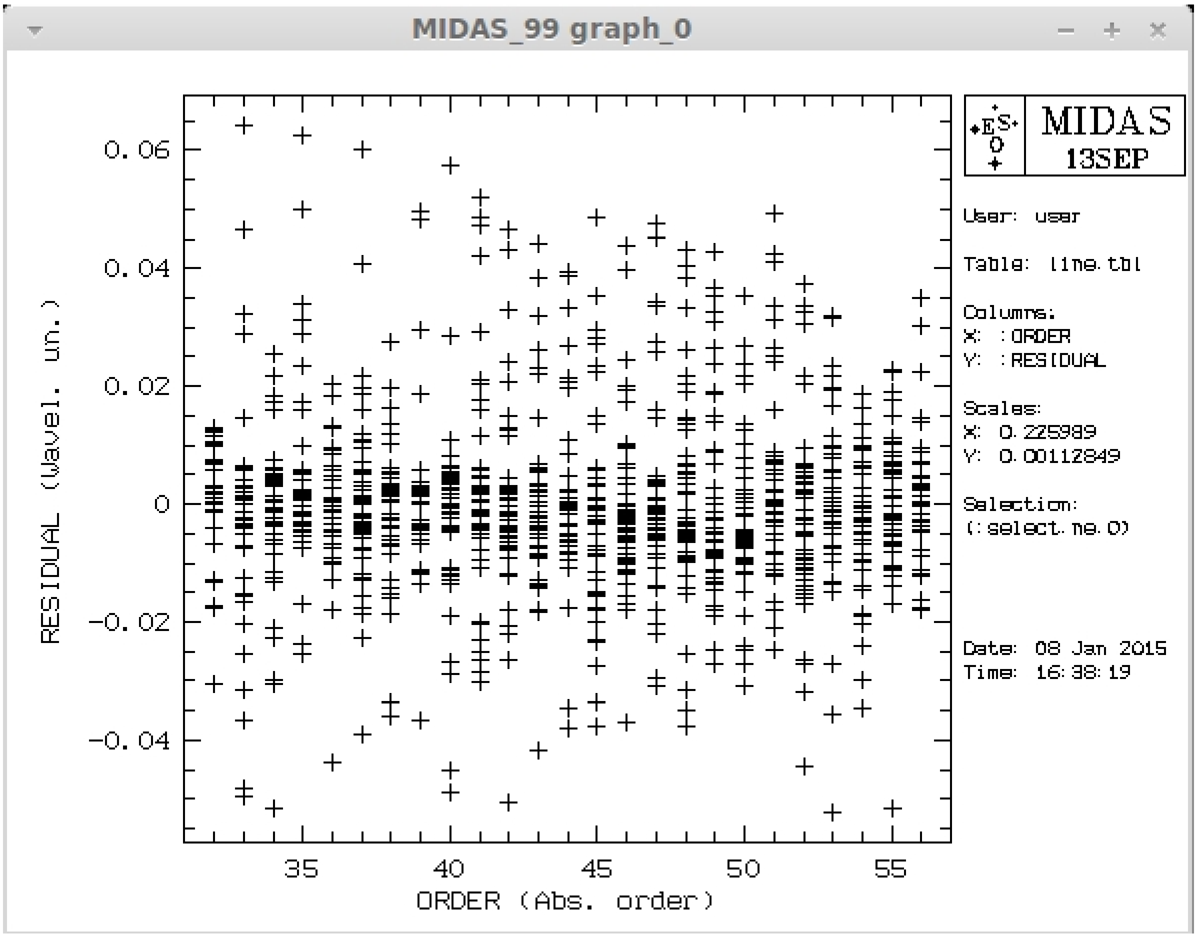


Fig. 37: Residual errors of the wavelength calibration.

You can now choose to delete or retain temporary files:

```
baches_calib: Do you want to clean temporary files [yn] (y)?
```

Enter "y".

```
baches_calib: Do you want to clean temporary files [yn] (y)?
clean: cleaning temporary files
use CREATE/DISPLAY or CREATE/GRAPHICS to recreate your windows...
baches_calib: Do you want to calculate R for thar60s.fit [yn] (y)?
```

Now you can calculate the spectral resolution R in different orders, and the **average spectral resolution R** of the ThAr reference spectrum (Fig. 38).

The average spectral resolution obtained is R=21,955 +/- 1,867, a very high value. The wavelength calibration of the ThAr spectrum is complete.

```
Resolving power computed in MIDAS table: thar60s_wrmR.fit
Postscript file generated in thar60s_wrmR.ps
Average (kappa-sigma-cleaned) resolution power: 2.19548E+04 +/- 1.86743E+03
Midas 007>
```

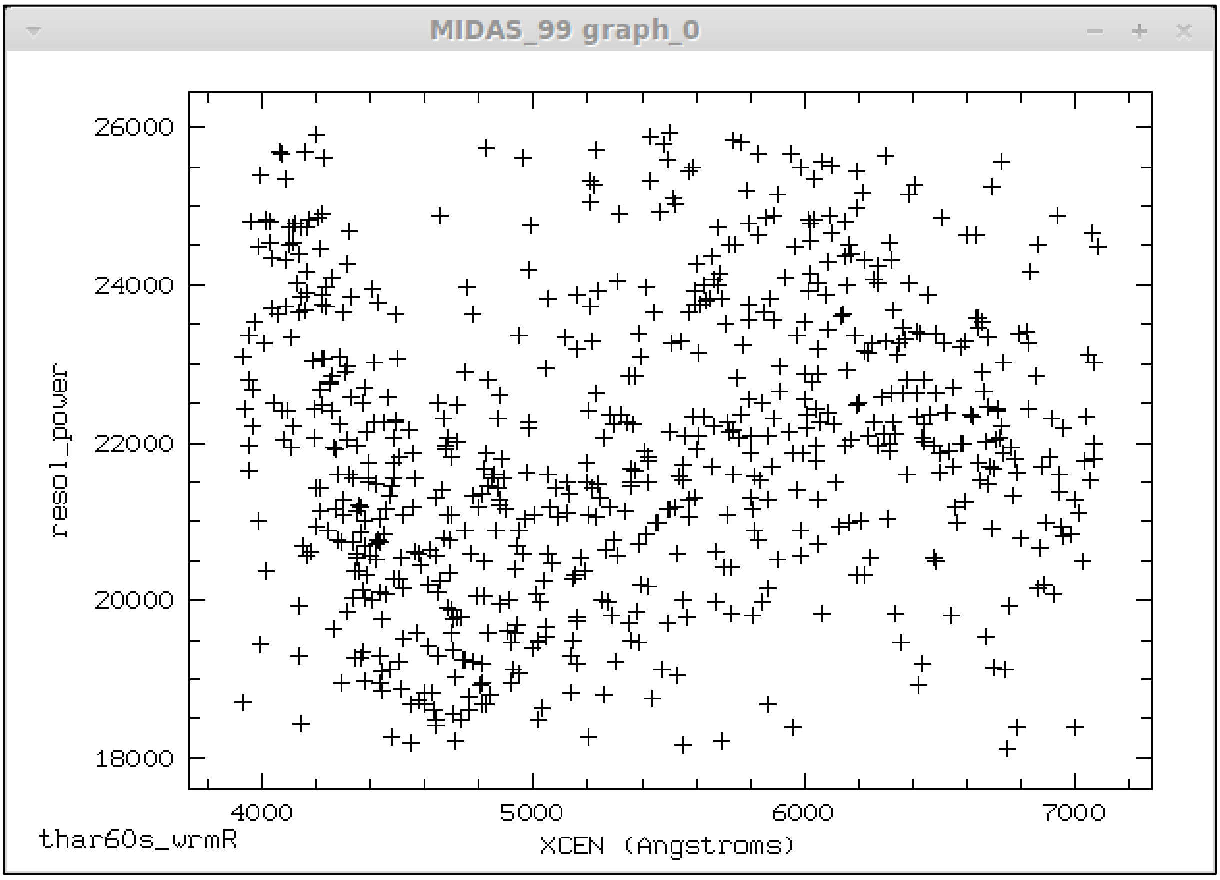


Fig. 38: The average spectral resolution R (File: thar60s_wrmR.fit).

4.7 Plotting the calibrated Thorium-Argon Spectrum

```
Midas > crea/grap

Midas > plot/axes 3900,7100 0,65535 0 "Wavelength" "rel. Intensity"

Midas > overplot thar60s_wrm.fit
```

```
Midas 008> plot/axes 3900,7100, 0,65535 0 "Wavelength" "rel. Intensity"
Midas 009> overplot thar60s_wrm.fit
```

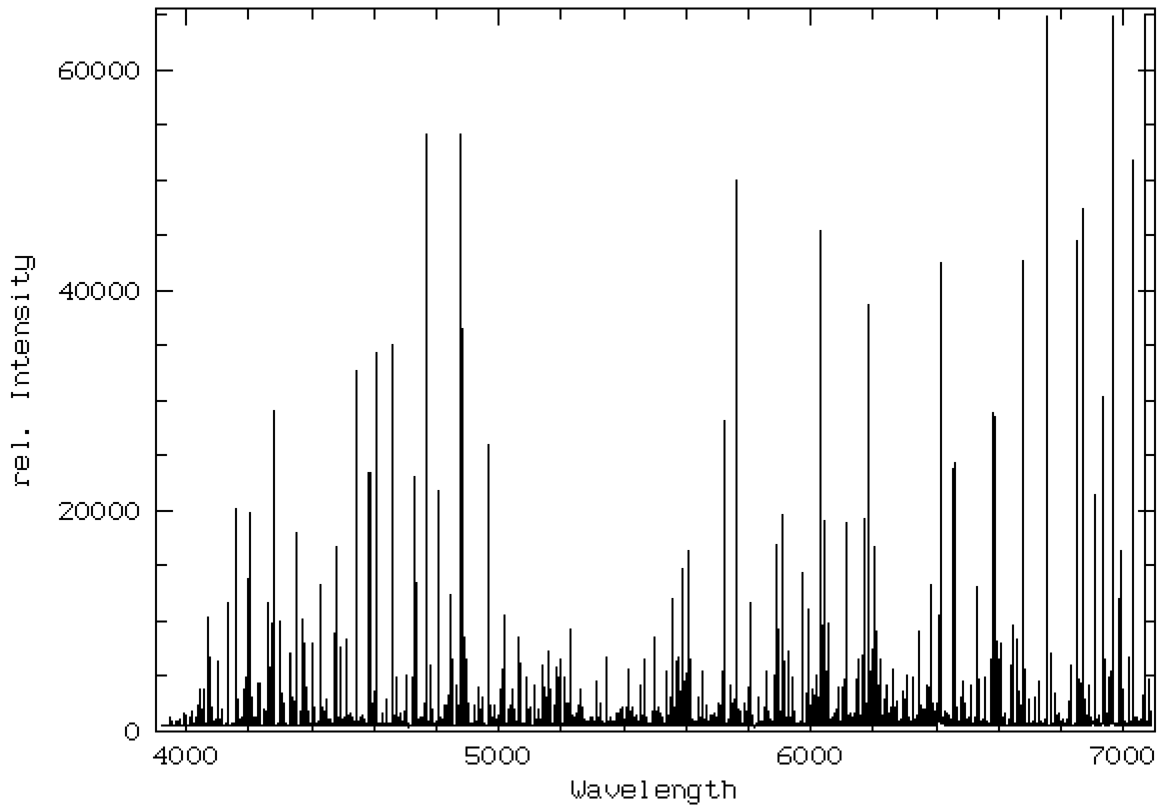


Fig. 39: The calibrated ThAr spectrum (file: thar60s_wrm.fit)

4.8 Calibration of Stellar Spectra

The next step is the calibration of the solar spectrum **sun240s.fit** by means of the calibrated ThAr spectrum. The calibration result of the ThAr reference lamp is now transfered to the solar spectrum. Required is the fact that in the period between the acquisition of the reference spectrum and the solar spectrum, no shifts larger than 9µm between both spectra occur. The BACHES echelle spectrograph was designed for optimum thermal stability and superior mechanical rigidity. If you encounter any drift between spectra, first please check the connection to the camera. In any case, the user is encouraged to take ThAr reference spectra frequently during the night session. This gives you an idea of very small drifts, which cannot be ruled out for long observing periods.

4.8.1 Creation of a Masterflat

Calibration with a darkframe (or a masterdark) can be performed with the camera image recording software. In the present image **sun240s.fit,** a darkframe has already been subtracted. The calibration with the flatfield **ff150s.fit** in MIDAS is now described. This flat corrects for dust settled on the optical elements in the light path or on the camera's sensor.

First, a file called **master_flat.bdf** must be deduced from the flatfield **ff150s.fit.** This can be accomplished with the following MIDAS command:

Midas > indisk/fits ff150s.fit master_flat.bdf

Note: The masterflat must be named exactly in this way, because it is retrieved later by the script baches_pipeline.prg under this name!

```
Midas 010> indisk/fits ff150s.fit master_flat.bdf
no CDELTi nor CDi_j matrix found... STEPi set to 1.0
FITS file: ff150s.fit converted to: master_flat.bdf
Midas 011>
```

During the calibration process quite a few temporary files have been generated within the folder **sun1603**. You may list them for further inspection. Later, at the end of the calibration process, they can be deleted.

Midas > $ls

```
bachesIORDE.fit    graph_wnd099.plt  outnames.cat        thar60s_wr.fit
bachesLINE.fit     i__i.cat          progress.out        thar60s_wrm.bdf
bachesLINE.tbl     line.tbl          r__r.cat            thar60s_wrm.fit
bachesORDE.fit     master_flat.bdf   sun240s.fit         thar60s_wrmR.fit
bachesORDE.tbl     middumma.tbl      thar_1000lines.tbl  thar60s_wrmR.ps
back.tbl           middummt.tbl      thar60s_.bdf        thar60s_wrmR.tbl
compute_fits.prg   nectab.tbl        thar60s.fit
ff150s.fit         NULL              thar60s_w.bdf
FORGRdrs.KEY       order.tbl         thar60s_wr.bdf
Midas 012>
```

4.8.2 Calibration of the Stellar Spectrum with the Masterflat

Midas > pipeline/baches sun240s.fit

The pipeline script converts the file into the MIDAS format ".bdf" and automatically performs the flatfield correction, indicated by a "p" using the file **master_flat.bdf.** Then the wavelength calibration follows, indicated by a "w". All detected orders are rebinned "r" to the same scale and merged "m" to a spectral profile.

The file **sun240s_pwrm.fit** is the resulting spectral profile after performing the following commands:

p: flatfield calibration
w: wavelength calibration
r: rebinning to the same scale
m: merging all detected orders

```
Midas 012> pipeline/baches sun240s.fit
pipeline: Version: baches_pipeline
pipeline: Bias=master_bias.bdf
pipeline: Dark table=master_dark.tbl
pipeline: Flat=master_flat.bdf
pipeline: Echelle session=baches
pipeline: Flux=master_flux.bdf

compute_fits.prg: sun240s.fit converted to sun240s_.bdf
pipeline: creating sun240s_p with master_flat.bdf divided
Background table back.tbl not stored. Created...
Creating table back.tbl...
pipeline: sun240s_pw calibrated in wavelength
 Sampling step =     0.1071
pipeline: sun240s_pwr rebined
pipeline: converting sun240s_pwr.bdf to sun240s_pwr.fit
pipeline: sun240s_pwrm merged
pipeline: converting sun240s_pwrm.bdf to sun240s_pwrm.fit
Midas 013>
```

Plotting the spectral profile:

Midas > crea/grap

Midas > plot/axes 3900,7100 0,5 0 "Wavelength" "Relative Intensity"

Midas > overplot/row sun240s_pwrm.fit

```
Midas 016> plot/axes 3900,7100, 0,5 0 "Wavelength" "rel. Intensity"
Midas 017> overplot sun240s_pwrm.fit
```

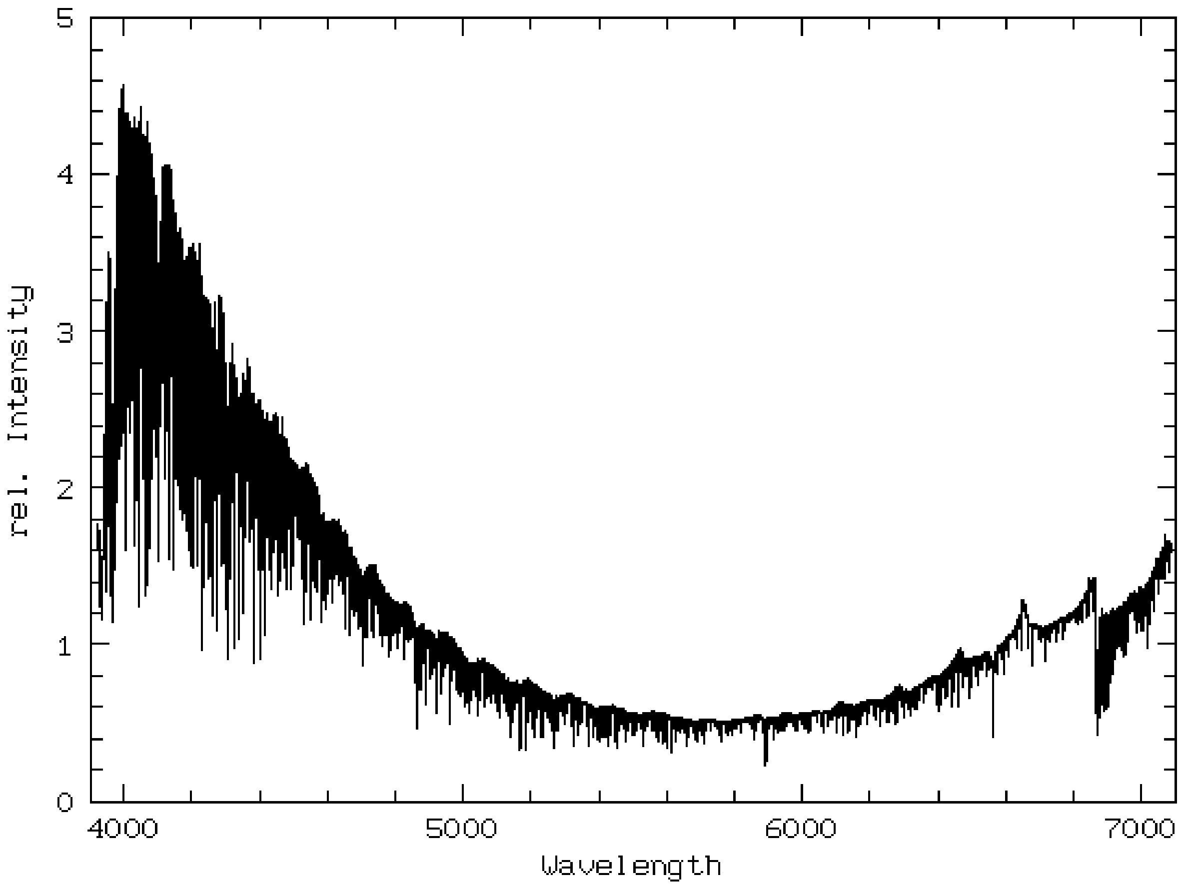


Fig. 40: Wavelength calibrated profile of the solar spectrum sun240s_pwrm.fit after flatfielding with the masterflat. Spectral range from about 3923Å to 7086Å.

The following conclusions can be drawn from the spectral profile:

1. The spectrum does not show the true intensity. A calibrated reference spectrum of a star of the same spectral type can be used to reveal the true intensity distribution of the continuum across the spectrum. Outside of MIDAS, this can be performed with third party software like VisualSpec[7] or ISIS[8]. Doing so is beyond the scope of this investigation.
2. The 25 merged orders are still detectable as small ”arches“. Flatfielding with a halogen lamp does not fully remove them.

[7] http://www.astrosurf.com/vdesnoux/
[8] http://www.astrosurf.com/buil/isis/isis_en.htm

4.8.3 Normalization of the Stellar Spectrum

At this point, note that you can do the normalization of a stellar spectrum and all subsequent analysis with third party software. Examples are velocity measurements of Doppler shifted lines, and flux measurements characterized by Equivalent Width (EW) and FWHM. The spectral profile is available in standard FITS format and can be processed by different spectroscopy software. Apart from ESO-MIDAS we strongly recommend the free Windows software VisualSpec.

For the sake of completeness, the normalization of a stellar spectrum will be demonstrated with MIDAS.

What is meant by the term "normalization"? For a couple of investigations of a stellar spectrum, a relative measurement to a normalized continuum level, usually set at "1", is sufficient[9]. Only for the purpose of measuring the absolute flux, for example the determination of the intensity maximum of an adapted Planck radiation curve, is absolute calibration with the help of a reference star necessary.

For normalization, the "pseudo-continuum" is extracted from the spectral profile (Fig. 40) of the star, then smoothed, and subsequently used as a divisor for the target spectrum. The pseudo-continuum is influenced by various factors such as the quantum efficiency of the camera sensor, and the selective absorption of the Earth's atmosphere. The division result is an instrumental function called "Response".

First, add a couple of additional echelle commands to the content:

Midas > set/cont echelle

Calculation of the response function **response.bdf:**

Midas > normalize/spec sun240s_pwrm.fit response.bdf

Now please have a look at Fig. 41: By pressing the left mouse button along the continuum you add interpolation points (crosses). Their respective coordinates are listed in the terminal window below. The more interpolation point you create, the better the calculation of the response function. Finalize the procedure by clicking the right mouse button while the cursor is on the image.

These are the first of a preferably large number of interpolation points required for a precisely fitted polynomial:

```
Midas 015> normalize/spec sun240s_pwrm.bdf response
                       >>> Use graphics cursor to enter data <<<
*** INFO: Creating new table file
Frame: sun240s_pwrm.bdf
     X-axis       Y-axis    Pixel   Line    X-position   Y-position    Pixel_value
       3928.8      1.75548     48      1     3928.7593            0        1.51292
      3946.38      2.37711    213      1     3946.4265            0        2.86068
      3946.38      3.20595    213      1     3946.4265            0        2.86068
      3990.32      3.79995    623      1     3990.3267            0        3.11184
       3999.1      4.29726    705      1     3999.1069            0        4.00798
      4007.89      4.51828    787      1      4007.887            0        3.40766
```

[9] http://www.ursusmajor.ch/downloads/analysis-and-interpretation-of-astronomical-sp.pdf (p. 21ff)

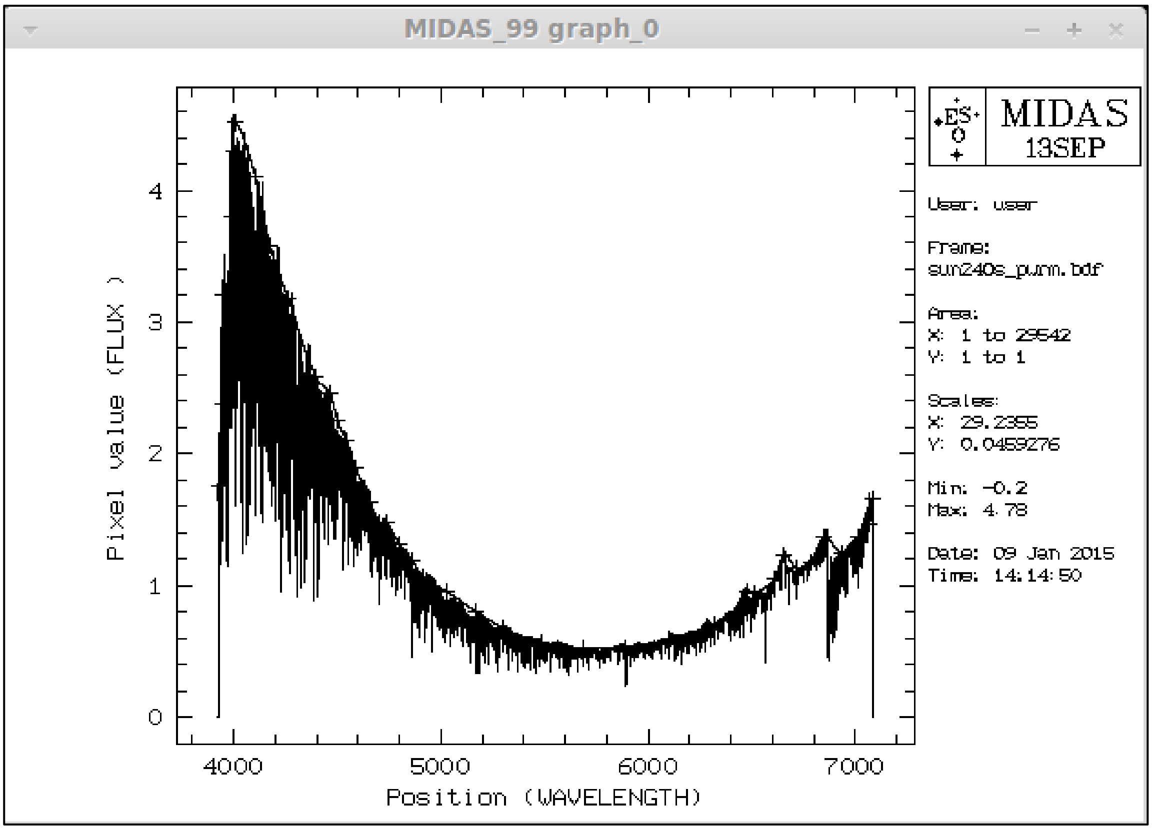


Fig. 41: Add interpolation points (crosses) by clicking the left mouse button along the continuum. Finalize by clicking the right mouse button while the cursor is on the image. The instrumental function response.bdf is now calculated and displayed. Note: the procedure is quite precise if the working window is scaled up to 1200 px by 800px or larger by the following command: Midas > crea/gra 1200,800,0,0

Now the instrumental function **response.bdf** is plotted:

```
Midas > plot/axes 3900,7100 0,5 0 "Wavelength" "Relative Intensity"
```

```
Midas > overplot response.bdf
```

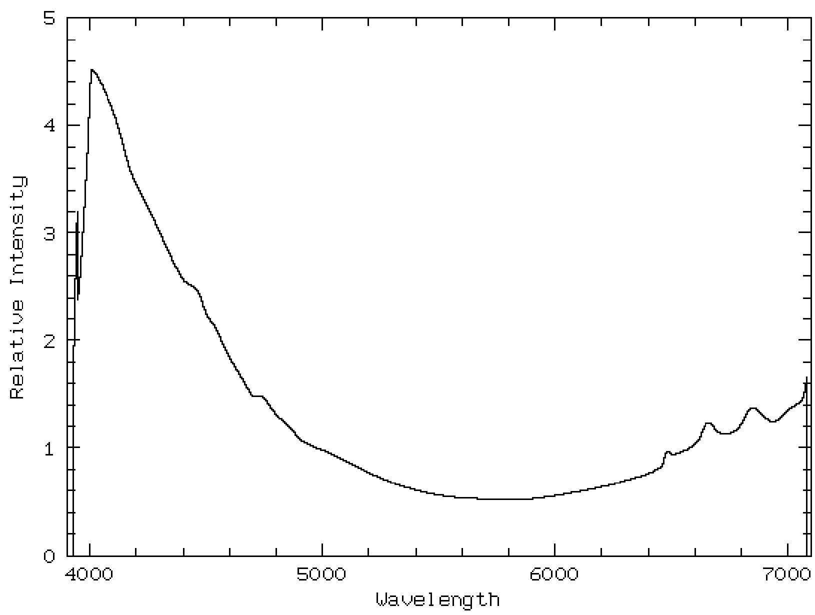


Fig. 42: The instrumental function **response.bdf**

In the next step,

the star's spectrum is divided by the instrumental function. The letter "n" indicates the normalization, and must be added manually by the following input:

```
Midas > compute/image sun240s_npwrm.bdf = sun240s_pwrm.fit/response.bdf
```

```
Midas > plot/axes 3900,7100 0,1.5 0 "Wavelength" "Relative Intensity"
```

```
Midas > overplot sun240s_npwrm.bdf
```

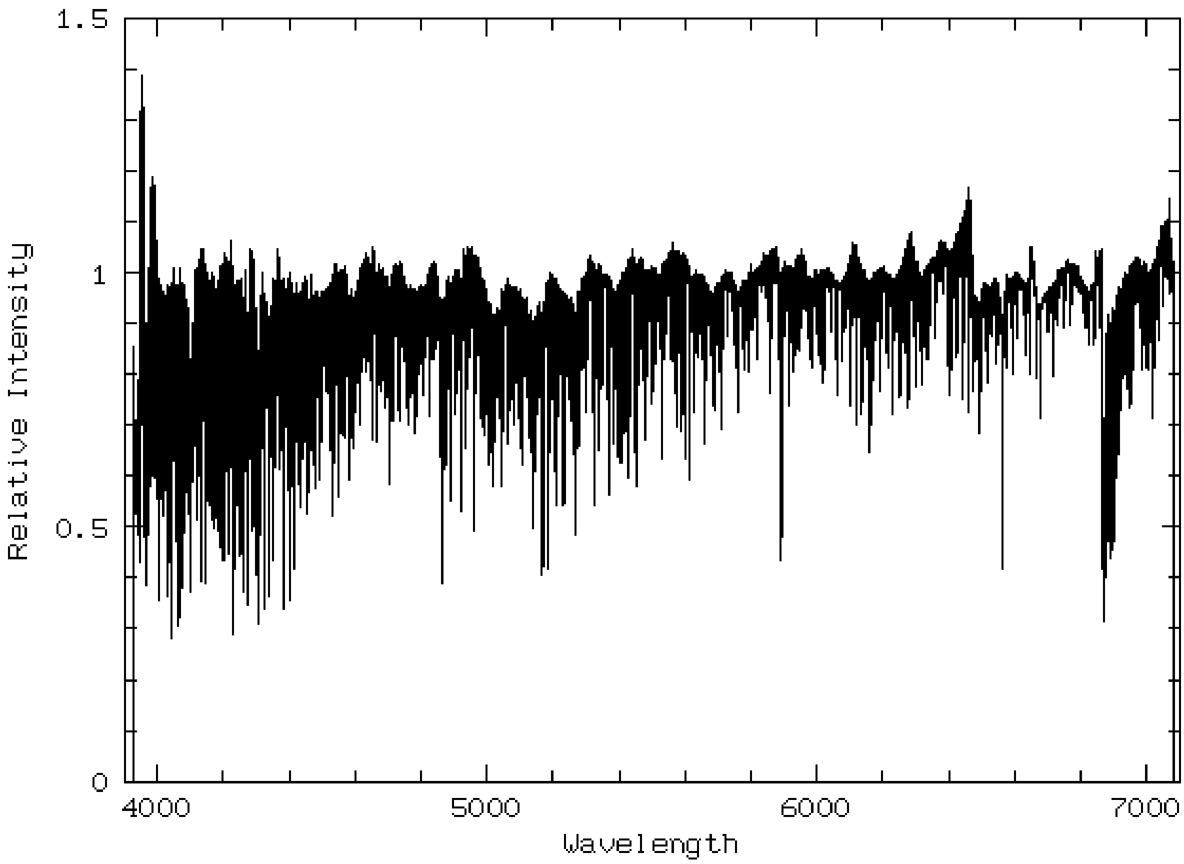


Fig. 43: The normalized profile sun240s_npwrm.bdf. Since only a few interpolation points had been set, the continuum is not perfectly normalized to a relative intensity value of "1". That needs to be done more precisely.

The resulting file **sun240s_npwrm.bdf** needs to be converted to a FITS format file, to make it available for different software.

```
Midas > outdisk/fits sun240s_npwrm.bdf sun240s_npwrm.fit
```

4.8.4 Plotting the entire Spectrum

For scientific investigation, the normalization process has to be performed much more accurately. Usually the profile needs to be normalized only in a defined, narrow wavelength range around the target wavelength of interest, for example around Hα.

For the creation of a synthetic black-and-white or color spectrum we recommend the software VisualSpec.

Fig. 44 shows the normalized spectrum **sun240s_npwrm.fit**

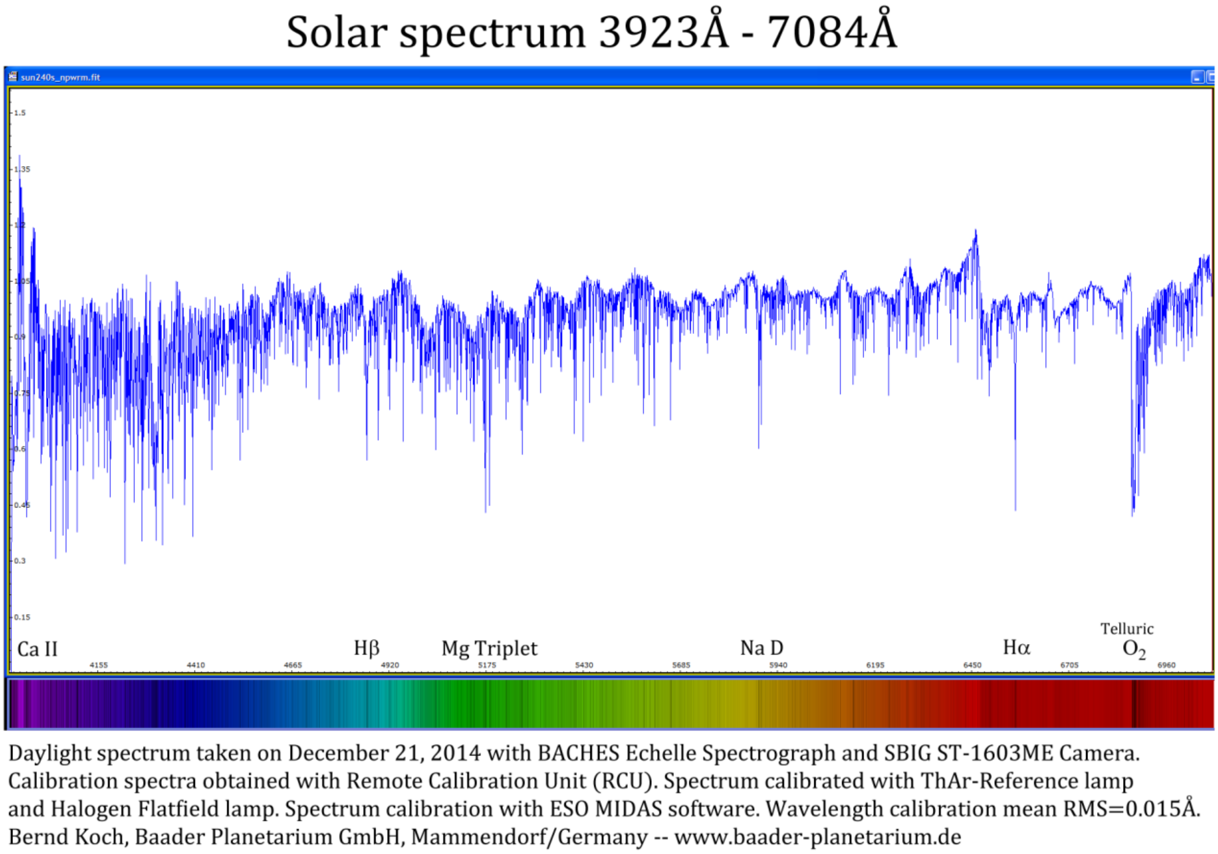


Fig. 44: Normalized spectral profile and synthesized color spectrum sun240s_npwrm.fit (ref: Fig. 40), created with VisualSpec Software.

In the following, the normalized daylight spectrum **sun240s_npwrm.fit** is examined in detail for the achieved calibration accuracy.

4.8.5 Calcium Lines Ca II K (3933.66Å) and H (3968.47Å) in the UV

```
Midas 022> plot/axes 3929,4000 0,1.5 0 "Wavelength" "rel. Intensity"
Midas 023> overplot sun240s_npwrm.fit
```

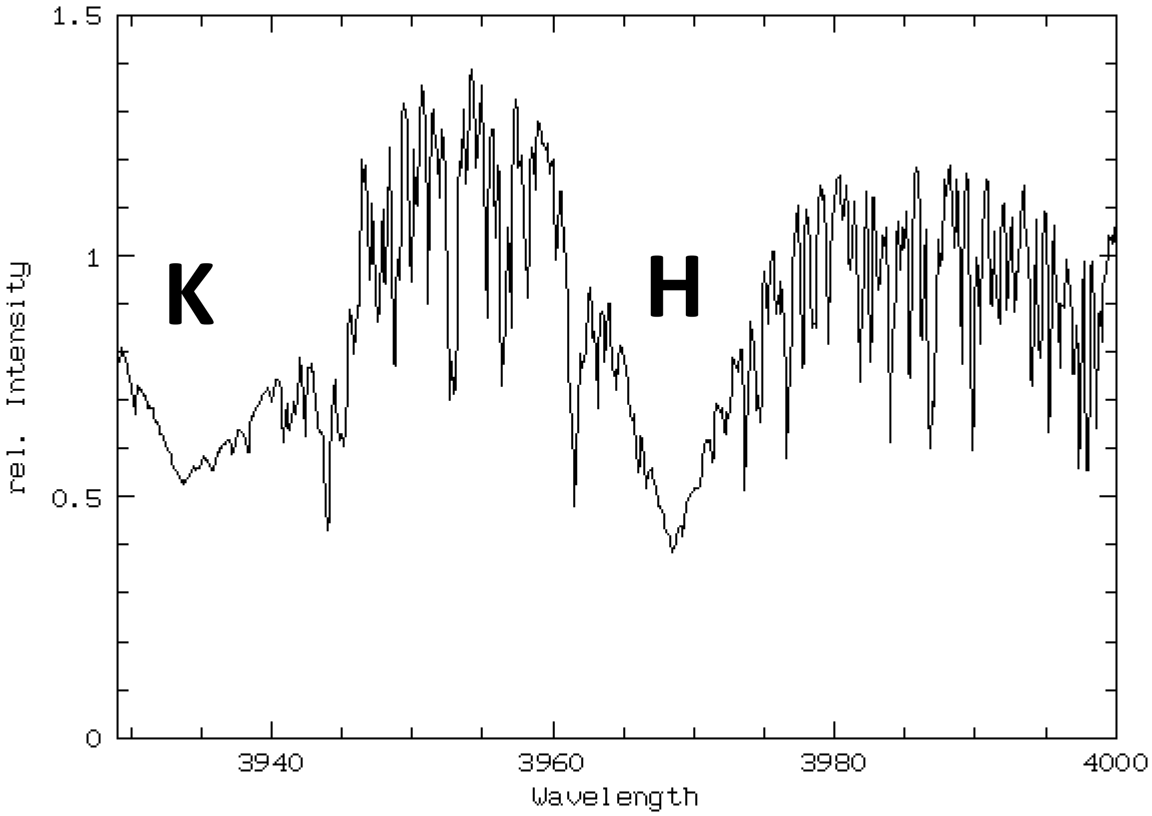
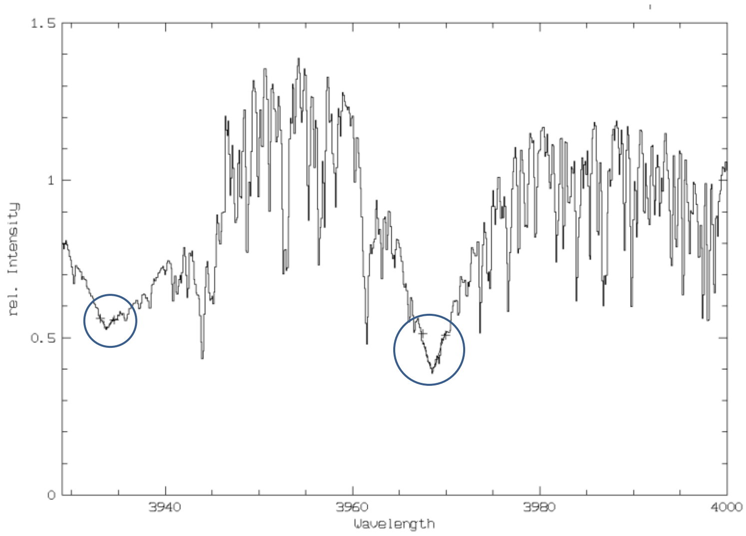


Fig. 45: The Calcium lines K & H in the solar spectrum. The profile is limited to ca. 3923Å in the UV due to the size of the sensor KAF-1603. A wider but less sensitive sensor like the KAF-8300 extends to ca. 3900Å.

```
Midas 013> center/gauss gcursor ? absorption
     start          end           center      pixel_value     FWHM

     3933.074      3934.555      3933.771    0.52652        0.74940
     3967.502      3969.946      3968.560    0.38664          1.6875
```



Note: The wings and cores of the Ca II lines deviate substancially from a fitted Gaussian profile. For measuring the line center, only a small range was used.

Fig. 46: Measured line centers and difference to observed wavelength (NIST Database).

$\Delta\lambda$=3933.771Å-3933.66Å=0.11Å
$\Delta\lambda$=3968.560Å-3968.47Å=0.09Å

4.8.6 Magnesium Triplet (5167.33Å / 5172.68Å / 5183.61Å)

```
Midas 017> plot/axes 5160,5190 0.4,1 0 "Wavelength" "rel. Intensity"
Midas 018> overplot sun240s_npwrm.fit
```

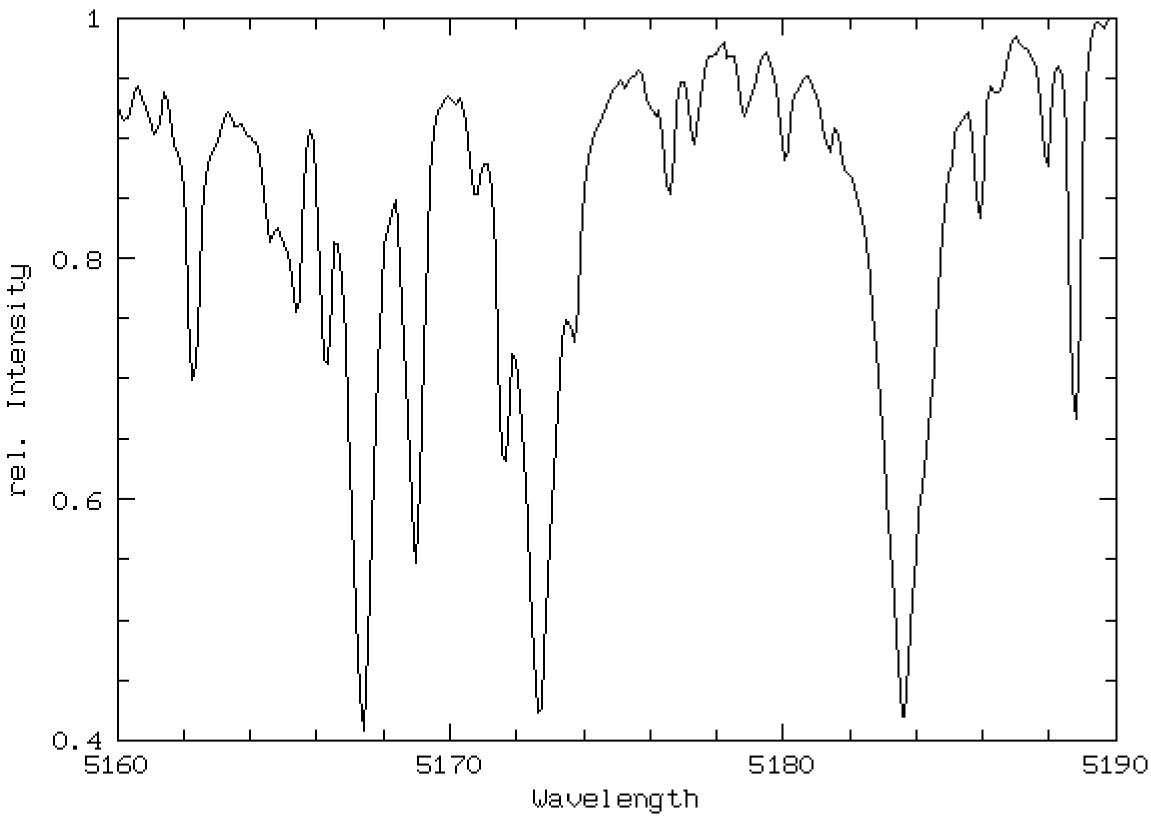


Fig. 47: Magnesium Triplet 5167.33Å, 5172.68Å, 5183.61Å

```
Midas 019> center/gauss gcursor ? absorption
     start          end          center      pixel_value     FWHM

     5166.572      5168.255      5167.370    0.40800       0.68790
     5172.042      5173.305      5172.682    0.42332       0.72136
     5180.699      5185.507      5183.640    0.41854         1.5486
```

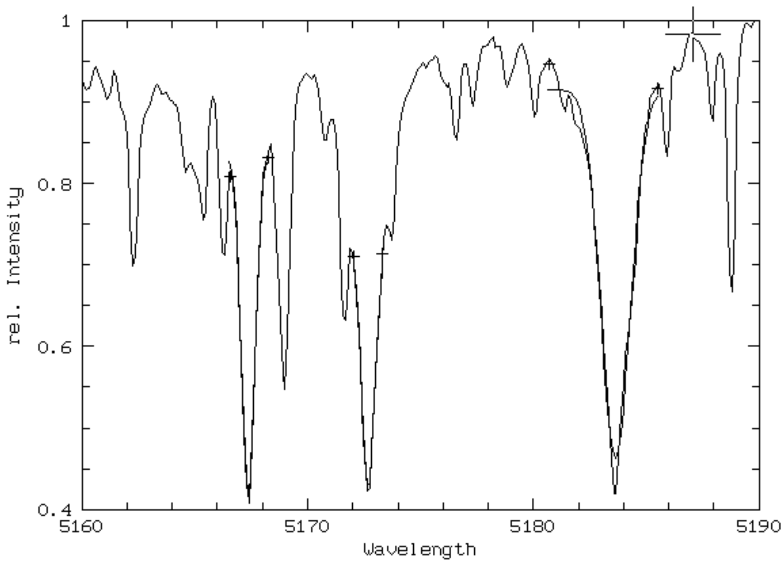


Fig. 48: Measured line centers and difference to observed wavelength (NIST Database):

$\Delta\lambda$=5167.370Å-5167.33Å= +0.04Å
$\Delta\lambda$=5172.68Å-5172.682Å=-0.02Å
$\Delta\lambda$=5183.64Å-5183.61Å=+0.03Å

4.8.7 Sodium Doublet (D_2: 5889.950Å / D_1: 5895.924Å)

```
Midas 012> plot/axes 5885,5900 0.4,1.1 0 "Wavelength" "rel. Intensity"
Midas 013> overplot sun240s_npwrm.fit
```

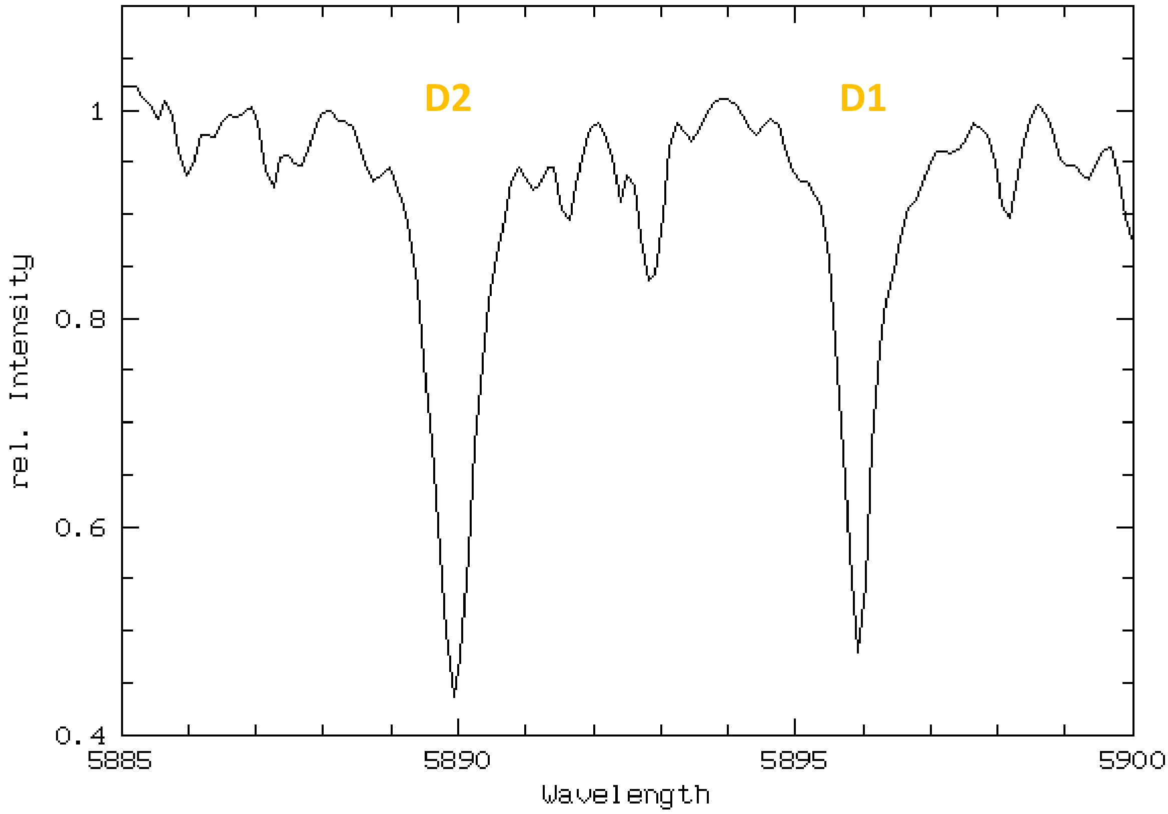


Fig. 49: The Sodium D lines D2: 5889.950Å and D1: 5895.924Å

```
Midas 014> center/gauss gcursor ? absorption
     start          end           center      pixel_value     FWHM

     5887.956       5892.013       5889.936   0.43685         0.75348
     5894.598       5897.724       5895.933   0.47956         0.61300
```

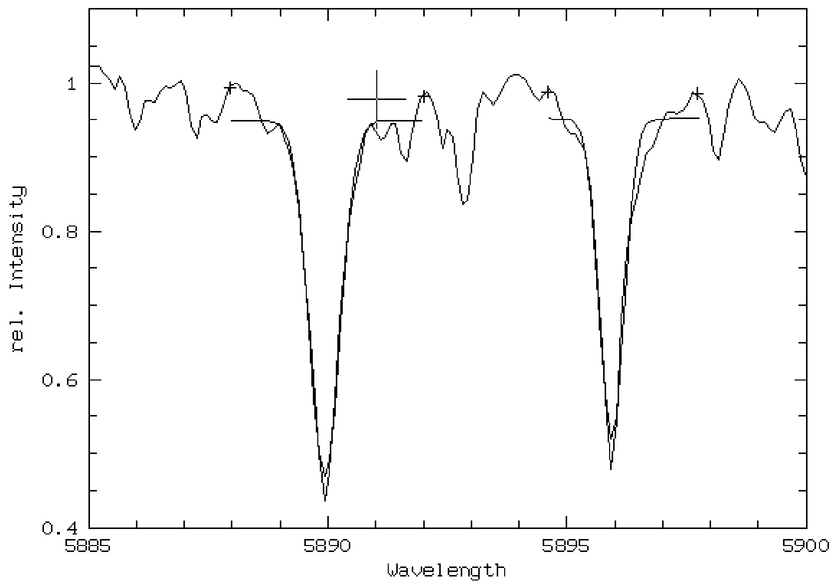


Abb. 50: Measured line centers and difference to observed wavelength (NIST Database).

D2: $\Delta\lambda$=-0.01Å
D1: $\Delta\lambda$=-0.009Å

4.8.8 Hα Line (6562.852Å)

```
Midas 008> plot/axes 6550,6580 0.4,1 0 "Wavelength" "rel. Intensity"
Midas 009> overplot sun240s_npwrm.fit
```

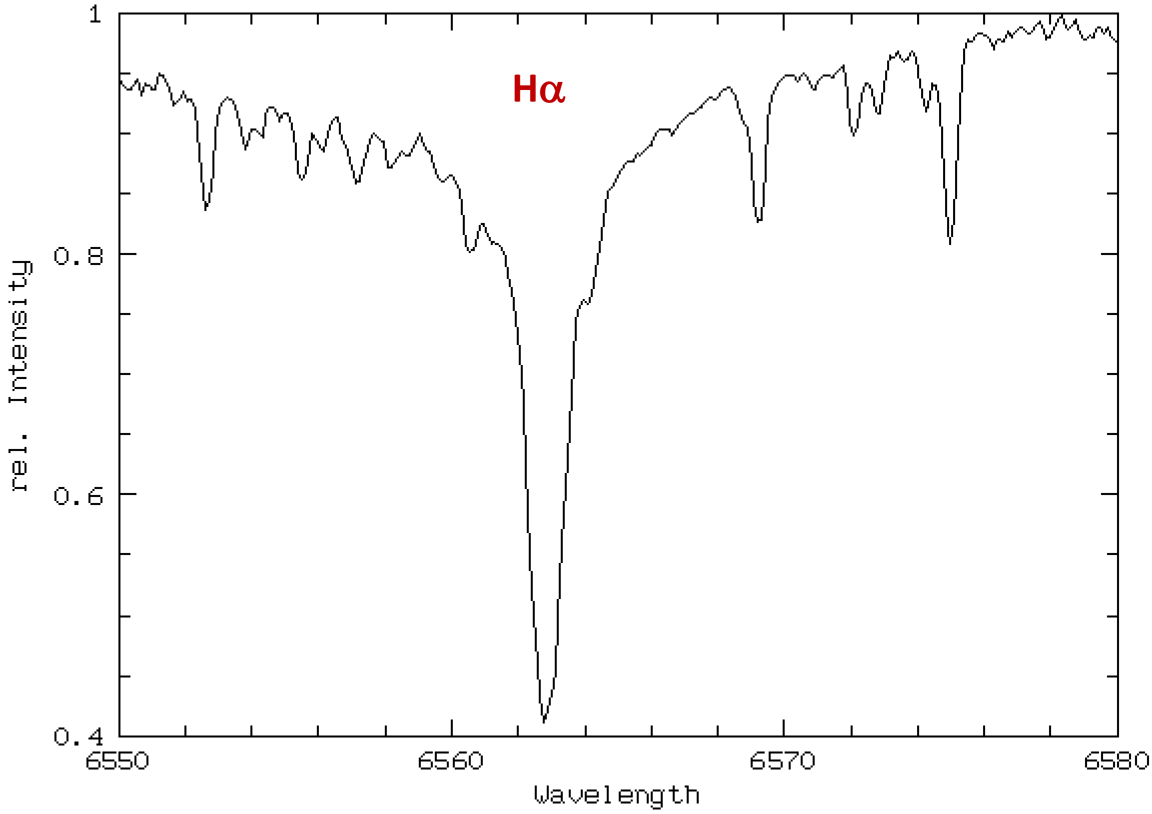


Fig. 51: Hα Line with telluric lines close-by.

```
Midas 006> overplot sun240s_npwrm.fit
Midas 007> center/gauss gcursor ? absorption
     start          end          center     pixel_value    FWHM

     6550.682      6579.535      6562.854   0.41775        1.8781
```

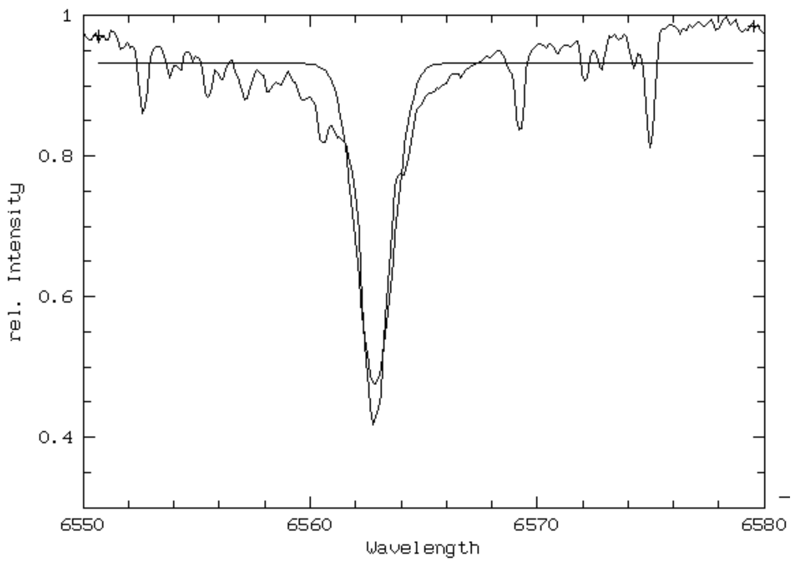


Abb. 52: Measured line center: Hα 6562.854Å.

Δλ=+0.002Å

FWHM: 1.8781Å

4.8.9 Fraunhofer B: O_2 Absorption in the Earth's Atmosphere

```
Midas 053> plot/axes 6860,6930 0,2 0 "Wavelength" "rel. Intensity"
Midas 054> overplot sun240s_pwrm.fit
```

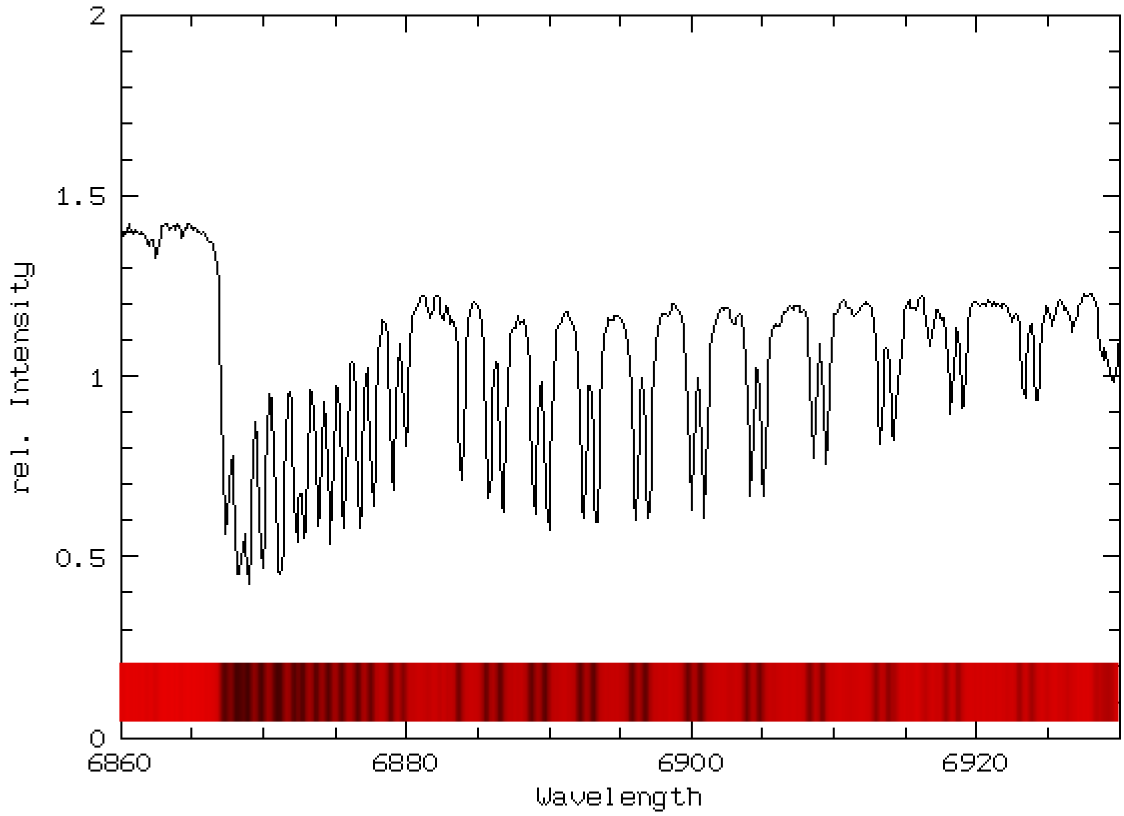


Fig. 53: Fraunhofer B. O_2 absorption in the Earth's atmosphere. MIDAS plot with synthezised color spectrum, created with VisualSpec software. Composite image in Photoshop.

4.9 Rebinning

With the command **rebin** the original spectrum profile is resampled. While this does not increase the actual resolution, it can improve the visual appearance of the spectrum.

Example: Spectrum profile **sun240s_npwrm.fit** rebined to 0.01Å/px. The letter “r” has to be added manually to the file name.

```
Midas > rebin/linear sun240s_npwrm.fit sun240s_rnprwrm.fit 0.01
```

```
Midas > plot/axes 6555,6570 0.3,1 0 "Wavelength" "Relative Intensity"
```

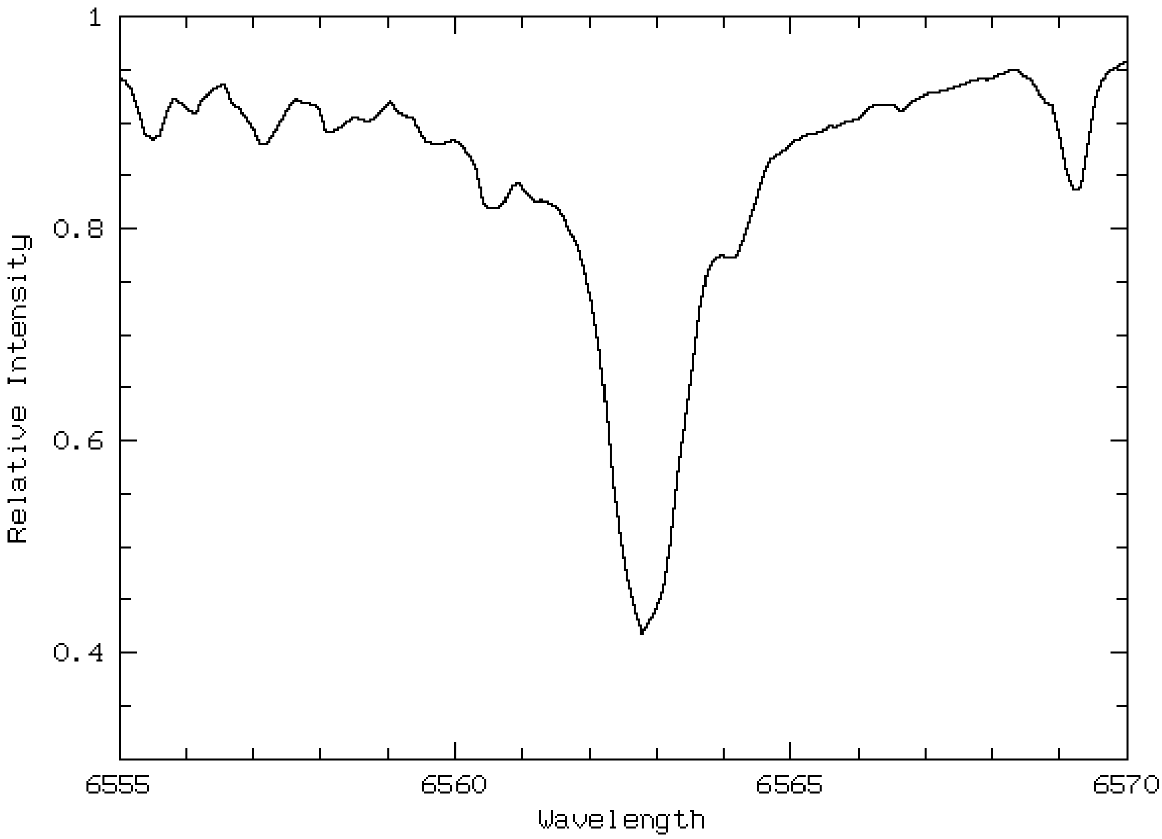


Fig. 54: Hα line in the rebinned daylight spectrum sun240s_rnpwrm.fit (0.01Å/px).

4.10 Signal-to-Noise Ratio

„In a normalized spectrum, noise is simply the standard deviation of the star signal. The ratio of the continuum intensity and the standard deviation is the signal-to-noise ratio S/N[10]".

Calculating the S/N of the normalized spectrum **sun240s_rnpwrm.fit** at 6500Å:

```
Midas > statis/imag sun240s_rnpwrm.fit [6500:6510]
```

```
Midas > comp 0.9602605 / 0.01601359
```

```
Midas 033> statis/imag sun240s_npwrm.fit [6500:6510]
frame: sun240s_npwrm.fit  (data = R4, format = FITS)
area [6500:6510] of frame
minimum, maximum:              9.156953e-01    9.793665e-01
at pixel (24101),(24154)
mean, standard_deviation:      9.602605e-01    1.601359e-02
3rd + 4th moment:                  -1.10113        3.60938
total intensity:                    90.2645
exact median, 1. mode, mode:   9.638411e-01   9.158202e-01   9.585173e-01
total no. of bins, binsize:         256      2.496911e-04
# of pixels used = 94 from 24062 to 24155 (in pixels)
Midas 034> comp 0.9602605 / 0.01601359
   59.96535
```

The signal is 0.9602605 (not exactly 1, since only roughly normalized), the standard deviation 0.01601359. Thus, the signal-to-noise ratio is S/N = 59.96535 ≈ 60

4.11 Exporting Spectral Profiles & Reading Tables

4.11.1 Exporting to FITS Format

Profiles in MIDAS' internal format BDF must be saved in FITS format to be processed in third-party spectroscopy software

```
Midas > outdisk/fits <file.bdf> <file.fits>
```

4.11.2 Exporting to Postscript Format

A graph window can be saved as Postscript file using the command

```
Midas > copy/graph postscript
```

The command must be typed exactly in this way. The saved file **postscript.ps** must be renamed afterwards.

4.11.3 Reading Tables

It is advisable to study the tables, which have been created by MIDAS during the calibration process.

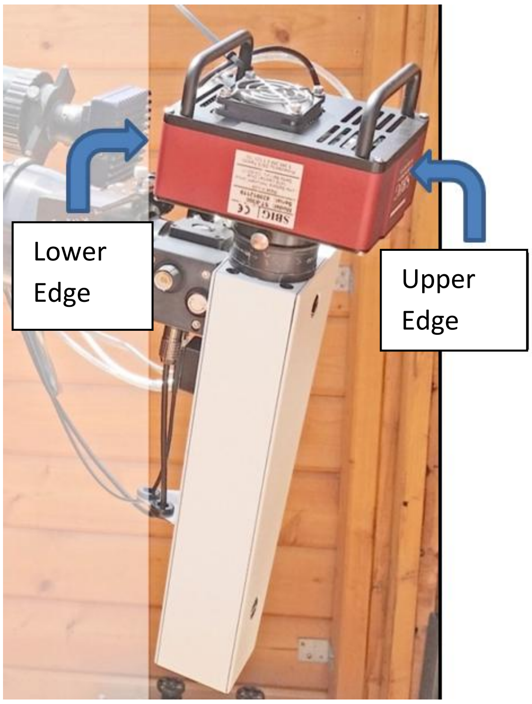
```
Midas > read/table <file.tbl>
```

[10] Günther Gebhard, "Erste Schritte in ESO-MIDAS", February 14, 2013 at www.spektros.de (in German only)

5 Calibration of a Daylight Spectrum of the ST-8300M CCD Camera

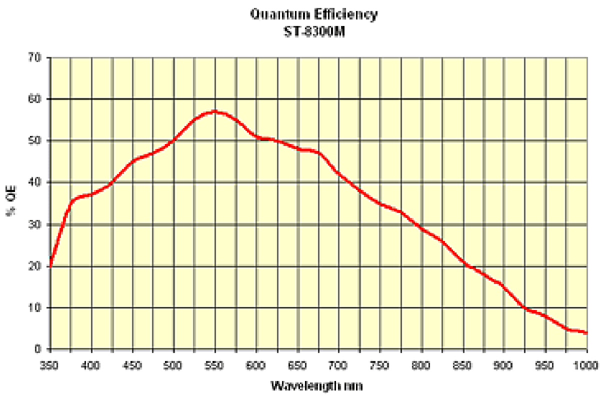
Please, first perform the calibration using the exercise files taken with the ST-1603ME camera, because the whole procedure was described in full detail. Thereafter you will be guided through the calibration of the ST-8300M spectra, where only the differences from the 1603 procedures will be explained in full detail.

5.1 ST-8300M Technical Data



Note on the camera: The BACHES echelle spectrograph has been optimized for a CCD pixel size of 9µm. The SBIG ST-8300M in this example oversamples with its actual 5.4µm pixel size. In 2x2 binning mode, the effective 10.8µm pixel size result in a somewhat lower spectral resolution, although fainter stars are within reach. Depending on the scientific application, one must choose the suitable camera binning. For the measurement of stellar flux only – the key figure is the Equivalent Width EW[11] - a 2x2 camera binning with 10.8µm pixel size is pretty sufficient. For measuring Doppler shifts precisely, one may choose 1x1 binning, but only for brighter stars as compared to 2x2 binning. The successor to the SBIG ST-8300M, with the same sensor, is the SBIG STF-8300M[12]

Fig. 55: The body of the BACHES echelle spectrograph is attached to the C14 Edge HD in north/south direction. The lower edge of the ST-8300M faces the telescope.



CCD	
CCD	Kodak KAF-8300
Pixel Array	3326 x 2504 pixels
CCD Size	17.96 x 13.52 mm
Total Pixels	8.3 million
Pixel Size	5.4 x 5.4 microns square
Full Well Capacity	~25,500 e-
Dark Current	~0.02e-/pixel/sec at -10C.
Antiblooming	1000X
Readout Specifications	
Shutter	Mechanical
Exposure	0.12 to 3600 seconds, 10ms resolution
Correlated Double Sampling	Yes
A/D Converter	16 bits
A/D Gain	TBD (prototype = 0.38e-/ADU)
Read Noise	~8e- rms
Binning Modes	1 x 1, 2 x 2, 3 x 3
Pixel Digitization Rate	> 1 million pixels per second
Full Frame Download	~7.7 seconds
Focus Mode	~1 second

Fig. 56: Technical Data and quantum efficiency of the ST-8300M. Successor with the same sensor is the STF-8300M.

[11] The „Equivalent Width“ (EW) is a measure for the stellar flux of an absorption or emission line.
[12] http://www.sbig.de/stf-8300/stf-8300.htm

5.2 Daylight and Calibration Spectra of the ST-8300M CCD Camera

The main difference between the two cameras ST-1603ME and ST-8300M is the different quantum efficiency (QE) of the sensors. The lower QE of the KAF-8300M demands a significantly longer exposure time to obtain the same signal-to-noise ratio. This can be achieved by averaging a couple of individual exposures, each exposed to about 50,000ADU, well below the saturation limit of 65,535ADU of a 16-bit camera. The advantage of the KAF-8300M sensor is the larger size to cover more spectral orders.

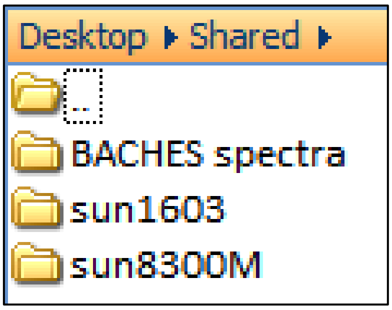
The following spectra have been recorded with the ST-8300M camera in 2x2 binning mode. The effective pixel size is 10.8µm. BACHES slit width: 25µm.

The ZIP-file sun8300M.zip contains the folder sun8300M with the following files:

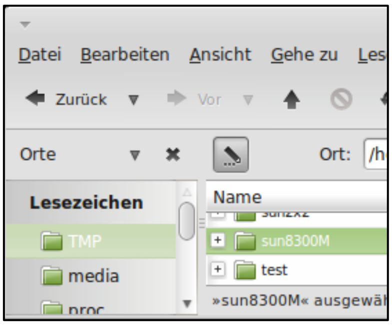
ff20sav.fit: flatfield spectrum taken with the RCU halogen lamp. The file is an average of 50 individual exposures, each exposed for 20s.

thar80sav.fit: Thorium-Argon reference spectrum of the RCU ThAr lamp. The file is an average of 10 individual exposures, each exposed for 80s.

sun360s.fit: daylight spectrum, 360s exposed.



WINDOWS: First, please copy the unzipped folder **sun8300M** to the folder **Shared**.



LINUX: Copy the folder to the temporary folder **TMP**. The folder **sun8300M** contains the files **ff20sav.fit**, **thar80s.sav.fit,** and **sun360s.fit**

The working directory:

```
MIDAS > ch TMP/sun8300M
```

Listing the contents:

```
MIDAS > $ls
```

5.2.1 The Flatfield Spectrum of the Halogen lamp

The flatfield spectrum (**ff20sav.fit**) recorded with the halogen lamp provides two features: first, it corrects for dust; second, it is imperative for a semi-automatic wavelength calibration with MIDAS. MIDAS detects the position of the orders by the flatfield spectrum, transfers the local information to the ThAr reference, and then to the object spectrum (Fig. 57).

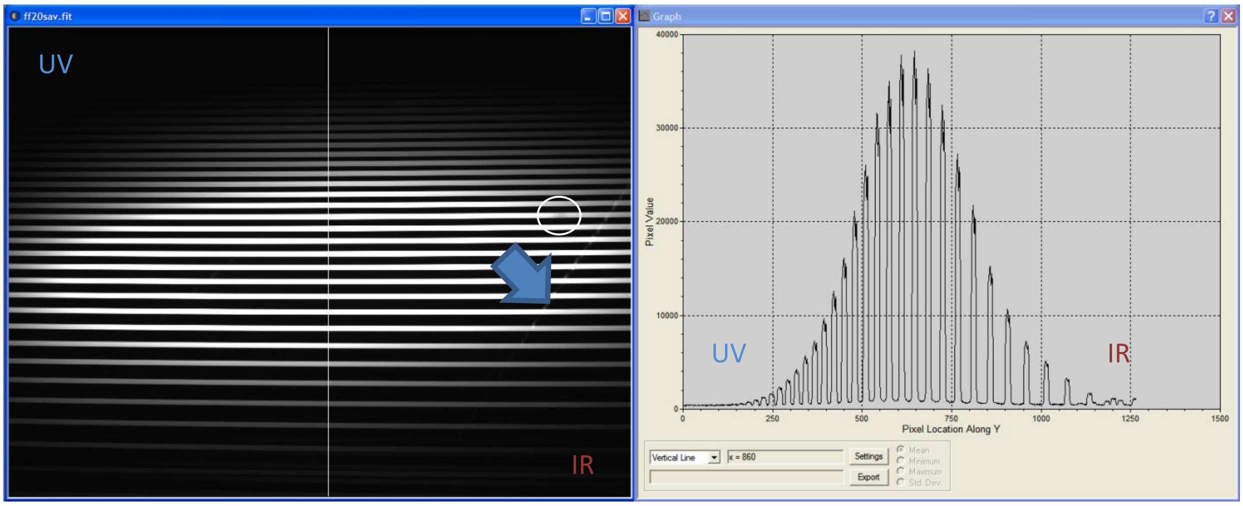


Fig. 57: Flatfield spectrum obtained with the RCU Halogen lamp. Average of 50x20s with a ST-8300M. Right: Vertikal scan across the spectrum in the center. The maximum intensity is well below the saturation limit of 65,535ADU. 30 Orders are recorded, as well as a dust spot (circle). The blue arrow point to reflections within the spectrograph. 27 of totally 30 orders can be detectd by MIDAS. That is a great result!

5.2.2 The Reference Spectrum of the ThAr Lamp

Due to its larger size, the KAF-8300M sensor catches significantly more orders than the KAF-1603ME, but at the cost of a lower signal-to-noise ratio. In the UV (Fig. 58, top) the limit is almost the same, but you have to increase the SNR by averaging a couple of images. Since higher orders overlap in the Infrared (IR), MIDAS is not able to process detected orders in that region. (By the way, you can utilize these IR orders by scanning and calibrating them individually with, for example, VisualSpec software. But let us now continue with the calibration process in MIDAS.)

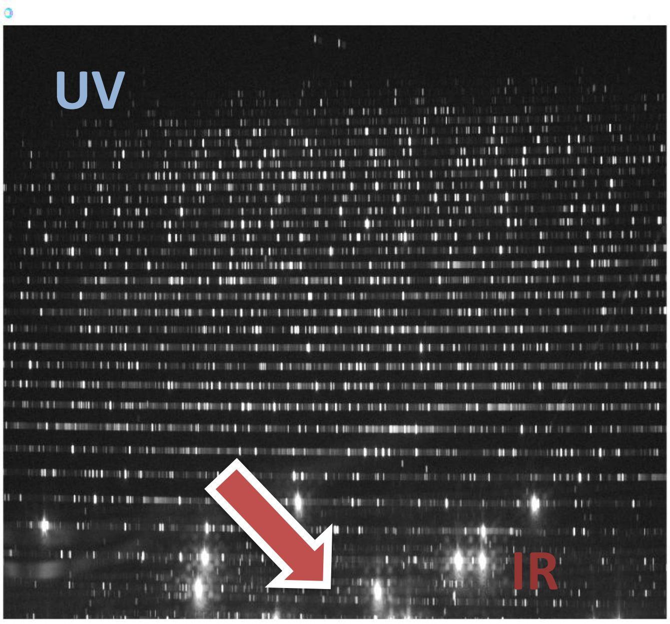


Fig. 58: ThAr spectrum, average of 10x80s (ST-8300M). The overlapping orders in the IR (red arrow) limit the semi-automatic detection of orders by MIDAS. But it works well between ca. 3900Å and 7600Å with this sensor.

5.2.3 The Daylight Spectrum

The recording of the solar spectrum can be done in the room without even using a telescope. Just point the spectrograph to a patch of the sky. It doesn't matter if the sky is clear or raining: The Earth's atmosphere scatters the sunlight.

Fig. 59 shows a daylight spectrum (**sun360s.fit**), where the atmospheric water vapor and oxygen lines are superimposed around and below the Hα order. Clearly visible are Hα, the Sodium doublet lines Na D1/D2, and the magnesium triplet. The typical G2 V spectrum starts in the UV (upper left) well ahead of the Ca II K line at ca. 3900Å, and it ends up in the infrared (lower right) around 7600Å. The exposure time was chosen to limit the intensity in the green range of the spectrum to about 50,000 ADU to avoid saturation and to ensure a correct radiometric correction. Since all sensors are less sensitive in the UV, spectral lines may be weak in this spectral region. You should take this into consideration of the total exposure of the spectrum which can be stacked from several partial exposures with different exposure times.

5.2.4 Edit "threshold" (Line 84)

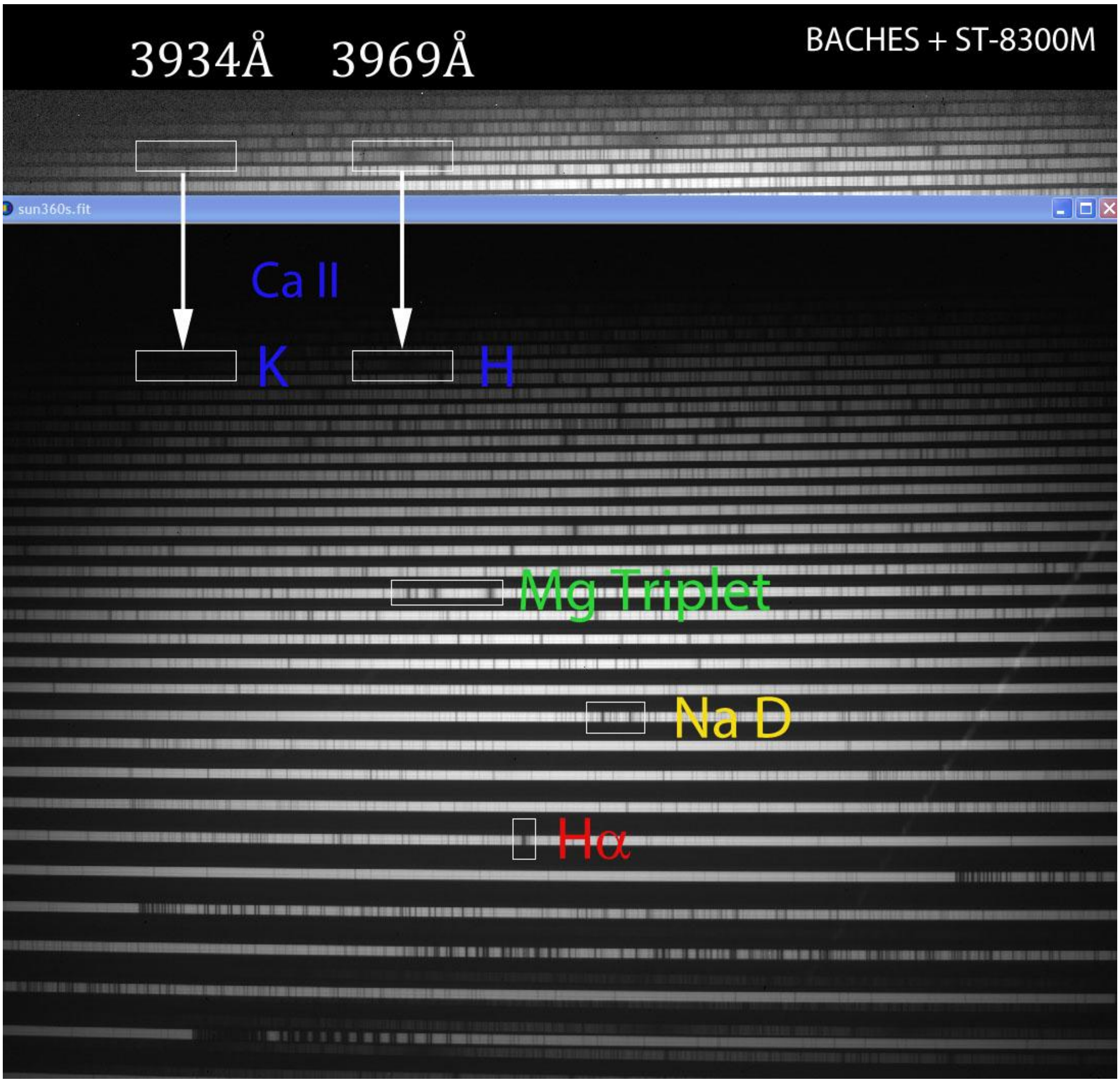


Fig. 59 : Daylight spectrum sun360s.fit, 360s exposed with a ST-8300M CCD camera. Spectral class G2V. Spectrum from blue (upper left) to red (lower right). The important Ca II lines K and H are well recorded. The spectrum ranges from ca. 3900Å to ca. 7600Å.

The threshold value affects the detection of reference lines in the ThAr reference spectrum. If too few reference lines are used in the calibration process (less than 50% of all lines detected), the threshold value must be lowered. If more than 60% are used, nothing must be changed.

Edit line 84 as following:

For ST-8300M (KAF-8300) use: DEFINE/LOCA threshold/i/1/1 2

We refer to section 4.5.1 for further information on how to access the threshold value in a LINUX operating system. If threshold = 2 does not work properly, please try another value.

5.2.5 Detection of the Spectral Orders and Wavelength Calibration of the ThAr Spectrum

Now let's start the calibration process. First, the **flatfield spectrum (ff20sav.fit)** is loaded. The intention is to identify a specified number of orders, and align each order horizontally. **Without flatfield, a reliable detection of orders is impossible.** Thereafter, the **reference spectrum (thar80sav.fit)** will be scanned for wavelength calibration.

In this example, MIDAS willl try to detect 27 orders.

`Midas > calib/baches ff20sav.fit thar80sav.fit 27`

```
PARAMETERS FOR THIS CALIBRATION:
===============================
Flat field  = ff20sav.fit
Calibration lamp = thar80sav.fit
Calibration table = thar.fit
Num. of orders  = 0027
Slit order width = 0020
Slit extraction width = 0020
Offset from center slit = 0.00000E+00
Tolerance on RMS = 1.00000E+00
Polynomial degree  = 0004
Threshold = 0002

baches_calib: Do you want to continue [yn] (y)?
```

Confirm with "y".

MIDAS presents an intensity scan of the flatfield spectrum (Fig. 60). Set the left and the right limits (+). If not all of the requested 27 orders are detected, terminate the process and set new left and right limits. The calculated green lines must lie exactly on the detected Flatfield orders (Fig. 61).

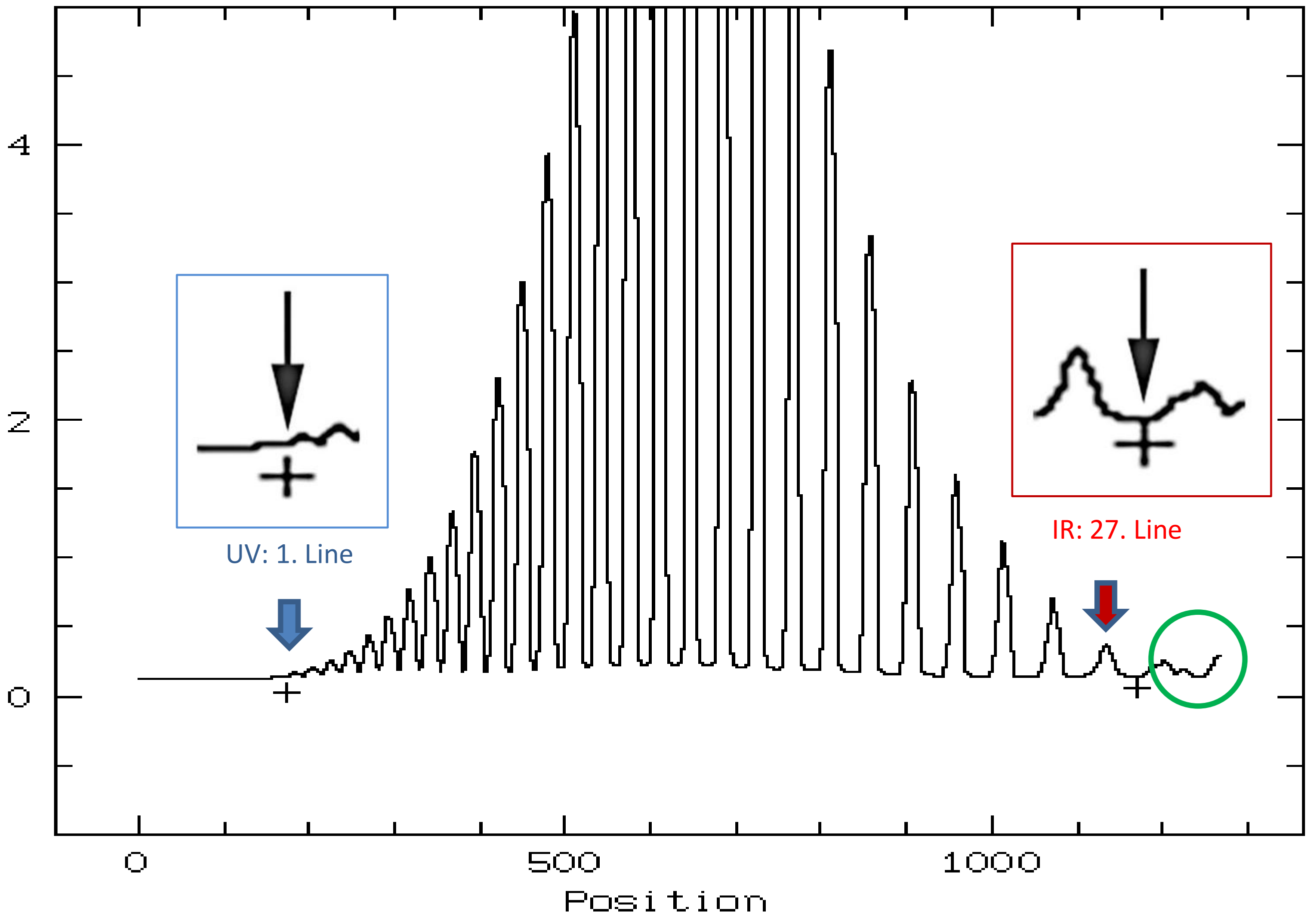


Fig. 60: The first cross must be set just to the left of the first completely detected order in the UV. The second cross at right limits the last order in the IR. Note: Never click outside the sensor field, which causes an error message. Green circle: Overlapping orders cannot be properly detected by MIDAS. You may scan them manually with VisualSpec or other software.

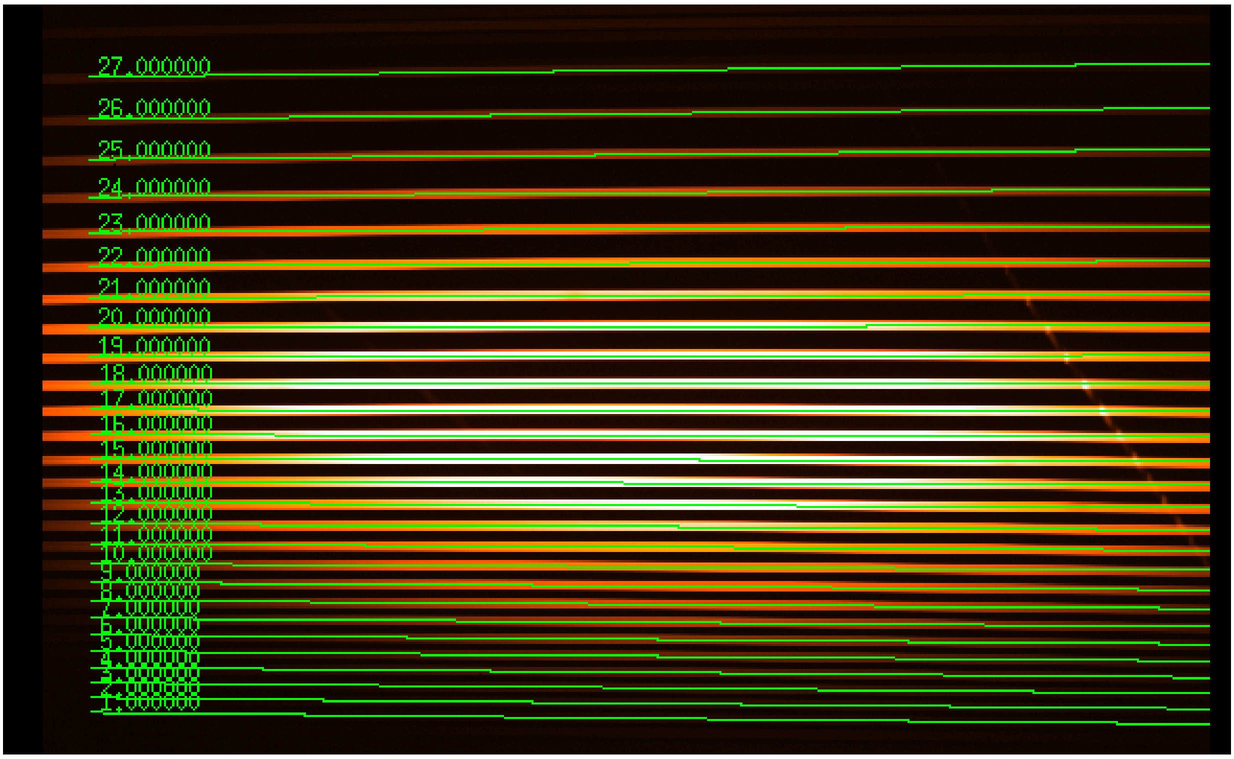


Fig. 61: Successful detection of 27 orders. If MIDAS detects less orders or plots slanted lines, try again.

Successful detection of 27 orders:

```
Order:   1  Threshold: 566.743994  Numb. of values: 123
Order:   2  Threshold: 673.768002  Numb. of values: 122
Order:   3  Threshold: 809.327991  Numb. of values: 127
Order:   4  Threshold: 1025.370016  Numb. of values: 126
Order:   5  Threshold: 1271.829962  Numb. of values: 129
Order:   6  Threshold: 1625.679944  Numb. of values: 131
Order:   7  Threshold: 1997.306055  Numb. of values: 134
Order:   8  Threshold: 2507.056036  Numb. of values: 138
Order:   9  Threshold: 3245.210114  Numb. of values: 138
Order:  10  Threshold: 4126.802087  Numb. of values: 139
Order:  11  Threshold: 5246.679852  Numb. of values: 142
Order:  12  Threshold: 6706.459802  Numb. of values: 140
Order:  13  Threshold: 8299.739819  Numb. of values: 144
Order:  14  Threshold: 9903.080017  Numb. of values: 146
Order:  15  Threshold: 11673.207587  Numb. of values: 151
Order:  16  Threshold: 12866.501569  Numb. of values: 151
Order:  17  Threshold: 12629.267949  Numb. of values: 156
Order:  18  Threshold: 12152.803079  Numb. of values: 157
Order:  19  Threshold: 10756.399178  Numb. of values: 162
Order:  20  Threshold: 9088.611781  Numb. of values: 165
Order:  21  Threshold: 7439.622569  Numb. of values: 165
Order:  22  Threshold: 5236.170721  Numb. of values: 166
Order:  23  Threshold: 4832.180804  Numb. of values: 151
Order:  24  Threshold: 3393.008908  Numb. of values: 158
Order:  25  Threshold: 2403.683926  Numb. of values: 159
Order:  26  Threshold: 1608.701971  Numb. of values: 156
Order:  27  Threshold: 940.487970  Numb. of values: 152
```

All orders are listed with reliable numbers. Calibration will surely work.

```
baches_calib: Order identification finished
baches_calib: Do you want to continue [yn] (y)?
```

Confirm with “y“.

The semi-automatic calibration is carried out by assigning two pairs of spectral lines according to Fig. 62 and following.

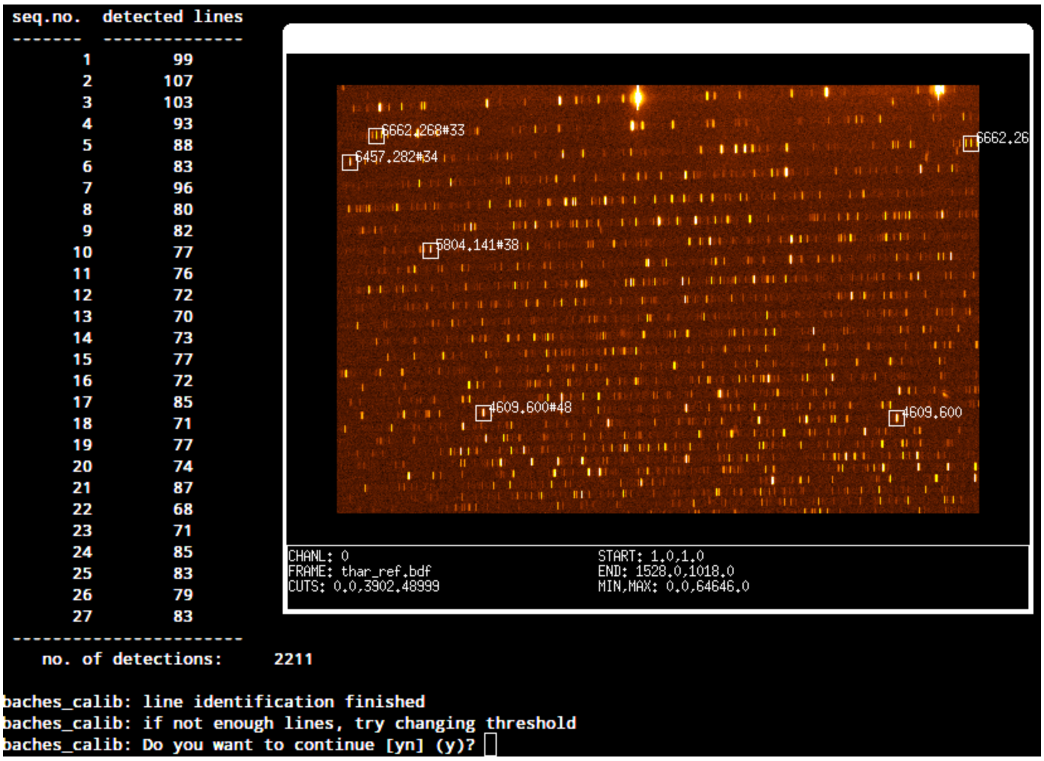


Fig. 62: In total 2,211 ThAr spectral lines have been detected within 27 orders.

Now, successively click at the following lines:

6662.268Å in order 33 (1. click top left, 2. click top right)

4609.600Å in order 48 (3. click bottom left, 4. click bottom right)

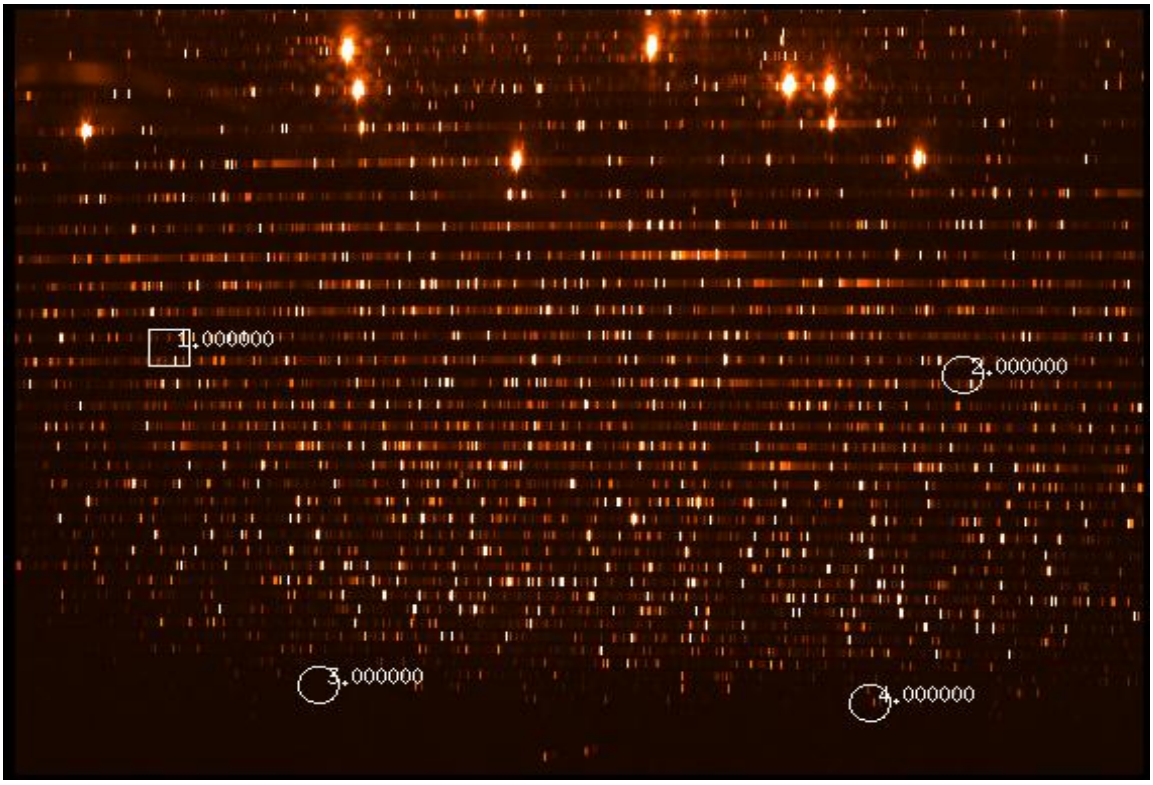


Fig. 63: MIDAS confirms the four clicks with this image.

The KAF-8300M is larger than necessary for a complete spectral calibration from the UV to the IR without wavelength gaps. So, an even larger sensor does not make sense. All by MIDAS identified spectral lines from the ThAr atlas are marked in Fig. 64. The residual error of the wavelength calibration is plotted in Fig. 65. The calibration of the 27 orders from #30 through #56 is very precise.

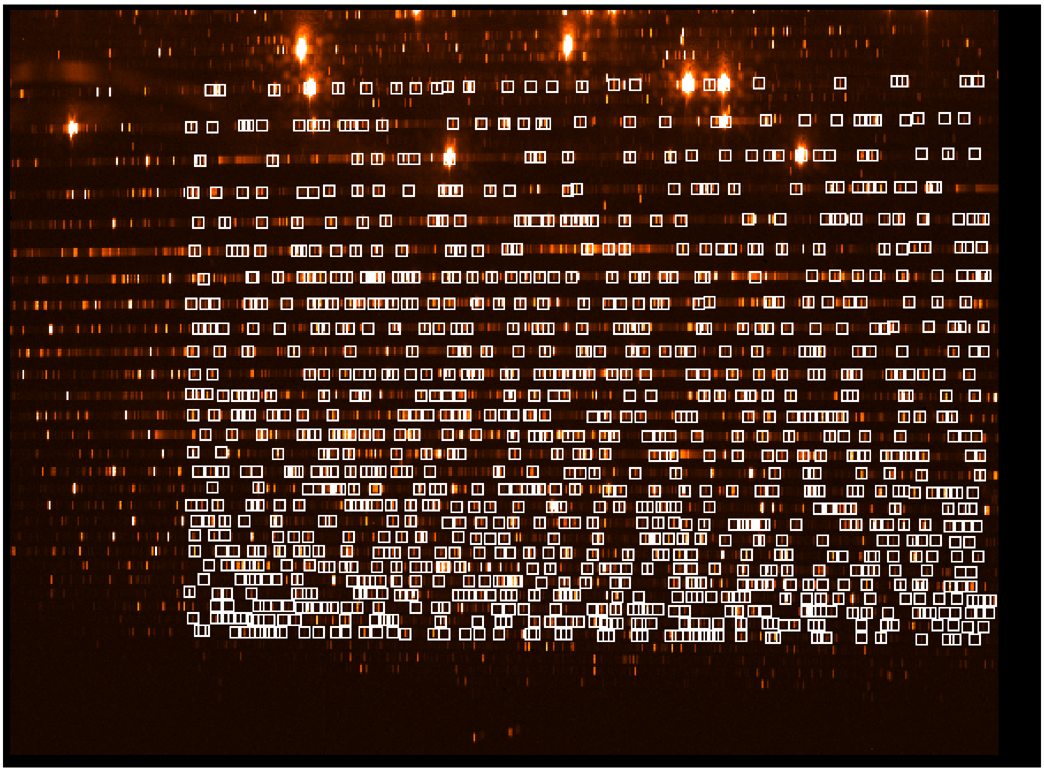


Fig. 64: By MIDAS identified ThAr lines.

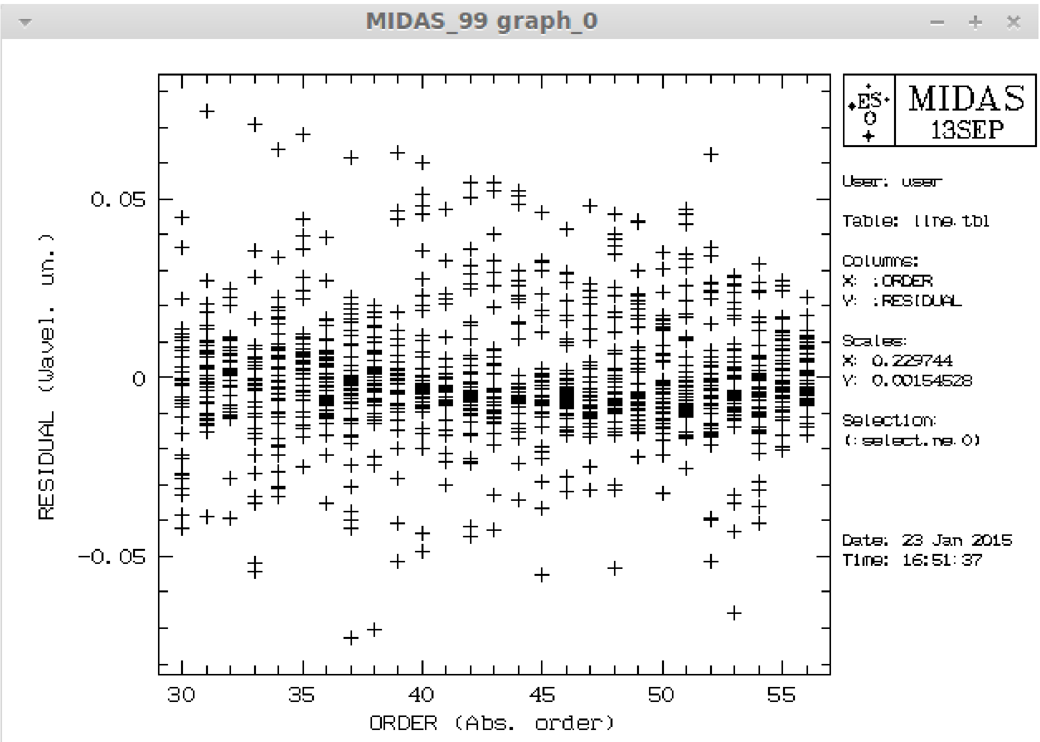


Fig. 65: Residual error of the wavelength calibration vs. absolute order #30 to #56. A precise result.

The result of the wavelength calibration is listed in the terminal window. 27 orders from ca. 3900Å to 7600Å, mean RMS = 0.01682Å. We recommend frequently saving the contents of the terminal window in a separate text file by copy & paste.

```
 SEQ.NO  SPECTRAL  NO.LINES  WL START    WL END  STD. DEV.
          ORDER                                  ANGSTROEM
 ------  --------  --------  --------    ------  ---------
      1        56        50   3902.71   4070.94    0.00819 *FROM 2D SOLUTION*
      2        55        52   3973.58   4144.95    0.01131 *FROM 2D SOLUTION*
      3        54        53   4047.09   4221.69    0.01450 *FROM 2D SOLUTION*
      4        53        48   4123.36   4301.31    0.01789 *FROM 2D SOLUTION*
      5        52        45   4202.57   4383.99    0.02023 *FROM 2D SOLUTION*
      6        51        46   4284.89   4469.90    0.01812 *FROM 2D SOLUTION*
      7        50        48   4370.50   4559.25    0.01396 *FROM 2D SOLUTION*
      8        49        43   4459.60   4652.23    0.01578 *FROM 2D SOLUTION*
      9        48        48   4552.43   4749.08    0.01937 *FROM 2D SOLUTION*
     10        47        47   4649.20   4850.04    0.01414 *FROM 2D SOLUTION*
     11        46        52   4750.18   4955.39    0.01408 *FROM 2D SOLUTION*
     12        45        43   4855.66   5065.42    0.01862 *FROM 2D SOLUTION*
     13        44        38   4965.92   5180.44    0.02010 *FROM 2D SOLUTION*
     14        43        43   5081.32   5300.81    0.01906 *FROM 2D SOLUTION*
     15        42        50   5202.22   5426.90    0.01880 *FROM 2D SOLUTION*
     16        41        37   5329.01   5559.14    0.01468 *FROM 2D SOLUTION*
     17        40        51   5462.14   5697.99    0.01997 *FROM 2D SOLUTION*
     18        39        37   5602.09   5843.95    0.02041 *FROM 2D SOLUTION*
     19        38        49   5749.41   5997.59    0.01429 *FROM 2D SOLUTION*
     20        37        51   5904.69   6159.53    0.01987 *FROM 2D SOLUTION*
     21        36        51   6068.58   6330.45    0.01196 *FROM 2D SOLUTION*
     22        35        40   6241.83   6511.14    0.01893 *FROM 2D SOLUTION*
     23        34        42   6425.27   6702.45    0.01813 *FROM 2D SOLUTION*
     24        33        38   6619.80   6905.35    0.02190 *FROM 2D SOLUTION*
     25        32        34   6826.48   7120.91    0.01267 *FROM 2D SOLUTION*
     26        31        39   7046.48   7350.38    0.01688 *FROM 2D SOLUTION*
     27        30        36   7281.12   7595.13    0.02029 *FROM 2D SOLUTION*
 ---------------------------------------------------------
                                     MEAN RMS:     0.01682
** TOTAL NUMBER OF LINES :    1211 **
**************************  Verification  ***********************************

1) Minimum number of selections per order : 6
   If the number of selections in any order (column NO.LINES above)
   is less or equal than the minimum, this order should be checked.

2) Percentage of identifications among the half brighter lines : 81 %
   This percentage must be as high as possible (above 50%). Low values
   indicate an uncertain calibration.

Set parameters SAMPLE=0.1316690445 and RIPK=122378.65625
Process tables are saved
baches_calib: Identification completed after 0010 iterations.
FITS file bachesORDE.fit will have 1 extensions
bachesORDE.tbl written to FITS file bachesORDE.fit
FITS file bachesLINE.fit will have 1 extensions
bachesLINE.tbl written to FITS file bachesLINE.fit
baches_calib: Do you want to clean temporary files [yn] (y)?
```

Confirm deleting the temporary files with a “y”, and follow the instruction for the calculation of the average spectral resolution: R=20,928 +/- 10% (Fig. 66).

```
Average (kappa-sigma-cleaned) resolution power: 2.09288E+04 +/- 2.15591E+03
```

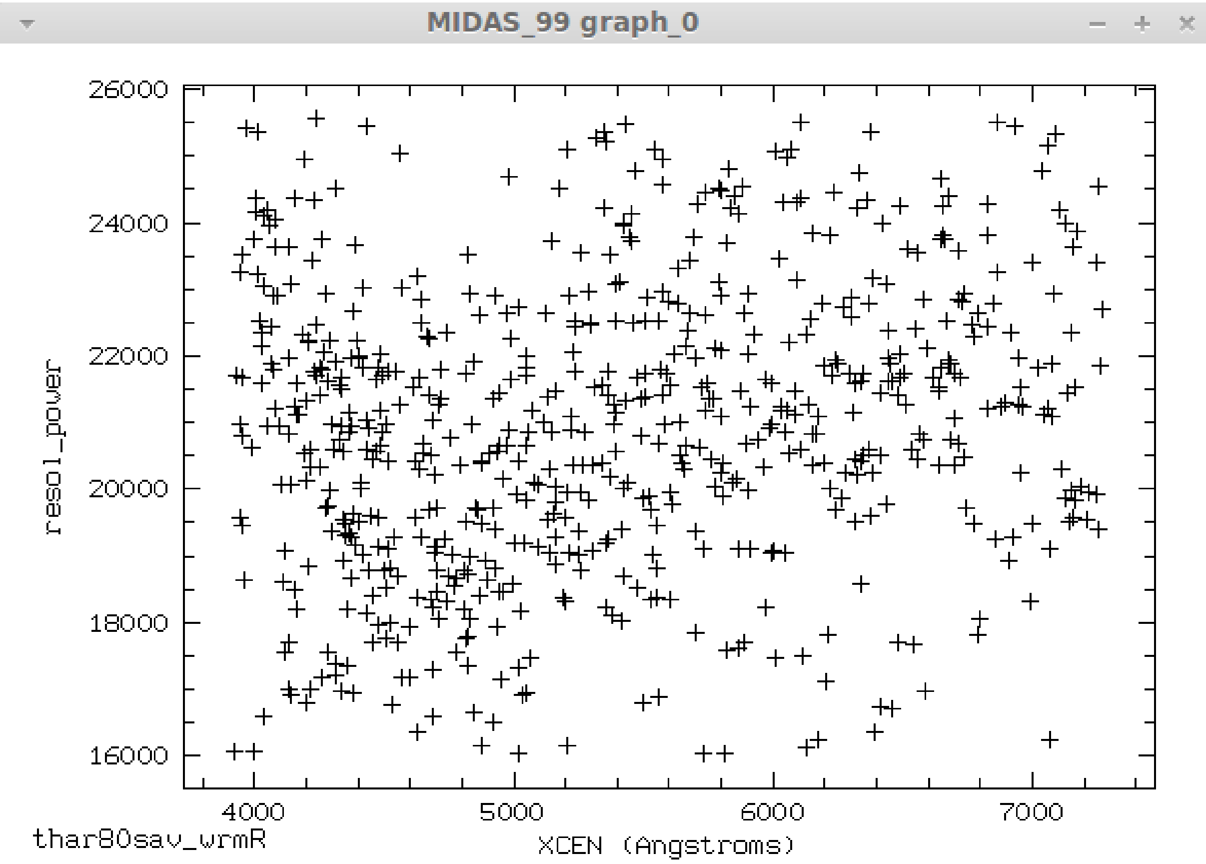


Fig. 66: The average spectral resolution of the ThAr spectrum (thar80sav_wrm.fit). Mean RMS R=20,928 +/- 10%.

5.2.6 Creation of a Masterflat

Calibration with a darkframe (or a masterdark) can be performed with the camera image recording software. In the present image **sun360s.fit,** a darkframe already has been subtracted. The calibration with the flatfield **ff20sav.fit** in MIDAS is now described. This flat corrects for dust on the optical elements in the light path or on the camera sensor. At first, a file called **master_flat.bdf** must be created from the flatfield **ff20sav.fit.**

```
Midas > indisk/fits ff20sav.fit master_flat.bdf
```

Note: The masterflat must be named exactly as shown, because it is retrieved later by the script **baches_pipeline.prg** under this name!

```
Midas 006> indisk/fits ff20sav.fit master_flat.bdf
no CDELTi nor CDi_j matrix found... STEPi set to 1.0
FITS file: ff20sav.fit converted to: master_flat.bdf
Midas 007>
```

5.2.7 Calibration of the Stellar Spectrum with the Masterflat

Midas > pipeline/baches sun360s.fit

The pipeline script converts the file into the MIDAS format ".bdf" and automatically performs the Flatfield correction, indicated by a "p" using the file **master_flat.bdf.** Then the wavelength calibration follows, indicated by a "w". All detected orders are rebined "r" to the same scale and merged "m" to a spectral profile.

The file **sun360s_pwrm.fit** is the resulting spectral profile after performing the following commands:

p: flatfield calibration
w: wavelength calibration
r: rebinning to the same scale
m: merging all detected orders

Plotting the spectral profile (Fig. 67):

Midas > crea/grap

Midas > plot/axes 3800,8000 0,10 0 "sun360s_pwrm.fit -- Wavelength" "rel. Intensity"

Midas > overplot sun360s_pwrm.fit

```
Midas 011> plot/axes 3800,7600 0,10 0 "sun360s_pwrm.fit -- Wavelength" "rel. Intensity"
Midas 012> overplot sun360s_pwrm.fit
```

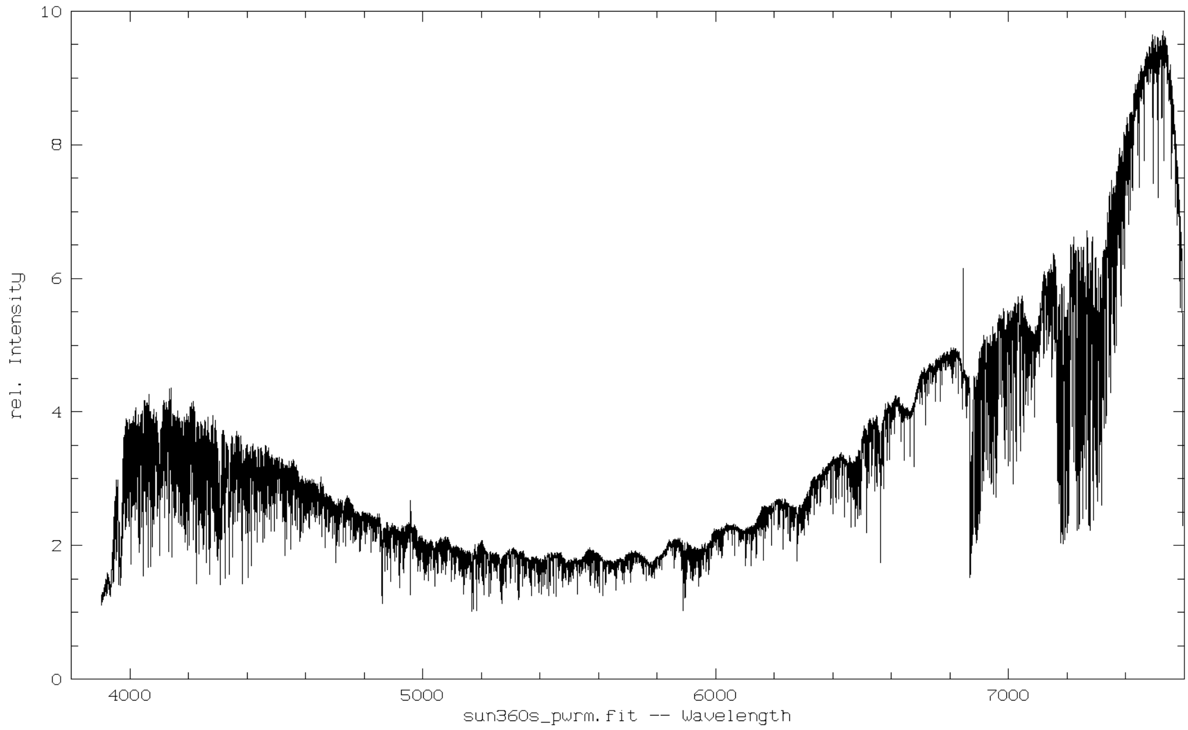


Fig. 67: Wavelength calibrated profile sun360s_pwrm.fit after flatfielding with the Masterflat.

5.2.8 Normalization of the Stellar Spectrum

For a couple of investigations of a stellar spectrum, a relative measurement to a normalized continuum level, usually set at "1", is sufficient[13]. Only for the purpose of measuring the absolute flux, for example the determination of the intensity maximum of an adapted Planck radiation curve, is an absolute calibration with the help of a reference star necessary.

For normalization, the "pseudo-continuum" is extracted from the spectral profile (Fig. 67) of the star, then smoothed, and subsequently divided into the target spectrum. The pseudo-continuum is influenced by various factors such as the quantum efficiency of the camera sensor and the selective absorption of the Earth's atmosphere. The division result is an instrumental function called "Response".

First, add a couple of additional echelle commands to the content:

`Midas > set/cont echelle`

Calculation of the response function **response.bdf**

`Midas > normalize/spec sun360s_pwrm.fit response.bdf`

Now please have a look at Fig. 67: By pressing the left mouse button along the continuum you now add interpolation points (crosses). The more interpolation points you create, the better the calculation of the response function. Finalize the procedure by clicking the right mouse button while the cursor is on the image.

The resulting response function **response.bdf** is plotted in Fig. 68:

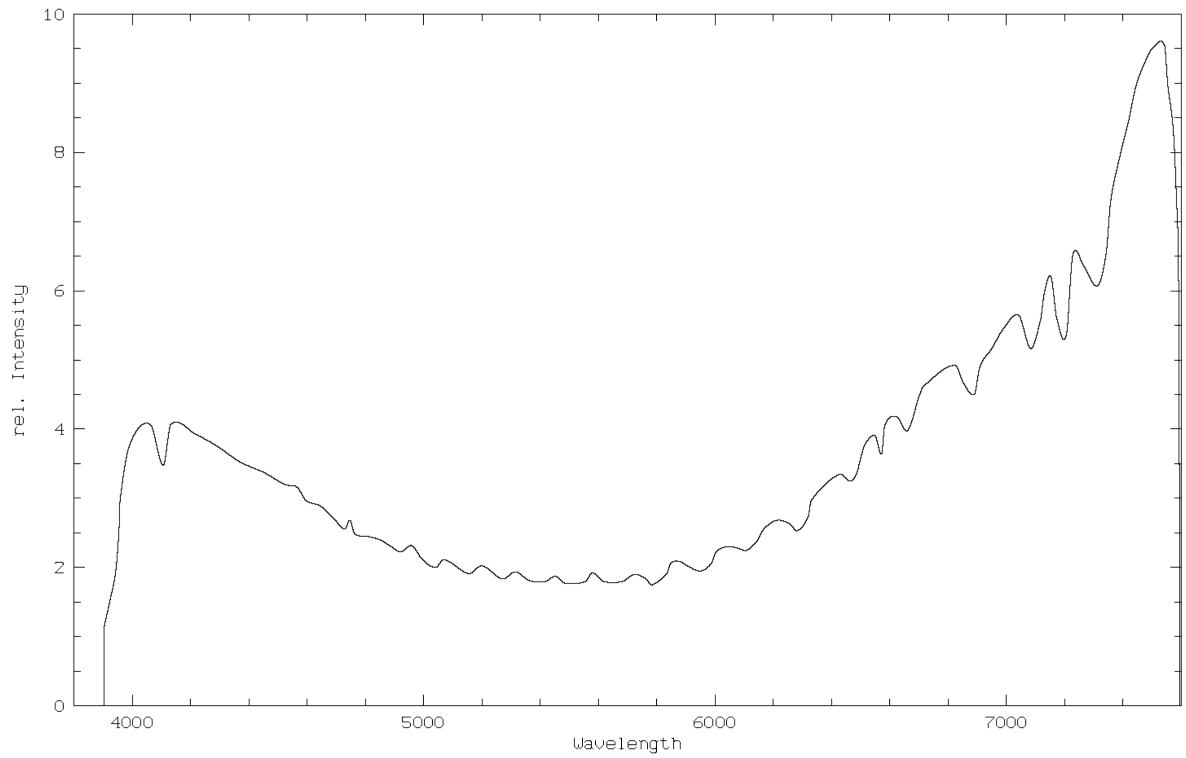


Fig. 68: The instrumental function response.bdf

---

[13] http://www.ursusmajor.ch/downloads/analysis-and-interpretation-of-astronomical-sp.pdf (p. 21ff)

In the next step, the star's spectrum is divided by the instrumental function. The letter "n" indicates the normalization, and must be added manually into the following input:

```
Midas > compute/image sun360s_npwrm.bdf = sun360s_pwrm.fit/response.bdf
```

Creation of the spectral profile **sun360s_npwrm.fit**:

```
Midas > outdisk/fits sun360s_npwrm.bdf sun360s_npwrm.fit
```

Plot the spectral profile **sun360s_npwrm.fit**. Try out values for the lower and upper limits of the relative intensity:

```
Midas > plot/axes 3800,7600 0.3,1.2 0 "Wavelength" "rel. Intensity"

Midas > overplot sun360s_npwrm.fit
```

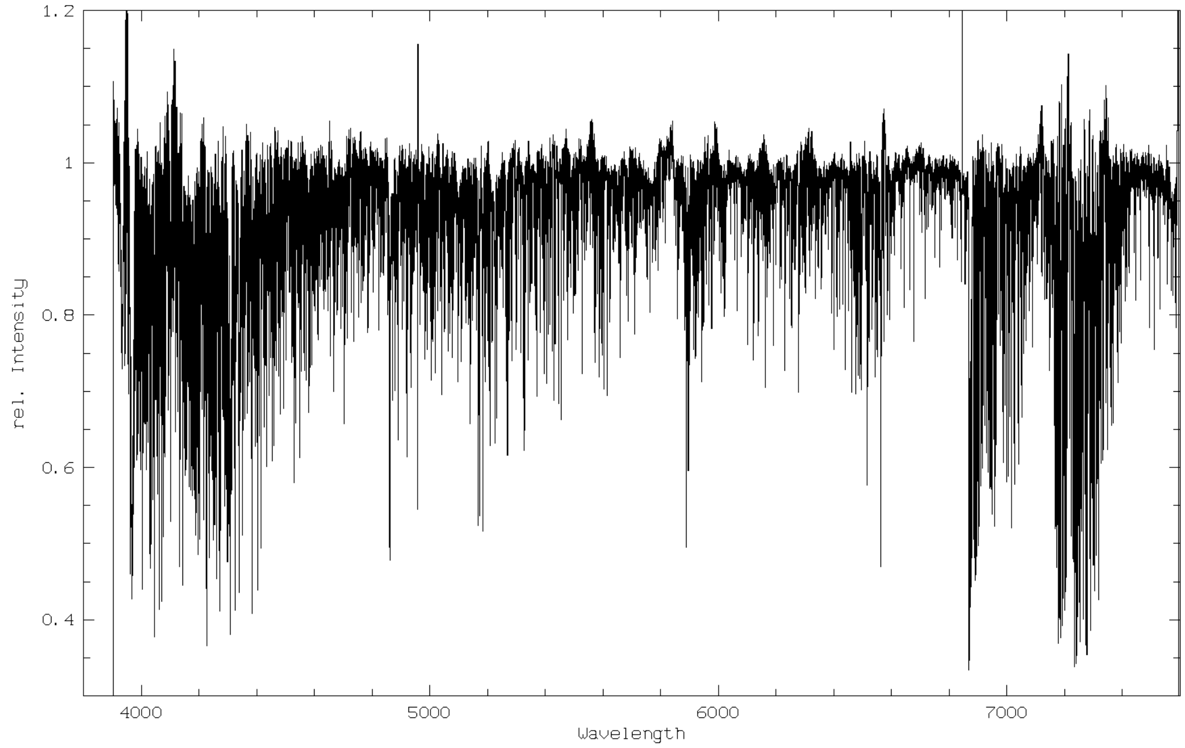


Fig. 69: The normalized profile sun360s_npwrm.fit. Due to the fact that only a few interpolation points had been set, the continuum is not perfectly normalized to a relative intensity value of "1". More points are necessary for higher precision. Also, note that unusual "emission peaks" can result from hot pixel.

Hot and cold pixels in the original spectrum image result in intensity values that are too low or too high after performing the spectral scan. They are seen here between 4900Å and 6850Å. The result can be a false spectral line, so these pixel should be removed prior to calibration with MIDAS. Ohne suitable tool is a Kernel filter as implemented in the image recording software MaxIm DL. A Single false pixel can be removed manually.

5.2.9 Synthetic Spectrum and “Drying“ the Daylight Spectrum at Hα

A synthetic black & white or even color spectrum is generated easily with VisualSpec software. Fig. 70 shows the normalized and synthesized daylight spectrum **sun360s_npwrm.fit.**

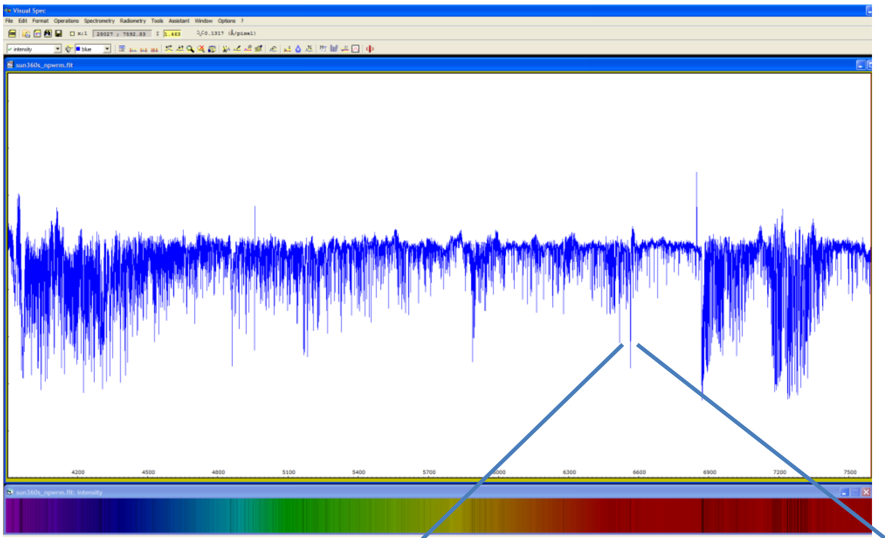


Fig. 70: Normalized and synthesized color daylight spectrum from 3900Å to 7600Å.

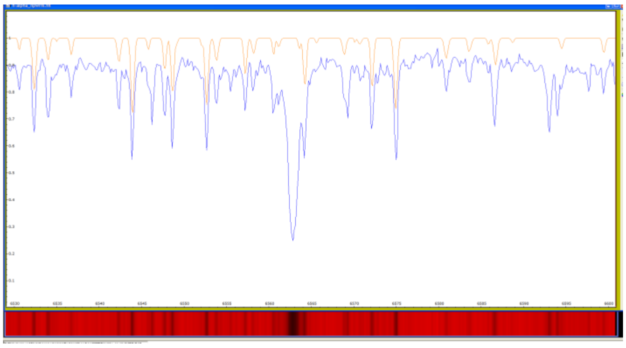


Fig. 71: Detail around Hα from 6530Å to 6600Å including telluric lines of the Earth’s atrmosphere.

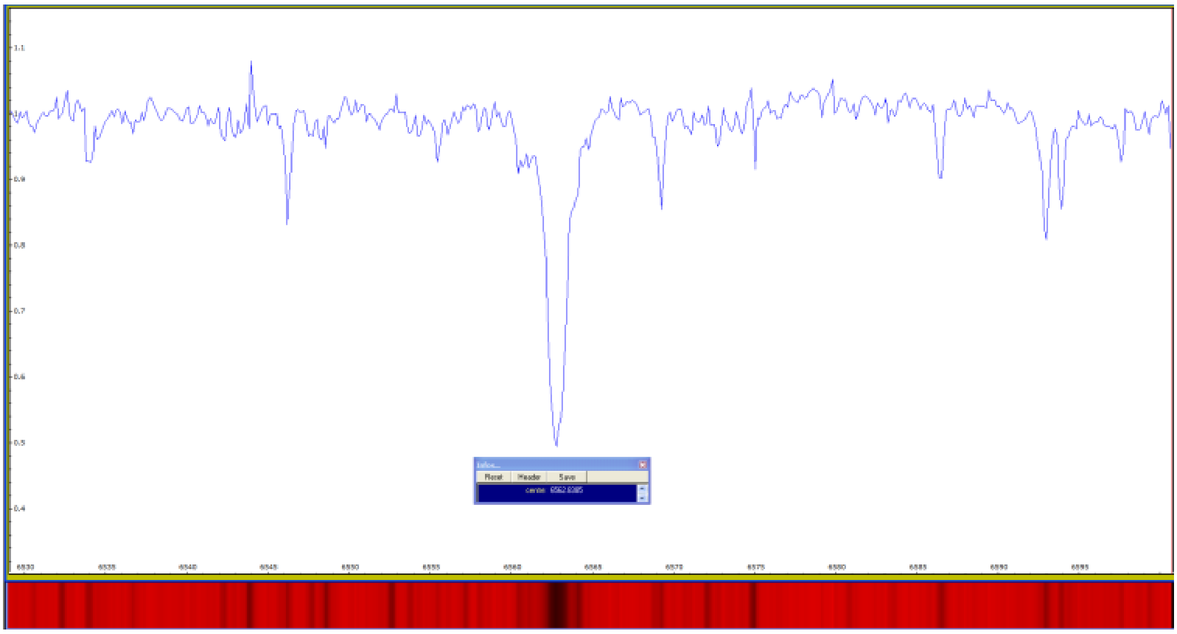


Fig. 72: “Drying“ a spectrum means removing the Earth’s water vapor lines (Tellurics), for example with VisualSpec software. The measured center wavelength of the Hα line is 6562.839Å. The difference from the at-rest wavelength 6562.852Å is -0.013Å

5.2.10 Calcium Lines Ca II K (3933.66Å) and H (3968.47Å) in the UV

Rebinning to 0.01px and plot:

```
Midas 049> rebin/linear sun360s_npwrm.fit sun360s_rnpwrm.fit 0.01
```

```
Midas 088> plot/axes 3925,4000 0.4,1.3 0 "Wavelength" "rel. Intensity"
Midas 089> overplot sun360s_rnpwrm.fit
```

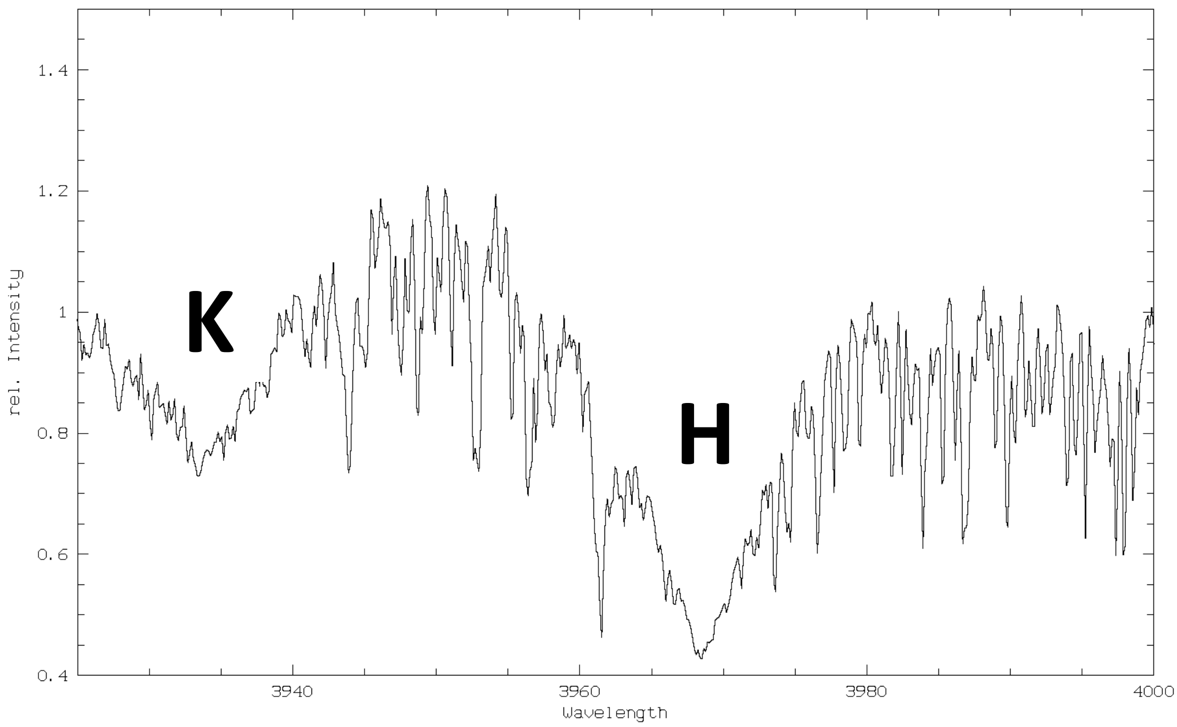


Fig. 73: The calcium lines K & H in the solar spectrum. The profile extends to ca. 3900Å in the UV.

Gaussian fit of the Calcium K line (3933.66Å) using the command **center/gauss** (Fig. 74):

```
Midas 076> plot/axes 3925,3945 0.7,1.1 0 "Wavelength" "rel. Intensity"
Midas 077> overplot sun360s_rnpwrm.fit
```

Midas > center/gauss gcursor ? absorption

```
Midas 078> center/gauss gcursor ? absorption
     start          end           center      pixel_value    FWHM

     3933.095      3933.801      3933.437   0.72943       0.55153
     3932.462      3936.200      3933.504   0.72943        1.3462
     3931.800      3936.583      3933.818   0.72943        4.8298
     3933.242      3933.639      3933.439   0.72943       0.53915
     3926.898      3940.101      3933.263   0.72943        10.483
     3932.491      3936.112      3933.484   0.72943        1.2431
     3932.550      3934.787      3933.446   0.72943       0.55722
     3930.563      3937.554      3933.796   0.72943        3.8656
```

Average of eight measurements of the line center: 3933.52Å.

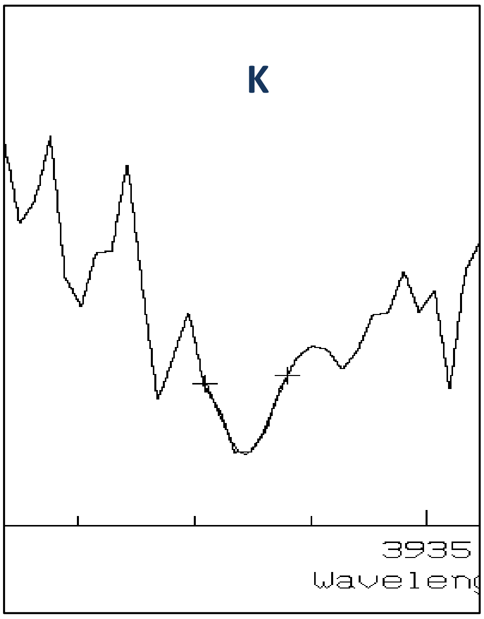


Fig. 74: The calcium line Ca II K with one of eight Gaussian fits (+).

Difference between the measured line center and observed rest wavelength of the calcium K line:
$\Delta\lambda$ = 3933.52Å – 3933.66Å = -0.14Å
Note: A Gaussian fit is difficult to manage due to interference from the many other nearby lines.

Gaussian fit of the calcium H line (3968.47Å) using the command **center/gauss**:

Average of three measurements: 3968.562Å. $\Delta\lambda$ = 3968.562Å – 3986.47Å = +0.09Å

```
Midas 088> plot/axes 3925,4000 0.4,1.3 0 "Wavelength" "rel. Intensity"
Midas 089> overplot sun360s_rnpwrm.fit
Midas 090> center/gauss gcursor ? absorption
     start          end          center      pixel_value    FWHM

     3964.917      3972.763      3968.561   0.42713        4.5703
     3967.057      3970.514      3968.529   0.42713        1.6623
     3959.979      3977.318      3968.597   0.42713        6.4896
```

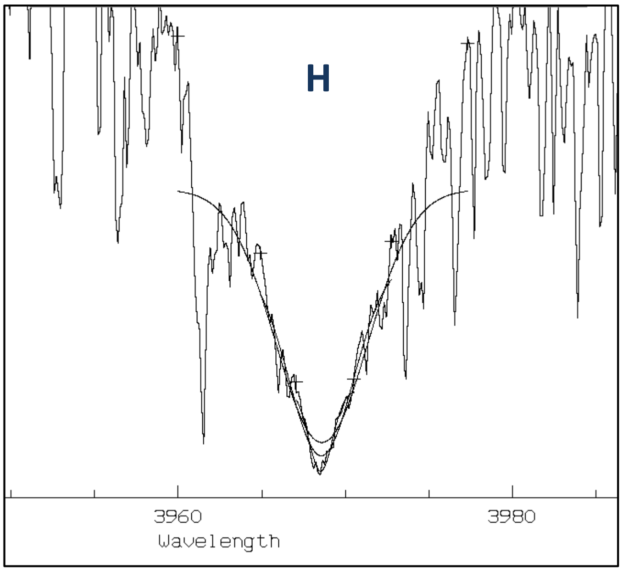


Fig. 75: Three fitted Gaussian profiles. Average of measured line centers of the Ca II H line: 3968.562Å

5.2.11 Magnesium Triplet (5167.33Å / 5172.68Å / 5183.61Å)

```
Midas 054> plot/axes 5160,5190 0.4,1.05 0 "Wavelength" "rel. Intensity"
Midas 055> overplot sun360s_rnpwrm.fit
```

Gaussian fits (+):

```
Midas 055> overplot sun360s_rnpwrm.fit
Midas 056> center/gauss gcursor ? absorption
     start         end          center      pixel_value    FWHM

     5166.711     5167.969      5167.357   0.52480       0.69770
     5172.010     5173.312      5172.672   0.53604       0.77674
     5182.320     5184.836      5183.629   0.51670        1.3586
```

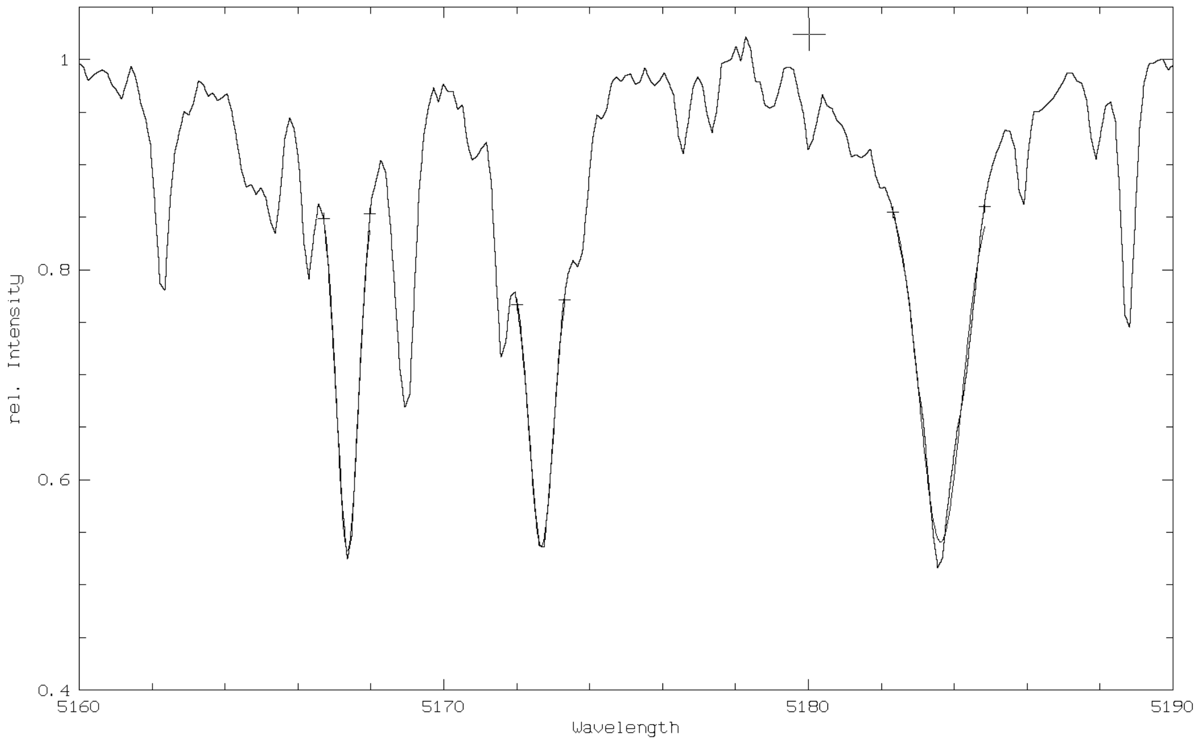


Fig. 76: Gaussian fits, applied to the three triplet lines of Magnesium.

After applying a Gaussian fit, MIDAS calculates the line centers of the three triplet lines and the difference to the observed rest wavelengths.

$\Delta\lambda$ = 5167.357Å - 5167.33Å = +0.027Å

$\Delta\lambda$ = 5172.672Å - 5172.682Å = - 0.010Å

$\Delta\lambda$ = 5183.629Å - 5183.61Å = +0.019Å

5.2.12 Sodium Doublet (D_2: 5889.950Å / D_1: 5895.924Å)

```
Midas 057> plot/axes 5885,5900 0.4,1.05 0 "Wavelength" "rel. Intensity"
Midas 058> overplot sun360s_rnpwrm.fit
```

Gaussian fits (+):

```
Midas 064> center/gauss gcursor ? absorption
     start          end          center      pixel_value     FWHM

     5889.404      5890.475      5889.934   0.49564        0.73447
     5895.674      5896.237      5895.943   0.59535        0.42347
```

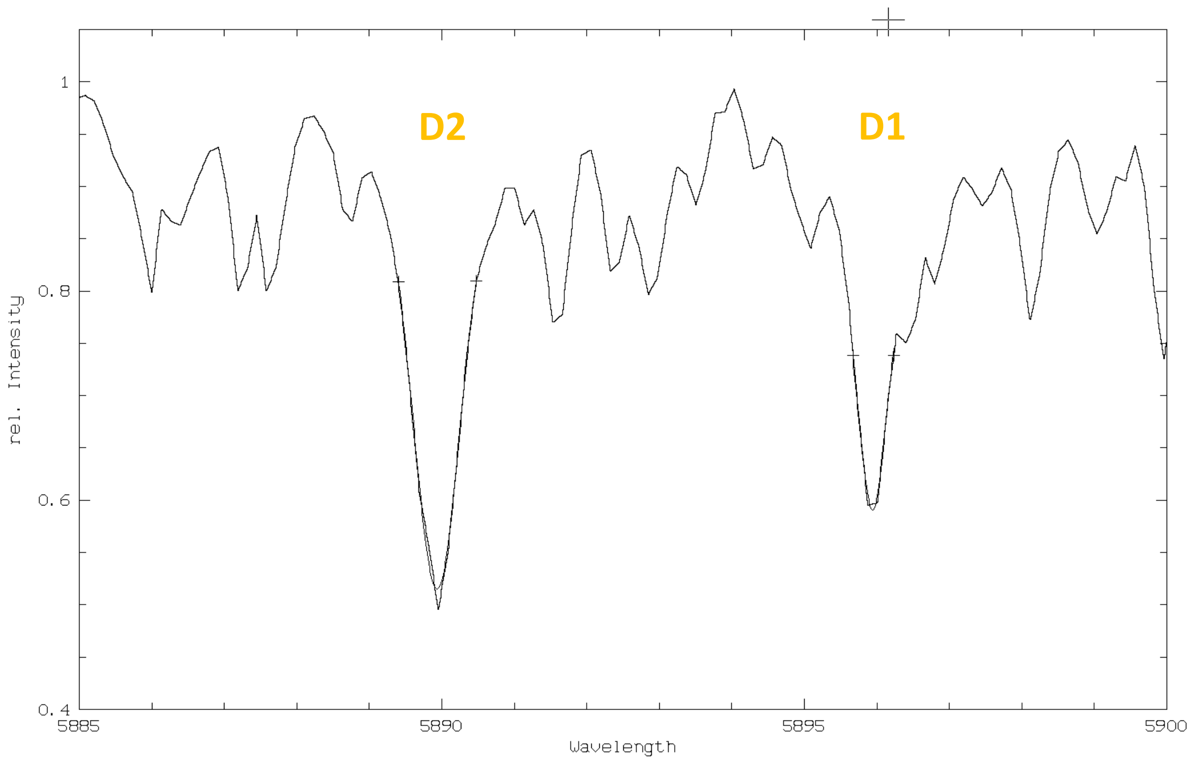


Fig. 77: : Gaussian fits, applied to the sodium doublet.

After applying a Gaussian fit, MIDAS calculates the line centers of the doublet lines of sodium and the difference from the observed at-rest wavelengths.

D2: $\Delta\lambda$ = 5889.934Å - 5889.950 = -0.016Å

D1: $\Delta\lambda$ = 5895.943Å – 5895.924Å = + 0.019Å

5.2.13 Hα Line (6562.852Å)

```
Midas 067> plot/axes 6550,6580 0.4,1.1 0 "Wavelength" "rel. Intensity"
Midas 068> overplot sun360s_rnpwrm.fit
```

Gaussian fits (+):

```
Midas 069> center/gauss gcursor ? absorption
     start          end          center      pixel_value     FWHM

     6562.076      6563.577      6562.814   0.46994        2.0396
     6561.634      6564.460      6562.815   0.46994       0.98972
     6562.341      6563.356      6562.790   0.46994        1.2325
     6557.793      6567.551      6562.873   0.46994        1.8316
     6557.727      6570.333      6562.876   0.46994        2.0562
```

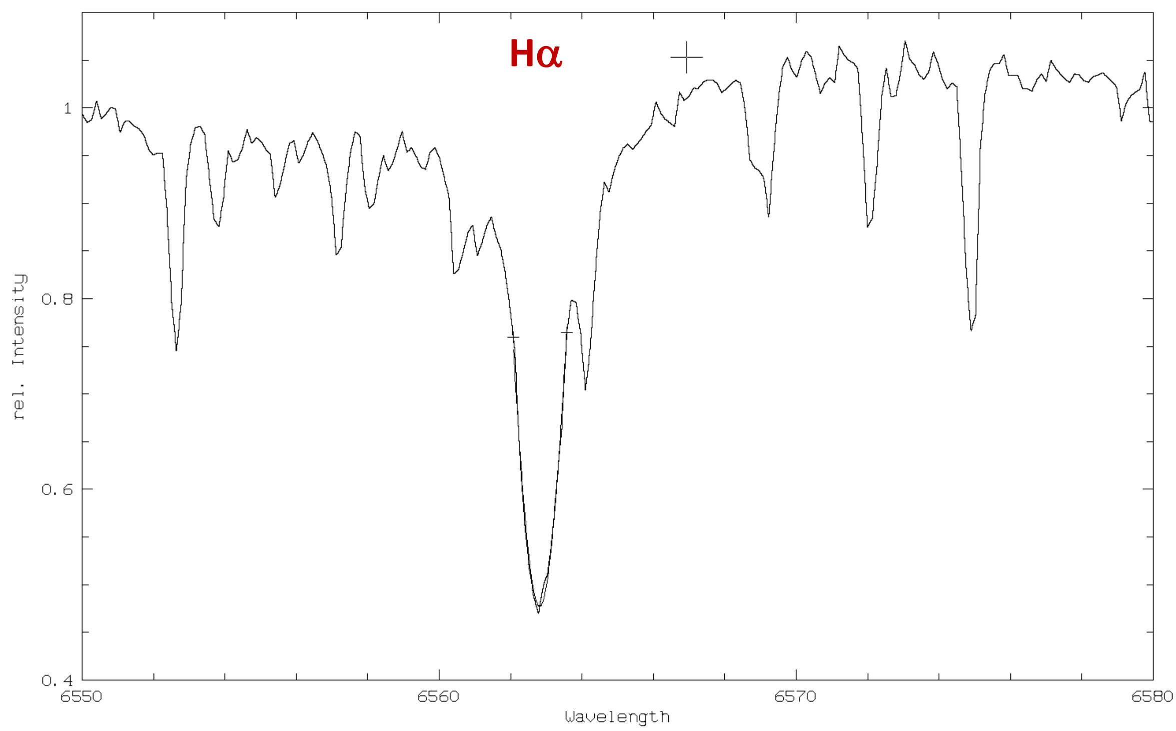


Fig. 78: The Hα profile is slightly distorted by overlapping telluric lines.

After applying a Gaussian fit, MIDAS calculates the line center of the Hα line and the difference to the observed at-rest wavelength. The profile is distorted due to overlapping telluric lines. These should be subtracted before performing a Gaussian fit to the Hα line (Fig. 72).

$\Delta\lambda$ = 6562.814Å – 6562.852Å = -0.038Å

6 References

The calibration of stellar spectra with ESO-MIDAS can be accomplished successfully by applying a few basic commands. For the analysis of spectral profiles, the author of this tutorial prefers the software Visual Spec by Valérie Desnoux http://www.astrosurf.com/vdesnoux/.

The comprehensive tutorial for the DADOS spectrograph http://www.baader-planetarium.de/dados/ explains in detail, how to analyze stellar spectra with Visual Spec.

If you would like to stay with MIDAS for further analysis, the following references are useful sources to gain a broader and deeper knowledge.

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