Southern African Large Telescope

Title: **HRS pipeline for LR red-arm data with MIDAS**

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ABSTRACT

In this report I present a pipeline for the High Resolution Spectrograph (HRS) red-arm data taken in low-resolution (LR) mode. This pipeline was implemented using standard system of astronomical data reduction MIDAS. All programs were written in MCL (MIDAS Command Language) and were developed and debugged by me within a total of two to three weeks. MCL programs are based on the standard MIDAS echelle packages `FEROS` *and* `ECHELLE`*. I present here the main ideas and results of my work.*

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1 Introduction

This story is very simple. A long long time ago in a galaxy far far away... Oh, sorry ... it is another story. So, after obtaining some HRS data in LR mode with SALT I needed some programs for reduction of these data. From my personal point of view, since HRS is a standard enough echelle spectrograph with two fibers, the easiest way to implement the first version of its data reduction is to use one of the standard systems of astronomical data reduction like IRAF, MIDAS or STARLINK. I know MIDAS exceptionally well and was involved in its first port to a PC computer and the development of its ÊCHELLE package (Kniazev, Shergin & Lipovetsky , 1992). Another four acquisition and data reduction packages based on MIDAS were developed by me and used at the SAO 6-m telescope. For that reason my choice of the standard system of astronomical data reduction was simple yet elegant – I selected MIDAS, the results of which I will show in this report.

2 Choice of MIDAS Packages

MIDAS contains several packages for echelle data reduction. The basic one is `ECHELLE` package, which consist of huge anount of basic procedures for echelle data reduction. `FEROS` is another package and it was developed for the reduction of of echelle data from Fiber-fed Extended Range Optical Spectrograph (FEROS). FEROS is a bench-mounted fiber-linked echelle spectrograph with spectral resolution of 48,000 covering spectral range from 3700-9200 Å. Two fibers are used simultaneously. The high spectral resolution is achieved by an image slicer.

Everything I mentioned above for FEROS looks very similar to me when comparing with HRS and therefore I was hoping that both instruments have very close type of echelle data. That was a reason for me to start with `FEROS` package first, but have in mind `ECHELLE` package as well.

I concentrated on the red-arm LR data only, because my science objects of interest are very red and practically do not have any blue signal.

3 Echelle Reduction Method

3.1 Input Data and Preprocessing

For all my reduction steps described below I use HRS data after the primary reduction with the SALT science pipeline (Crawford et al. (2010)). This includes BIAS, OVERSCAN and GAIN corrections.

The information involved in subsections below consists of user data and system tables. User data is a set of echelle images, observed with HRS in the same configuration, including a wavelength calibration image (ARC), a flat field image (FLAT) and astronomical objects OBJ. Optionally, this set can include standard stars (STD) to be used for the relative flux calibration.

Before to start the actual reduction people usually need some preprocessing of the data to correct for standard detector effects. In case of `FEROS package` these corrections are:

- Rotation of input frames.
  After this rotation, the dispersion direction of the echelle orders will be vertical, with wavelengths increasing from bottom to top and spectral order numbers decreasing from left to right of the image. As always in MIDAS, the origin is the pixel (1; 1), located in the lower left corner of the image.

- Updating START and STEP descriptors.
  Descriptors START and STEP must be set to 1.,1. for all images processed.

In case of `ECHELLE package` these corrections are:

- Rotation of input frames.
  After this rotation, the dispersion direction of the echelle orders will be horizontal, with wavelengths increasing from left to right and spectral order numbers decreasing from bottom to top of the image. As always in MIDAS, the origin is the pixel (1; 1), located in the lower left corner of the image.

- Updating START and STEP descriptors.
  Descriptors START and STEP must be set to 1.,1. for all images processed. Session keyword CCDBIN must be set to the original binning factor along x- and y-axis.

- Checking exposure times in OBJ and STD frames.

Just to exclude all future mistakes I include all above corrections inside of my programs.

3.2 General Description

The general Echelle data reduction scheme used in MIDAS is shown in Figure 1.

The first problem in the reduction of echelle spectra is, of course, the solution of the dispersion relation. That is the mapping between the space (λ,m) wavelength, spectral order and space (x, y) sample x, line y in the raw image. This relation gives the position of the orders on the raw image, and defines the wavelength scale of the extracted spectrum. The mapping is performed in two steps:

- A first operation (order definition), gives the position of the orders in the raw image. In Figure 1, this operation corresponds to the step "Find Order Position". The required input is an order reference frame (usually FLAT or STD) and the output is a set of polynomial coefficients. These coefficients are an input of the step "Extract Orders".

- A second operation (wavelength calibration) defines the wavelength scale of the extracted spectrum. The successive steps of this operation are shown in the second column of Figure 1. The output is a set of dispersion coefficients required by the step "Sample in Wavelength".

FLAT	WLC	STD	OBJECT
⇓	⇓	⇓	⇓
FIND ORDER POSITIONS	EXTRACT ORDERS	*SUBTRACT BACKGROUND*	SUBTRACT BACKGROUND
⇓	⇓	⇓	⇓
SUBTRACT BACKGROUND	IDENTIFY LINES	*FLAT FIELD CORRECTION*	*FLAT FIELD CORRECTION*
⇓	⇓	⇓	⇓
DEFINE BLAZE	COMPUTE DISP.COEFFS.	*EXTRACT ORDERS*	EXTRACT ORDERS
		⇓	⇓
		SAMPLE IN WAVELENGTHS	SAMPLE IN WAVELENGTHS
		⇓	⇓
		COMPUTE RESPONSE	*MULTIPLY BY RESPONSE* or *FIT BLAZE*
			⇓
			MERGE ORDERS

Figure 1: Echelle Reduction Scheme

The second step in the reduction is to estimate the image background. The background depends mainly on the characteristics of the detector, but includes the additional components of the scattered light in the optics and spectrograph. This operation corresponds to the step "Subtract Background" in Figure 1.

After corrections for all above effects, the information in the spectral orders is extracted using different methods described in MIDAS. The extracted flux, used in conjunction with the dispersion relation, gives the photometric profiles of the spectral orders. Two more instrumental effects are still present in these profiles. First, due to the blaze effect of the echelle grating, the efficiency of the spectrograph changes along each order. Second, the efficiency of the whole instrument is not uniform with wavelength. There are two possibilities to correct both effects – to normalize the fluxes using calibration stars (STD) or correct for the blaze effect using FLAT data.

4 HRS LR red-arm data reduction implementation

4.1 Order Definition

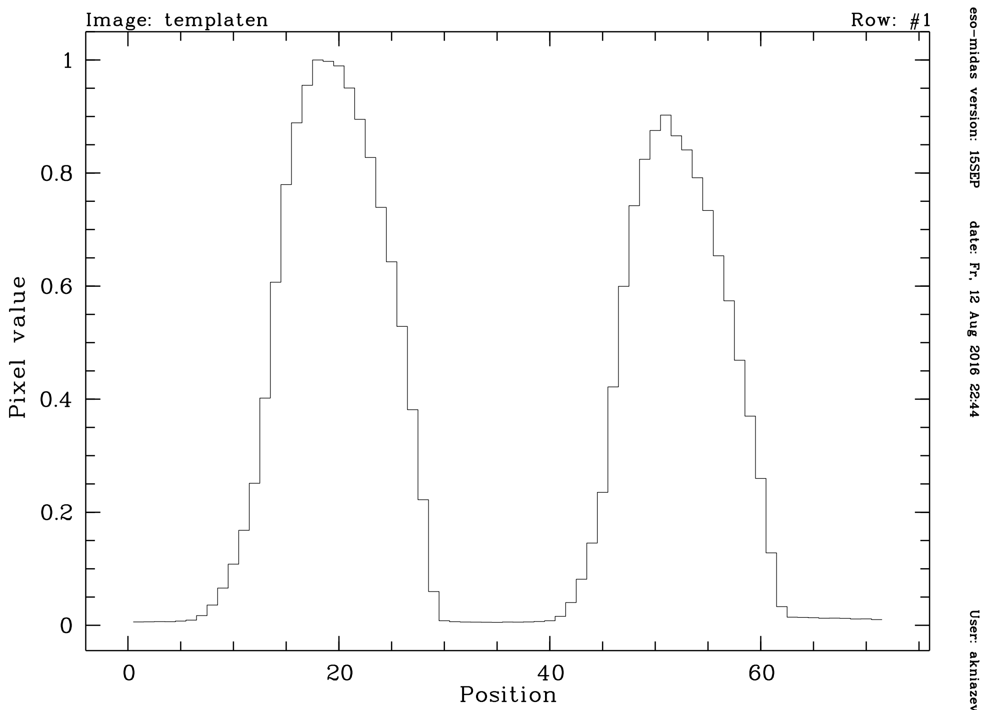


Figure 2: Template used for order definition with HRS LR red-arm data.

In general, the dispersion relation is defined by the following equations:

$$y = f_1(x, m) \tag{1}$$

$$\lambda = f_2(x, m) \tag{2}$$

The first of the equations defines the position of the spectral orders m in the raw image. The second equation gives for each order the dispersion relation in one dimension. The mapping between the spaces (λ, m) and (x, y) is separated into two different equations. The first one belong to this subsection. The second equation involved into Section 4.5. The function $f1$ is approximated by a polynomial, where its coefficients are computed using least squares techniques on a grid (x_k, y_k), i.e. sample number and line number located within the spectral orders of the image. These points in the grid are found automatically by an order-following algorithm, normally using the FLAT ot STD echelle spectrum.

The feature for HRS and FEROS echelle spectra is that each order consist of two fibers. Additionally, the profile for each order could be complex because an image slicer (not for HRS LR mode, fortunately). For that reason, positions of orders with `FEROS` package are calculated using deconvolution of orders profile template with real data. I created such the

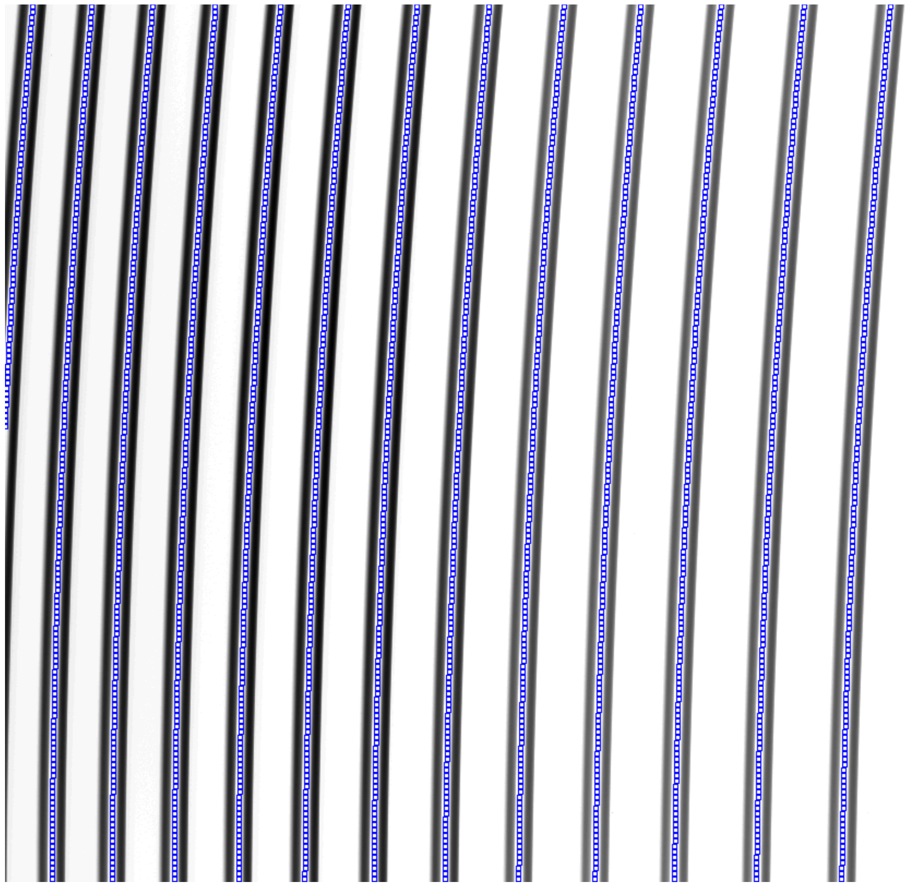


Figure 3: An example of order definition with `DEFINE/FEROS` procedure for HRS LR red-arm flat-field image. Only part of the image is shown. Found central positions of orders is shown with blue squares.

template using FLAT image for HRS LR red-arm data and it is shown in Figure 2. With this template `FEROS` package program `DEFINE/FEROS` found 33 echelle orders in FLAT data. The result of work of t`DEFINE/FEROS` pocedure is shown in Figure 3.

4.2 Background Definition

The estimation of the background is one of the critical points in the reduction of echelle spectra for two reasons. On one side, a correct estimate of the background level is necessary to compute the true flux of the object spectrum; on the other side, a wrong estimate of the background in either the flat-field image (FLAT), the object (OBJ) or (optionally) the standard star (STD), will severely affect the accuracy with which instrumental effects – such as the blaze – can be corrected for. The background in an echelle image consists of:

- a constant offset introduced by the electronics (bias),
- an optional constant pedestal due to the pre-flashing of the CCD,

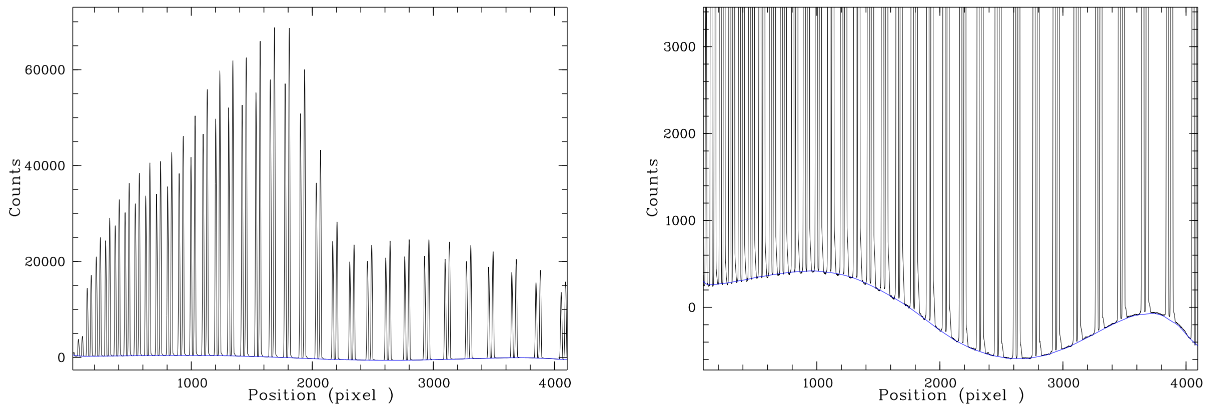


Figure 4: The result of work of program for background definition for one central row of FLAT echelle spectrum. The top panel shows plot with high cut-values and background which was found by program is shown with blue line. The bottom panel shows the same plot but for lower cut-values. It is easy to see that background was found correctly even for left part of the frame, where echelle orders are located very dense. Take into account that for work with `FEROS` package image was rotated.

- general scattered light,
- diffuse light in the interorder space coming from adjacent orders.

The first three components have to be removed during the SALT science pipeline preprocessing as described in Section 3.1. Correction for the general scattered light and diffuse light background needs to be produced at this step.

`ECHELLE` and `FEROS` packages have different options for background definition. I have tested some of them, but finally used algorithm SOC, developed in Special Astrophysical Observatory and described in Shergin, Kniazev, & Lipovetsky (1996). This algorithm was implemented in MIDAS by me and used successfully for both direct images reduction for survey KISS and for different types of spectral data. The result of work of this program for one central row of FLAT echelle spectrum is shown in Figure 4. *As it is possible to see from the bottom panel of this figure, the part of the frame has negative counts after OVERSCAN and BIAS correction, that will surely affect constructed flats without proper background definition. The existence of such negative level in the FLAT is the separate problem with HRS data and has to be studied as well.*

4.3 Order Extraction

With MIDAS ideology individual echelle orders are extracted by adding the pixel values over a numerical slit running along the orders, with the position of the slit centre defined at Section 4.1. The width of the slit is one pixel and its length, as well as an optional offset to shift the slit perpendicular to the dispersion direction, could be defined by the user. The pixel values in the numerical slit are found by linear interpolation of the values in the image.

There are several effects to consider when defining the length of the extraction slit. If the length is too small, the orders are only partially extracted and they present a periodic variation due to the inclination of the orders with respect to the lines in the image. On the other side, if the slit is too large, the extracted flux will include noisy pixels from the flatfielded background, when the flat-field correction is applied.

To make such alignment of the slit length easier, `FEROS` package splits order extraction into two separate step. The step number one has name `RECTIFY/FEROS`. This step write the information from the curved orders in an easy to handle format. For two fiber spectra the data are stored in separate files for each fiber. As the result of this step user has images, where all orders found with procedure are extracted WITHOUT rebinning and written into separate images. That gives a nice possibility to user to play with parameters of extraction like length of the extraction slit and shifts for slit for each fiber from the defined center. An example of the work of this procedure is shown in Figure 5.

The next step is real order extraction and could be done using `EXTRACT/FEROS` procedure. This procedure extracts straightened echelle spectrum using (1) the standard, (2) the standard extraction with cosmic masking or (3) the optimum extraction algorithm. The method described in the paper by Mukai (1990) is implemented for optimum extraction of cross-dispersed spectra. Optimum extraction requires the detailed knowledge of the cross-order profile (COP) to determine optimum weights. In case of fiber-linked spectrographs, the COP is very stable and independent from the source of illumination. For that reason we can derive the COP for HRS from a flat-field spectrum and use it for the extraction of science spectra. This makes the computation of the COP easier, since it has to be computed only once. It is well known that high accuracy in the COP is essential, since errors in the COP introduce a bias in the extracted spectra. This effect is specially true for data with high S/N, where optimum extraction is normally not very useful. Additionally, in case of HRS in MR and HR modes the COP has to be very complex due to use of an image slicer.

FEROS people calculates COP at the beginning of the each night. HRS get FLATs images only once per week and for this reason the optimal extraction has to be studied carefully. Since the size of extracted data is very small in comparison to the size of original data, I have calculated COP on the base FLAT images and extracted each object with two different modes – (1) the standard extraction with cosmic masking and (2) the optimum extraction with cosmic masking. ARCs are extracted just with the standard extraction method.

NOTE: *It is well known, that HRS data have additional feature – all lines in reality are slightly tilted, but not perpendicular to the dispersion direction. The angle of this tilt is very small and about possibly 5%, from my point of view. So, it is surely second order effect, which could be ignored at this stage. Potentially,* `ECHELLE` *package has an option to correct fo tilting during the extraction.*

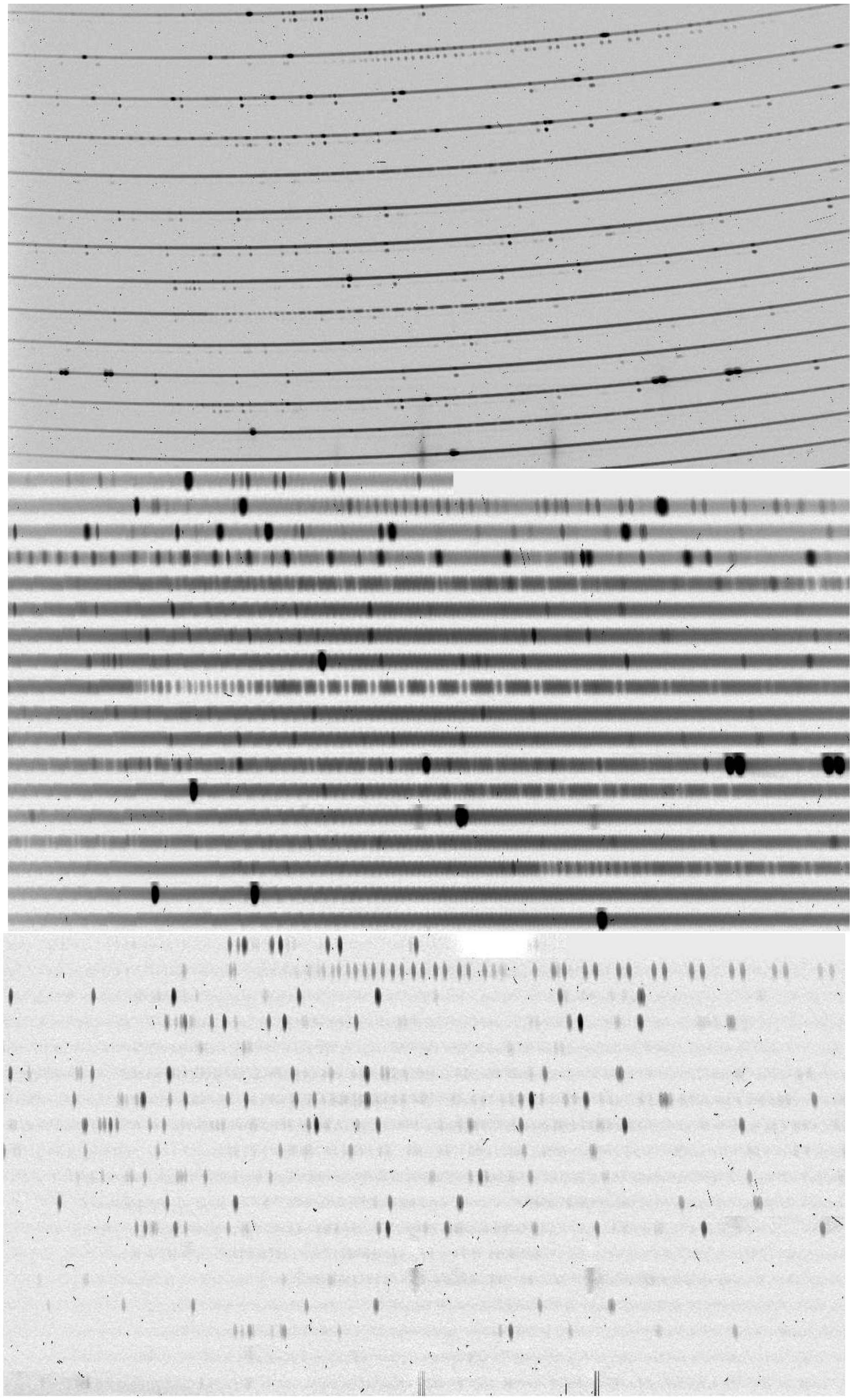
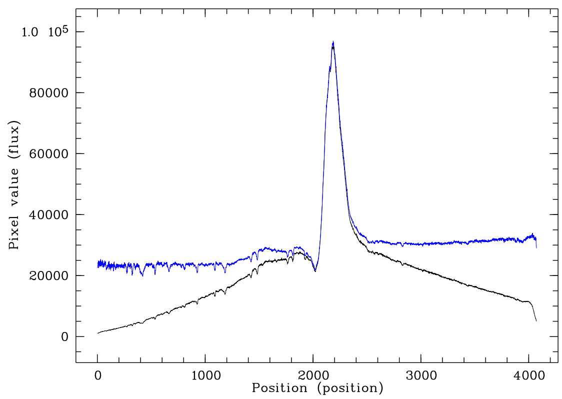


Figure 5: *Top:* Some part of the raw HRS frame for the PN with exposure time 2600 sec. *Middle:* Some part of the rectified object fiber. *Middle:* the part of rectified Sky fiber. I would like to point you out how many emission lines are from the sky, because long exposure. Many cosmic events are also visible because so long exposure.

4.4 Flat Field Correction



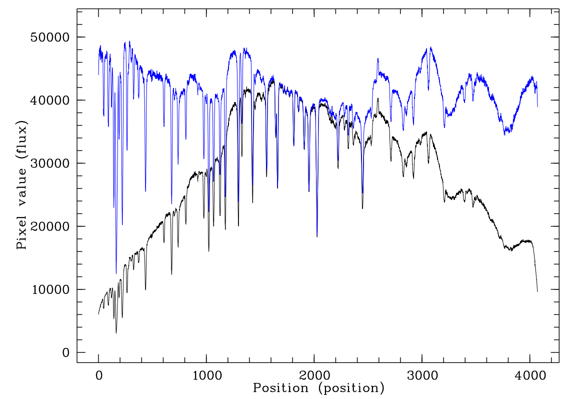


Figure 6: Two examples of the flat field correction for two orders from the spectrum of new LBV candidate star. The left panel is spectral area of HeI λ7065 and the right panel is the spectral area of Paschen lines. The object is red and for that reason the area of around λ7065 is red after correction. The area of Paschen lines is red as well, but sensitivity of HRS goes down there.

In echelle spectra it is often difficult to combine echelle orders in a contiguous 1D spectrum. The main problem is incomplete removal of the echelle blaze function by flat-fielding alone. However, in case of fiber-linked echelle spectrographs, the flat-fielding can remove the echelle blaze to high accuracy. This makes order merging much easier than with classical echelle spectrographs. Insufficient accuracy of the background correction is normally only the problem at very low flux levels. For example, with FEROS, the flat-fielding removes the blaze to better than about 1% if the background subtraction is accurate enough. As I can see with the current version of reduction HRS has about the same type of accuracy after the proper flat-fielding.

For that reson, I did the flat field correction for all objects from HRS data after their orders were extracted. The correction itself is just removing blaze function from spectrum through division by spectrum of flatfield lamp. The procedure `FLAT/FEROS` is doing that job.

Figure 6 shows two examples of the flat field correction for two orders of object. Counts were not changed in the centers of orders after flat-fielding.

NOTE: *After this step I was need to turn my mind from* `FEROS` *package to* `ECHELLE`*. I have tried to understand how programs in* `FEROS` *package work for wavelength calibration during about three days, but unfortunately without big progress in the implementation them to HRS data. For that reason I have decided switch to* `ECHELLE`*. Two more days of reading help pages, looking into MCL codes and* `FORTRAN` *and* `C` *codes and solution was found. Of course, I was need to rotate again input frames and tables which where created by* `FEROS` *package, but it did not take a lot of time. Much more time I used to fix one* `C` *program not properly working for lines identification in our case. Anyway, five days only is a very good price for such important step as wavelength calibration, from my point of view.*

4.5 Wavelength Calibration

A preliminary step to the wavelength calibration with MIDAS consists of extraction the orders from the ARC image, which can then be used to determine the dispersion relation in two steps:

- The calibration lines are detected on the extracted orders by means of a simple thresholding algorithm. The center of the line is estimated by its center of gravity or by a gaussian fit to the line profile. This could be done with the command `SEARCH/ECHELLE`.
- A few lines need to be identified interactively on the 2D image display and a set of global dispersion coefficients are derived by comparing the identified lines with the line catalogue available. This global model for the dispersion is a function of the wavelength and the spectral order number. Finally, dispersion coefficients for each order are computed using the global coefficients as a first approximation. A polynomial of degree 2 or 3 is sufficient to obtain, for each order a good approximation of the wavelength scale.

`SEARCH/ECHELLE` command finds usually ∼800 lines in all 33 orders for each extracted fiber in case of HRS LR red-arm data.

The second step has to be done with `IDENTIFY/ECHELLE` procedure. This procedure involves the echelle relation and requires the identification of two lines in overlapped regions of adjacent orders (method PAIR). The calibration can as well be performed for spectra which orders are not overlapped, this time requiring a minimum of four identifications (method ANGLE). Both methods are based on the echelle relation and therefore are not applicable if the disperser is not an echelle grating. The method TWO-D allows to start directly the calibration with a two-dimensional fitting polynomial and requires more initial identifications. In case of several observations with the same, or near the same instrumental configuration, it is possible to use the global dispersion model from a previous calibration. The method GUESS implements this mode of operation. Solutions are computed either for each independent order (WLCOPT=1D) or using a global bivariate polynomial (WLCOPT=2D).

After about one day of games I finally started to use the TWO-D method with initial interactive identification for about 15 different not bright lines, which are located more or less uniformly across 2D ARC frame. Final solution was saved after that with `SAVE/ECHELLE` procedure for each fiber and used for all next wavelength calibrations in GUESS mode, where new found line positions in extracted ARC spectra are cross-correlated with previous solution, identified and new solution is found automatically.

An examples for such solution for both object and sky fibers are shown in Figures 7 and 8. This is the standard output from `IDENTIFY/ECHELLE` procedure. It shows the absolute number of spectral order, amount of finally used lines to build wavelength solution, calculated starting and final wavelengths as well as the standard deviation. The output for the sky fiber shows that for the bluest spectral order with absolute number 85 the amount of finally identified lines is less than required and for that reason the global bivariate polynomial solution was used for this order.

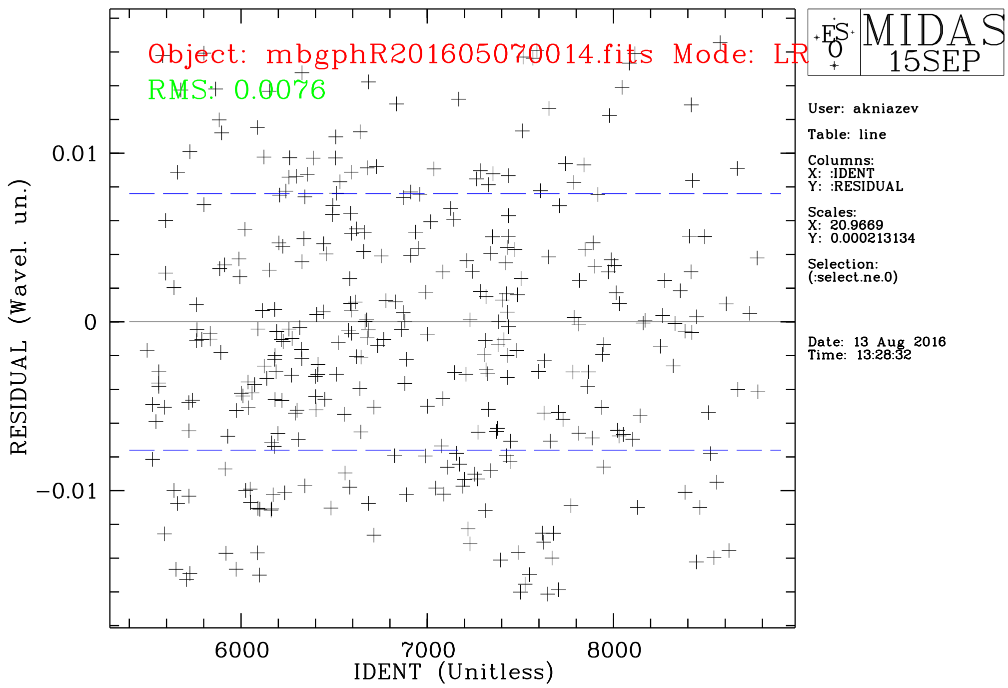
Figure 9 shows the distribution in wavelength of residuals for each finally used lines from ARC. Blue lines show the standard deviation level.

```
 POLYNOMIAL DEGREE :   3
 SEQ.NO  SPECTRAL  NO.LINES  WL START    WL END  STD. DEV.
         ORDER                                  ANGSTROEM
 ------  --------  --------  --------    ------  ---------
      1        85         5   5414.90   5531.14    0.00566
      2        84         7   5478.27   5597.16    0.00763
      3        83         6   5544.39   5664.36    0.00408
      4        82         7   5611.97   5733.62    0.00642
      5        81         9   5681.26   5804.36    0.00633
      6        80         6   5752.47   5876.94    0.00608
      7        79        10   5825.40   5950.54    0.00981
      8        78         8   5900.07   6027.39    0.00384
      9        77        12   5976.79   6105.63    0.00809
     10        76        12   6055.38   6186.08    0.00548
     11        75        18   6136.19   6268.56    0.00485
     12        74        12   6219.11   6353.21    0.00824
     13        73        12   6304.31   6440.33    0.00749
     14        72         9   6391.99   6529.69    0.00744
     15        71        10   6482.08   6621.54    0.00614
     16        70        17   6574.71   6716.12    0.00715
     17        69        10   6669.99   6813.63    0.00755
     18        68         9   6768.14   6913.58    0.00511
     19        67        11   6869.13   7016.89    0.00929
     20        66        10   6973.33   7122.92    0.00792
     21        65        13   7080.60   7232.55    0.00864
     22        64        14   7191.25   7345.58    0.00861
     23        63        22   7305.44   7462.18    0.00689
     24        62        16   7423.30   7582.49    0.00901
     25        61        17   7545.05   7706.72    0.00784
     26        60         9   7670.75   7835.25    0.00721
     27        59        14   7800.84   7967.99    0.00353
     28        58        10   7935.38   8105.30    0.00481
     29        57         7   8074.47   8246.39    0.00474
     30        56         7   8218.84   8394.74    0.00203
     31        55        11   8368.24   8547.23    0.00509
     32        54         5   8522.88   8707.22    0.00971
     33        53         8   8683.95   8872.87    0.00453
 ----------------------------------------------------------
                                        MEAN RMS:  0.00718
** TOTAL NUMBER OF LINES :    353 **
Set parameter SAMPLE=0.0414179079
```

Figure 7: Wavelength solution for fiber with object (fiber two in LR mode).

```
 POLYNOMIAL DEGREE :   3
 SEQ.NO  SPECTRAL  NO.LINES  WL START    WL END  STD. DEV.
          ORDER                                  ANGSTROEM
 ------  --------  --------  --------    ------  ---------
      1        85         4   5413.32   5531.14    0.16047 *NOT ENOUGH LINES*
      2        84         7   5478.12   5597.00    0.00591
      3        83         7   5544.21   5664.22    0.00729
      4        82         7   5611.34   5733.47    0.00793
      5        81         7   5681.86   5804.14    0.00556
      6        80         5   5752.32   5876.73    0.00461
      7        79         9   5825.25   5950.35    0.00725
      8        78         9   5899.90   6027.22    0.00731
      9        77        12   5976.65   6105.44    0.00806
     10        76        14   6055.20   6185.91    0.00777
     11        75        17   6136.04   6268.36    0.00508
     12        74        13   6218.89   6353.02    0.00792
     13        73        11   6304.12   6440.11    0.00932
     14        72        11   6391.89   6529.42    0.00576
     15        71        12   6481.92   6621.37    0.00454
     16        70        17   6574.52   6715.92    0.00592
     17        69         9   6669.79   6813.46    0.00639
     18        68         9   6767.99   6913.38    0.00580
     19        67         9   6868.94   7016.70    0.00605
     20        66         9   6973.13   7122.71    0.00860
     21        65        14   7080.39   7232.35    0.00866
     22        64        17   7191.13   7345.34    0.00698
     23        63        21   7305.24   7461.97    0.00599
     24        62        16   7423.08   7582.28    0.00912
     25        61        16   7544.80   7706.52    0.01102
     26        60        10   7670.59   7834.98    0.00681
     27        59        13   7800.61   7967.76    0.00529
     28        58        13   7935.14   8105.07    0.00730
     29        57         7   8074.49   8245.85    0.00994
     30        56         7   8218.61   8394.50    0.00164
     31        55        13   8368.01   8547.14    0.00816
     32        54         7   8523.09   8705.11    0.00962
     33        53         5   8703.73   8797.72    0.00910
 ----------------------------------------------------------
                                        MEAN RMS:  0.00760
** TOTAL NUMBER OF LINES :    357 **
Set parameter SAMPLE=0.0419031195
```

Figure 8: Wavelength solution for fiber with sky (fiber one in LR mode).



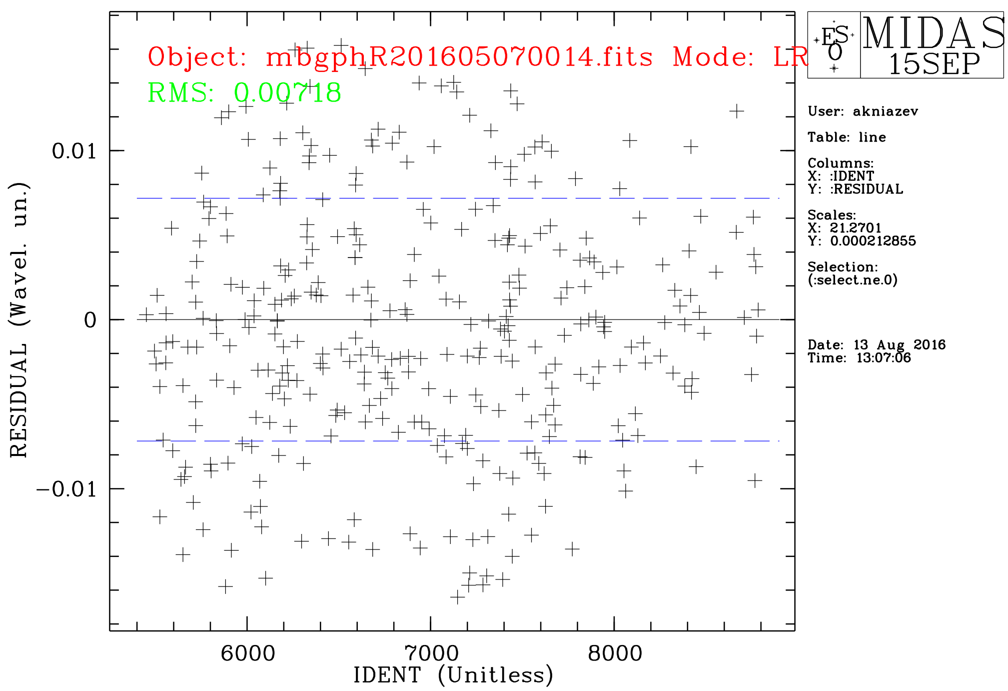


Figure 9: The distribution in wavelength of residuals for each finally used line from ARC. Blue lines show the standard deviation level. The top panel shows this distribution for the first fiber and the bottom panel shows is for the second fiber.

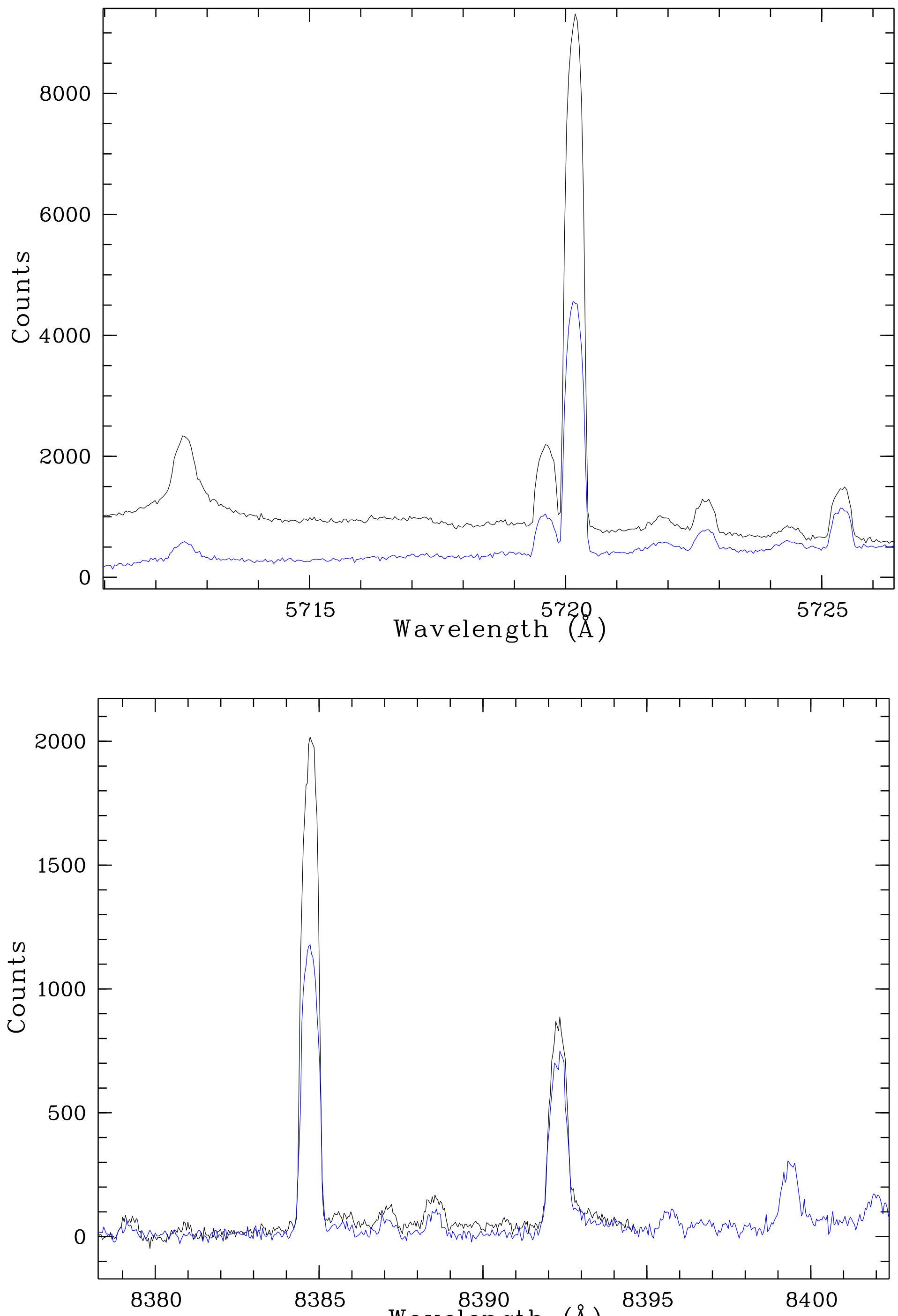


Figure 10: Two examples of edges for adjacent orders from wavelength calibrated ARC spectrum. Different orders are shown with different color. Blue (top) and red (bottom) spectral regions are shown.

Finally, the extracted orders, sampled to the constant wavelength step, which calculated during previous procedure and shown in Figures 7 and 8.

Figure 10 shows quality of the wavelength calibration in the way that edges of two adjacent orders are shown in the blue and red parts of spectra. It is easy to see that positions of emission lines are very accurate in all shown examples.

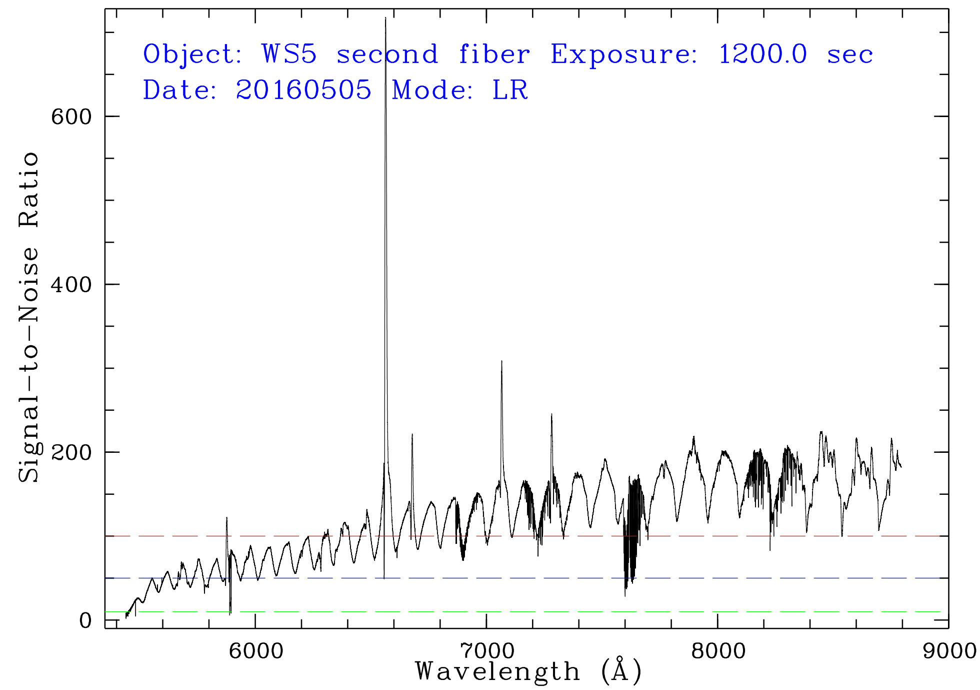
4.6 Order Merging

Finally, the extracted orders, sampled at constant wavelength steps and corrected for the blaze effect, can be merged into a one dimensional spectrum which is suitable for further analysis. MIDAS standard procedure `MERGE/ECHELLE` has different options:

- NOAPPEND – individual orders are separated in 1D files
- AVERAGE – the orders are merged into a 1D file, the algorithm computes a weighted average in the overlapping region of adjacent orders. The normalized weight is a linear ramp between 0 and 1 in the overlapping region.
- OPTIMAL – the orders are merged into a 1D file, the algorithm computes a weighted average in the overlapping region of adjacent orders. Specify the weights to be used by input spectrum of weights, which have to have the same START and STEP as the input frame.

After carefull study I have selected AVERAGE solution with wavelength interval to be skipped at both edges of the overlapping region as 10Å. The OPTIMAL method looks very perspective but need some additional time for the implementation.

Figures 11 and 12 show examples of the final reduction of two objects after all 33 orders were merged in one spectrum.



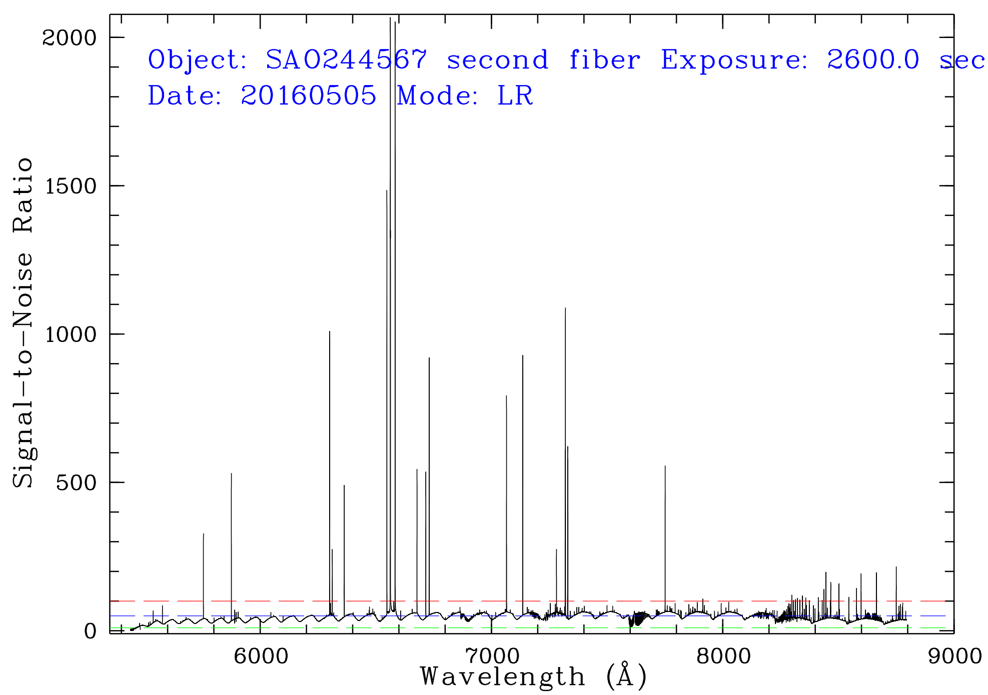
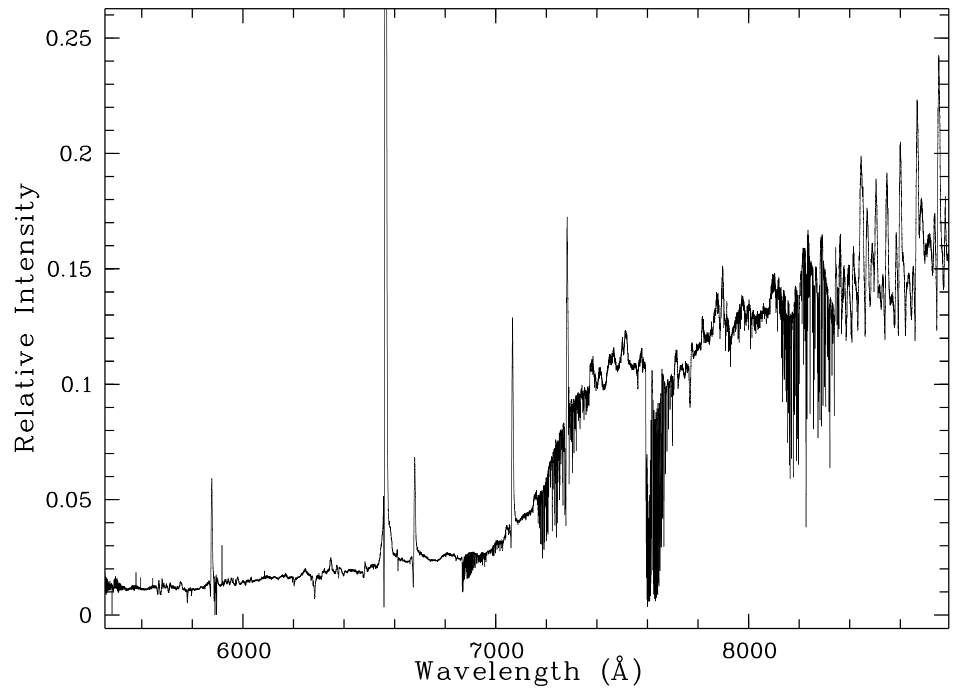


Figure 11: Merged spectra without flat-field correction. My standard procedure for estimation of SNR for observed spectrum.



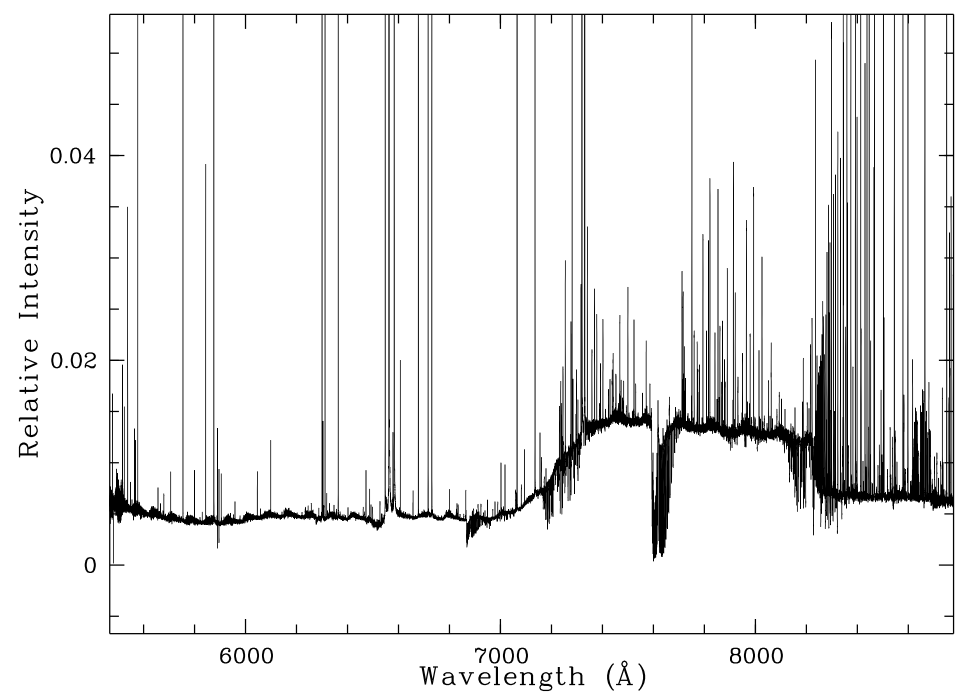


Figure 12: Examples of the final HRS data reduction for two previously shown objects, but after flat-field correction. *Top:* Tne new LBV candidate star. *Bottom:* The central star SAO 244567 of young planetary nebulae. Paschen jump at ∼8200 Å is obvious. Since its SNR low enough in the continuum, there is some faint waves in the final spectrum.

4.7 The Final Sky Subtraction

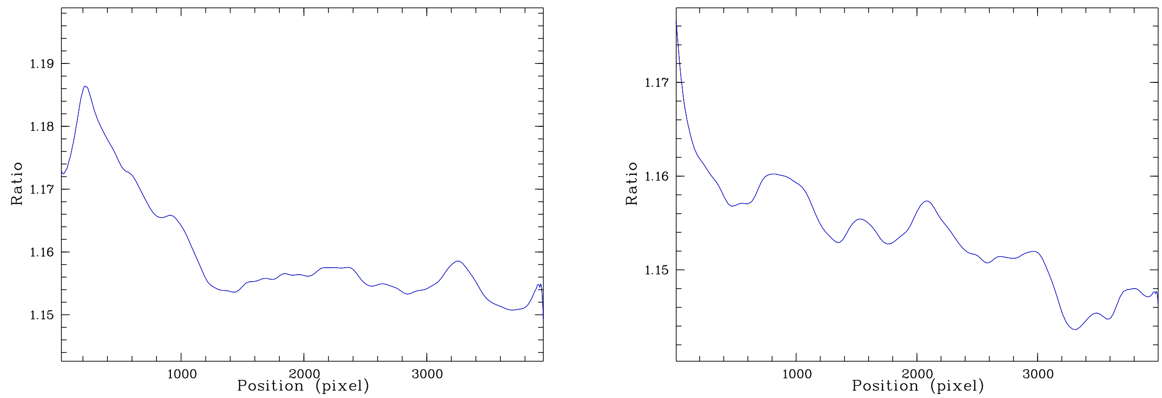
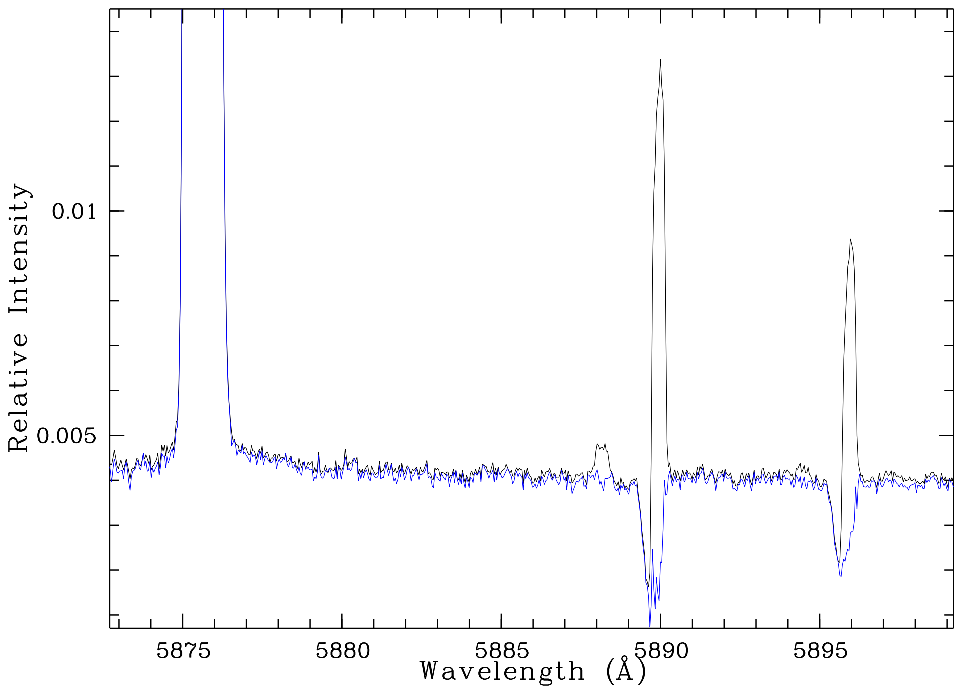


Figure 13: Two examples of edges for adjacent orders from wavelength calibrated ARC spectrum. Blue (left) and red (right) orders are shown.

The last step for the HRS data reduction is the sky subtraction. Since transparency for both fibers is different it is not just subtraction of the sky fiber from the object fiber. The dependence of such difference in the transparency of two fibers on the wavelength and HRS optics (the optical way for both fibers is slightly different as well) could be easily calculated using flat-fields images. In suggestion that intensity of the input light from QTH lamp is about the same for both fibers, such dependence could be calculated by just dividing by flat from each fiber to each other. Of course, this ratio has to be well smoothed after that.

Figure 13 shows examples of such ration for two orders. The left panel shows this ratio fo one of the blue orders (absolute number ∼80), and the right panel shows such ratio for one of the red orders (absolute number ∼50). I am not sure that smoothing was enough since small waves are visible. *This topic should be studied more careful.*

Figure 14 shows examples how night sky lines were removed from HRS spectra after my reduction described in this report. Both panels show result of the night sky removing in the HRS spectrum for the central star SAO 244567 of young planetary nebulae. The top panel shows such result in the very blue order, spectral region of HeI λ5876 line and two NaD λ5889.953,5895.923 lines. The spectrum from the fiber for object is shown with black color. Two emission from sky NaD λ5889.953,5895.923 are obvious. They are located at the red edge of NaD lines, belong to the object or ISM in the object direction. The result of sky subtraction is shown with blue color. Both lines disappeared. Additionally, no any PCyg profiles is visible, that shows the quality if wavelength calibration for both fibers. The bottom panel shows result in the same manner, but for the very red order, the spectral region close to the Paschen jump. All night sky lines were removed as well without any PCyg profiles. Sometimes they were located on the top of object's lines. I can suggest some small oversubtraction for some lines, but is is really small from my point of view.



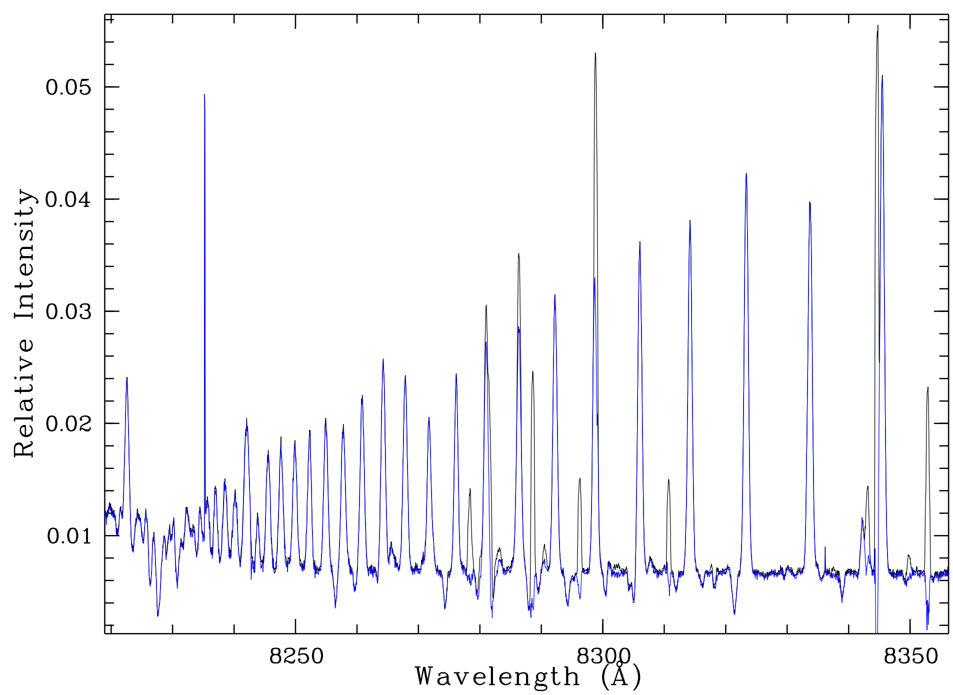


Figure 14: Examples of removing of night sky lines from HRS spectra after reduction with MIDAS. Both panels show result of the night sky removing in the HRS spectrum for the central star SAO 244567 of young planetary nebulae. The top panel shows such result in the very blue order, and the bottom panel shows such result in the very red order.

5 MIDAS pipeline for HRS LR red-arm data

All programs are written in MCL. The total length of the code is 450 MCL strings excluding comments. All steps are summarised into three main procedures:

1. **FLAT reduction**
   During this step FLAT image is reduced. The output of this procedure consist of extracted and smoothed flats for both fibers and file with their ratio.

2. **ARC reduction**
   During this step ARC image is reduced. The output consist of all tables, which are necessary for wavelength calibration of both fibers and extracted, calibrated and merged ThAr+Ar spectra for both fibers.

3. **Object reduction** The output consist of extracted, calibrated and merged spectra for both fibers and result of subtraction of the sky fiber from the object fiber as well as extracted, calibrated but not merged spectra for both fibers.

The output of all procedures is mostly FITS-files except configuration files, which are saved by system in the internal MIDAS format.

Each procedure has as minimum two modes of work: (1) **visualization mode**, when practically after each step user has a possibility to see and check the result of step, and (2) **silent mode**, when procedures work without any graphical output. Only the ARC reduction procedure has one more interactive mode for the possibility of re-identification of the reference spectrum.

Since the low level programs are implemented with `C` and `FORTRAN` code, reduction works very fast. The average time work of my procedures in silent mode on my laptop is ~ 25 sec for FLAT reduction, ~ 10 sec for ThAr reduction and ~ 30 sec for one OBJ.

6 Conclusions

HRS pipeline for HRS LR red-arm data is created and works. All reduction described in details in this report was published in the paper Kniazev, Gvaramadze, & Berdnikov (2016).

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