Southern African Large Telescope

Title: **HRS pipeline for MR 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 Medium Resolution (MR) 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 time of **one and half hour**. *MCL programs are based on the standard MIDAS echelle packages* `FEROS` *and* `ECHELLE`. *I present here results of my work.*

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1 Introduction

After obtaining some HRS data in MR mode with SALT I needed programs for reduction of these data. Since I have HRS pipeline for LR red-arm data with MIDAS working, I modified all procedures for work with MR mode. It took a total time of one and half hours. In the current report I will display the result of this work. I concentrated on the red-arm MR data only, because my science needs only the red part of HRS spectra. I will NOT discuss all HRS data reduction steps, that I did in my previous report about HRS pipeline for LR data, but will concentrate only on some key points of reduction from my point of view.

2 HRS MR red-arm data reduction implementation

2.1 Order Definition

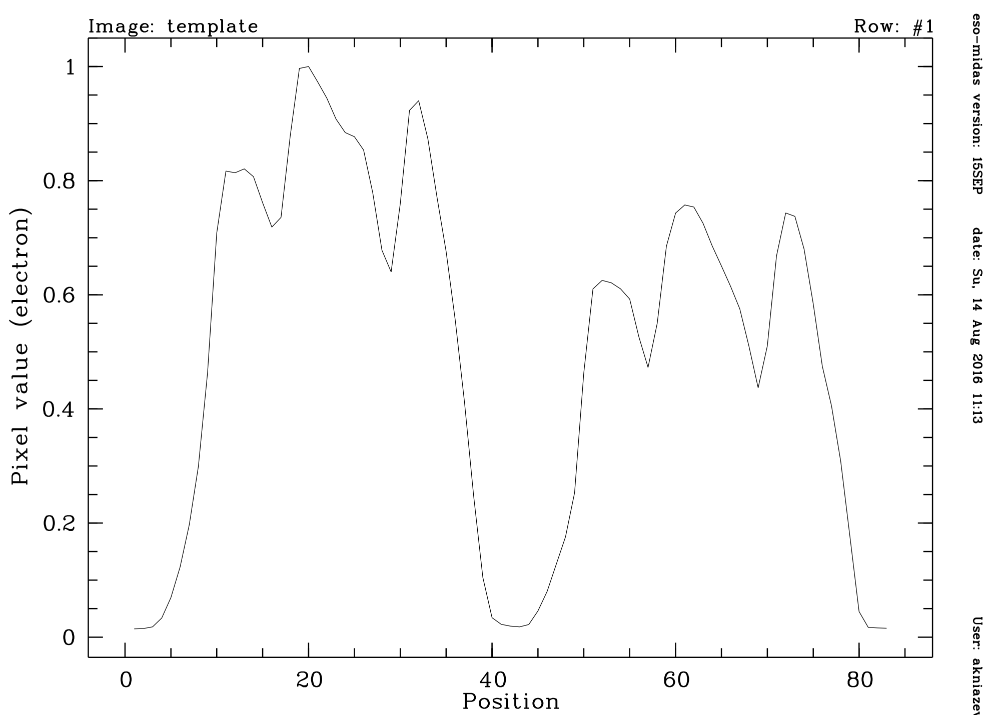


Figure 1: Template used for order definition with HRS MR red-arm data.

I created template using FLAT image for HRS MR red-arm data and it is shown in Figure 1. 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 2.

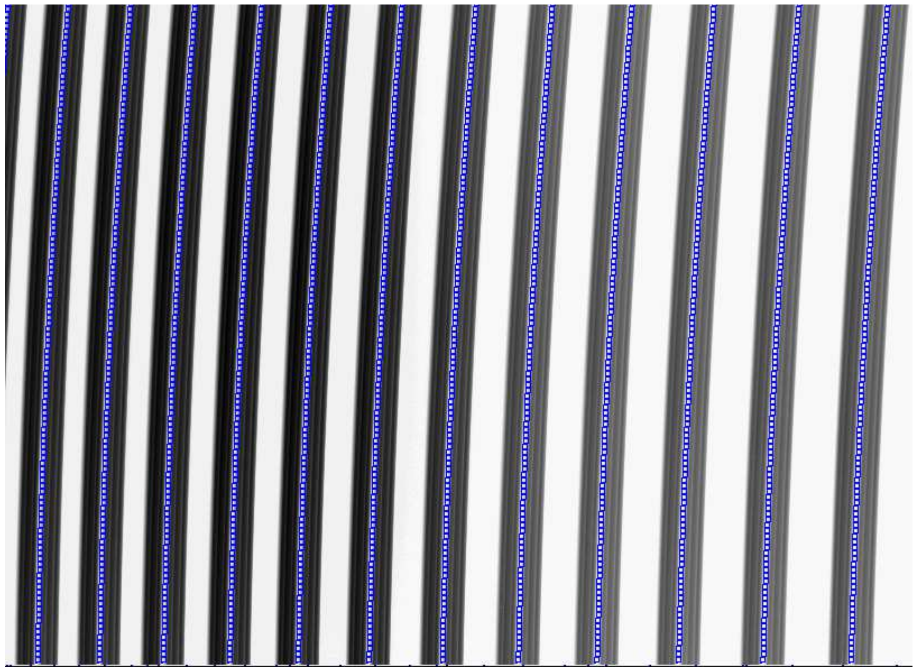


Figure 2: An example of order definition with `DEFINE/FEROS` procedure for HRS MR red-arm flat-field image. Only part of the image is shown. Found central positions of orders is shown with blue squares.

2.2 Background Definition

The estimation of the background is one of the critical points in the reduction of echelle spectra. The result of work of my background program for one central row of FLAT echelle spectrum is shown in Figure 3.

2.3 Order Extraction

The only parameters which have to be changed for this step is the width of slits for extraction. Since orders are wider compare to LR mode, it is more hard to find the correct solution. I found some solution, but possibly it is not optimal yet.

2.4 Flat Field Correction

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.

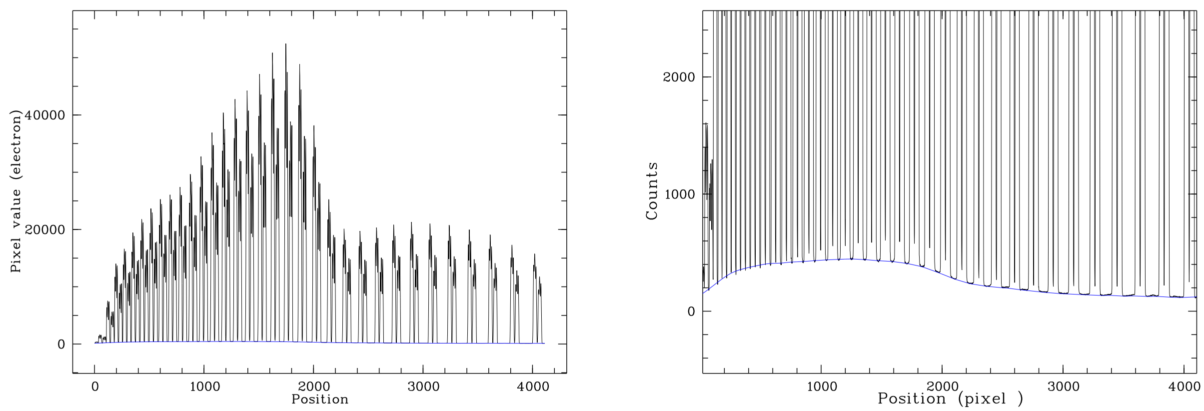


Figure 3: The result of work of program for background definition for one central row of FLAT echelle spectrum. The top panel shows plot with high cut-values and background which was found by program is shown with blue line. The bottom panel shows the same plot but for lower cut-values. It is easy to 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.

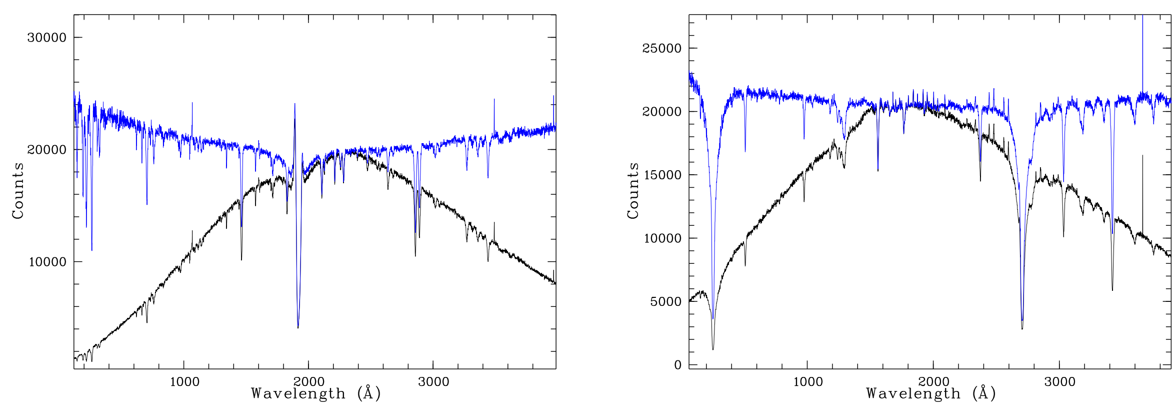


Figure 4: Two examples of the flat field correction for two orders from the spectrum of cepheid star from my program. The left panel is spectral area of the line Hα and the right panel is the spectral area of Paschen lines.

Figure 4 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. The left panel is spectral area of the line Hα and the right panel is the spectral area of Paschen lines. It is possibly to see that left side of both orders goes up slightly. Possibly, the correction was not very optimal because parameters of extraction are slightly wrong.

2.5 Wavelength Calibration

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

I use the TWO-D method with initial interactive identification for the same 15 different not bright lines, which are located more or less uniformly across 2D ARC frame as I did for LR mode. 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 5 and 6. 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.

Figure 7 shows the distribution in wavelength of residuals for each finally used lines from ARC. Blue lines show the standard deviation level.

Finally, the extracted orders, sampled to the constant wavelength step, which calculated during previous procedure and shown in Figures 5 and 6.

Figure 8 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.

2.6 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.

POLYNOMIAL DEGREE : 3

SEQ.NO	SPECTRAL ORDER	NO.LINES	WL START	WL END	STD. DEV. ANGSTROEM
1	85	5	5416.12	5535.55	0.00031
2	84	10	5482.64	5601.51	0.00567
3	83	10	5548.76	5668.98	0.00801
4	82	8	5612.55	5738.64	0.00573
5	81	10	5685.95	5808.88	0.00318
6	80	9	5757.04	5881.50	0.00659
7	79	16	5829.94	5955.89	0.00711
8	78	13	5904.73	6031.98	0.00792
9	77	17	5981.48	6110.53	0.00515
10	76	20	6060.23	6190.88	0.00581
11	75	23	6141.06	6273.41	0.00488
12	74	26	6224.10	6358.14	0.00655
13	73	20	6309.40	6445.20	0.00648
14	72	18	6397.03	6534.69	0.00819
15	71	16	6487.22	6626.70	0.00551
16	70	25	6579.90	6721.34	0.00583
17	69	13	6675.27	6818.95	0.00638
18	68	14	6773.49	6918.97	0.00556
19	67	14	6874.60	7022.19	0.00678
20	66	15	6978.83	7128.54	0.00698
21	65	23	7086.19	7238.21	0.00874
22	64	23	7196.98	7351.29	0.00665
23	63	22	7311.23	7468.00	0.00428
24	62	19	7429.19	7588.37	0.00799
25	61	21	7551.04	7712.72	0.00461
26	60	10	7676.92	7841.25	0.00712
27	59	16	7807.02	7974.13	0.00795
28	58	18	7941.65	8111.62	0.00678
29	57	12	8080.99	8253.88	0.00523
30	56	7	8225.37	8401.27	0.00636
31	55	15	8374.88	8554.03	0.00752
32	54	10	8530.01	8712.36	0.00731
33	53	11	8690.89	8876.86	0.00419
				MEAN RMS:	0.00665

** TOTAL NUMBER OF LINES : 509 **

Set parameter SAMPLE=0.0426256098

Figure 5: Wavelength solution for fiber with object (fiber one in MR mode).

POLYNOMIAL DEGREE : 3

SEQ.NO	SPECTRAL ORDER	NO.LINES	WL START	WL END	STD. DEV. ANGSTROEM
1	85	5	5418.67	5535.51	0.00014
2	84	10	5482.69	5601.57	0.00541
3	83	10	5548.81	5669.02	0.00807
4	82	6	5612.85	5738.27	0.00529
5	81	10	5686.02	5808.94	0.00191
6	80	9	5757.10	5881.54	0.00673
7	79	16	5829.99	5955.95	0.00677
8	78	10	5904.77	6032.04	0.00668
9	77	17	5981.55	6110.52	0.00550
10	76	19	6060.30	6190.93	0.00614
11	75	23	6141.12	6273.48	0.00373
12	74	24	6224.16	6358.19	0.00516
13	73	18	6309.46	6445.25	0.00637
14	72	17	6397.10	6534.75	0.00651
15	71	17	6487.27	6626.75	0.00735
16	70	24	6579.96	6721.39	0.00586
17	69	12	6675.34	6818.97	0.00637
18	68	14	6773.54	6919.03	0.00682
19	67	14	6874.67	7022.26	0.00832
20	66	17	6978.90	7128.62	0.00799
21	65	22	7086.27	7238.28	0.00918
22	64	24	7197.02	7351.38	0.00786
23	63	22	7311.30	7468.08	0.00514
24	62	16	7429.26	7588.45	0.00782
25	61	18	7551.10	7712.80	0.00514
26	60	8	7676.96	7841.39	0.00352
27	59	15	7807.10	7974.20	0.00695
28	58	17	7941.72	8111.70	0.00897
29	57	12	8081.05	8253.96	0.00554
30	56	7	8225.42	8401.36	0.00260
31	55	14	8374.92	8554.39	0.00470
32	54	8	8530.04	8712.56	0.00334
33	53	8	8690.89	8878.27	0.00072
				MEAN RMS:	0.00652

** TOTAL NUMBER OF LINES : 483 **

Set parameter SAMPLE=0.0430845208

Figure 6: Wavelength solution for fiber with sky (fiber two in MR mode).

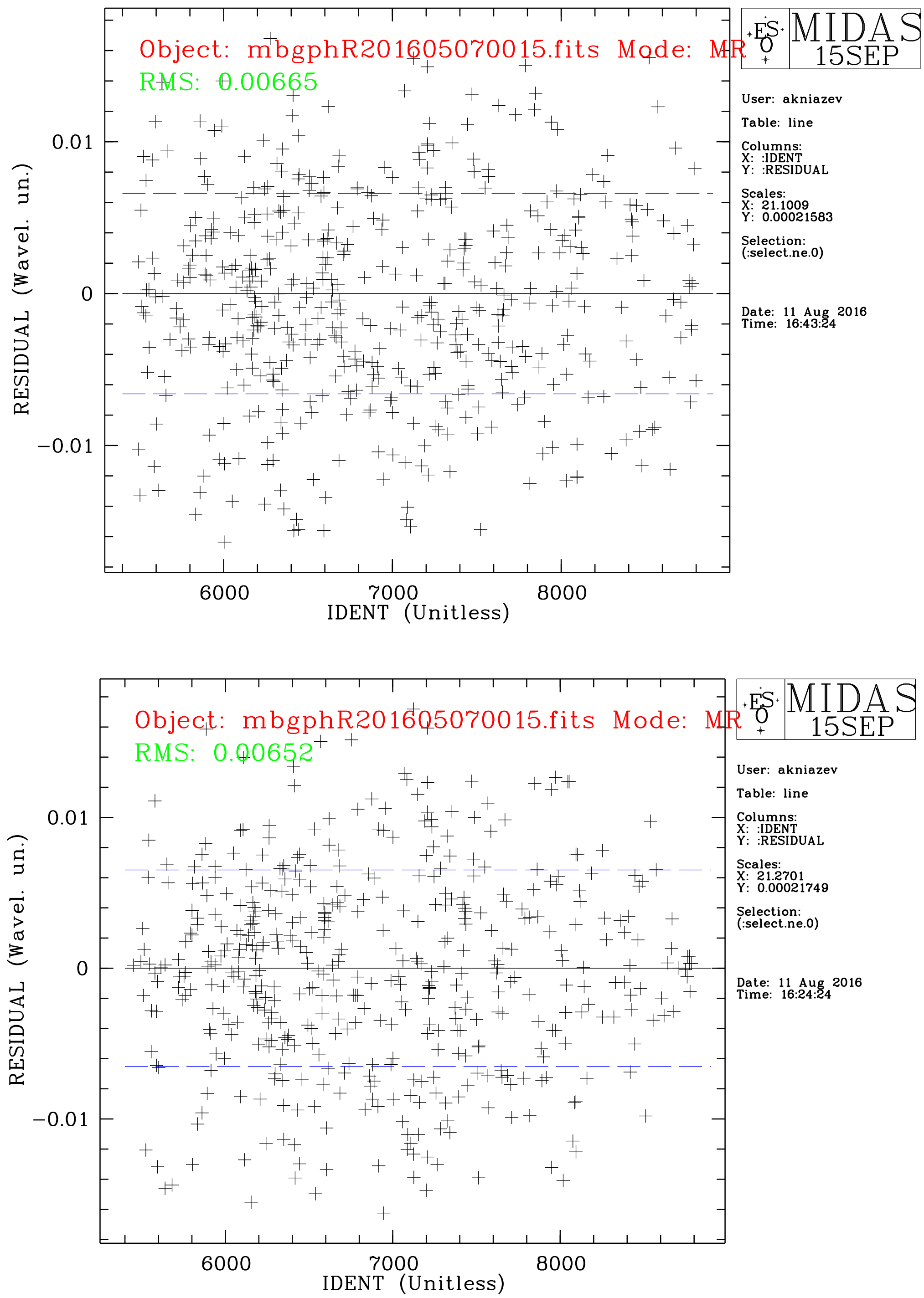


Figure 7: The distribution in wavelength of residuals for each finally used lines from ARC. Blue lines show the standard deviation level. The top panel shows this distribution for the first fiber and the bottom panel shows is for the second fiber.

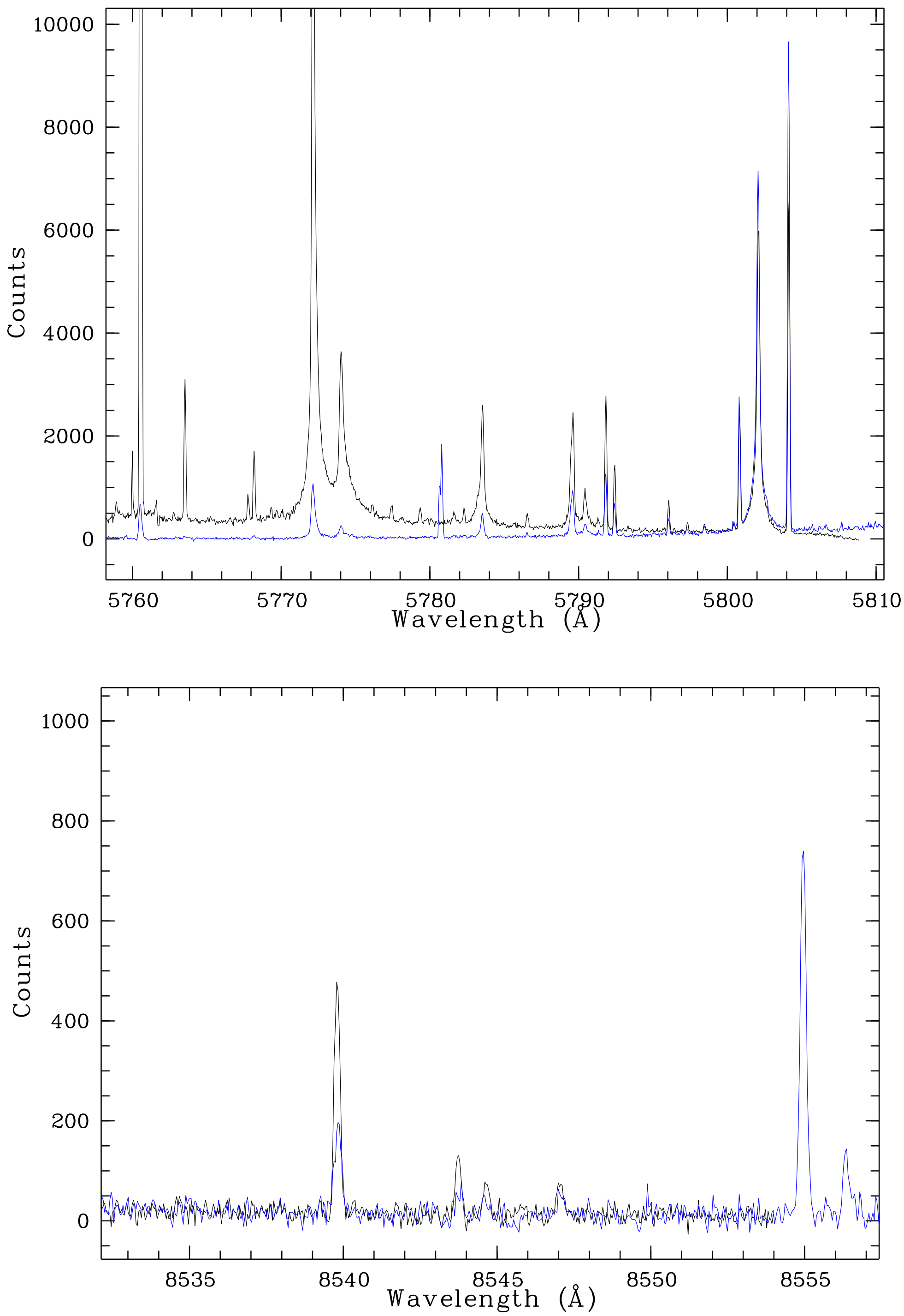
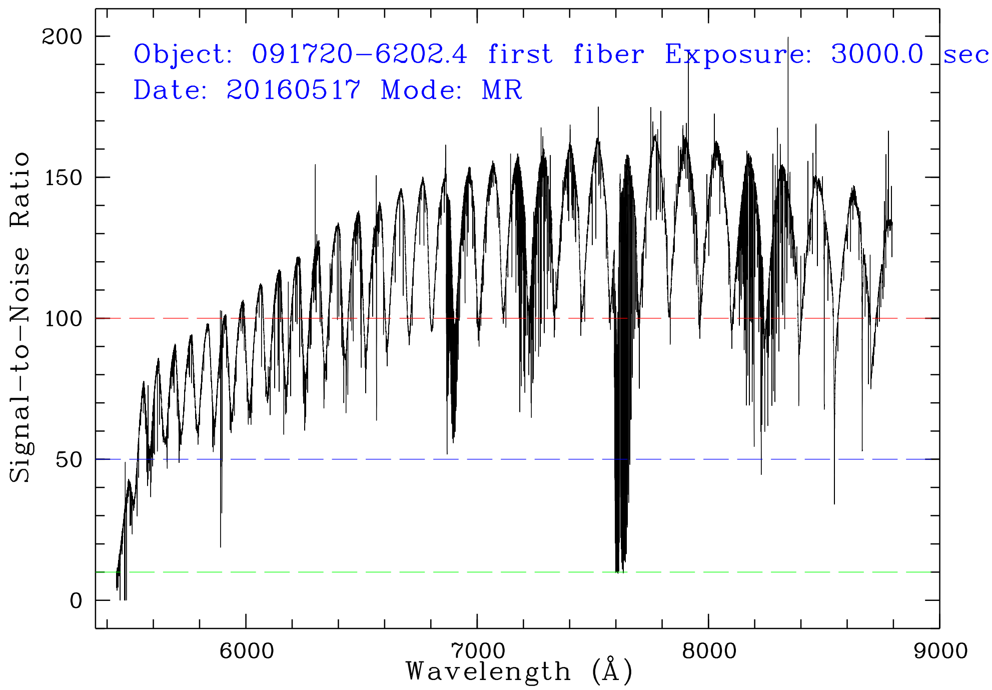


Figure 8: Two examples of edges for adjacent orders from wavelength calibrated ARC spectrum. Different orders are shown with different color. Blue (top) and red (bottom) spectral regions are shown.



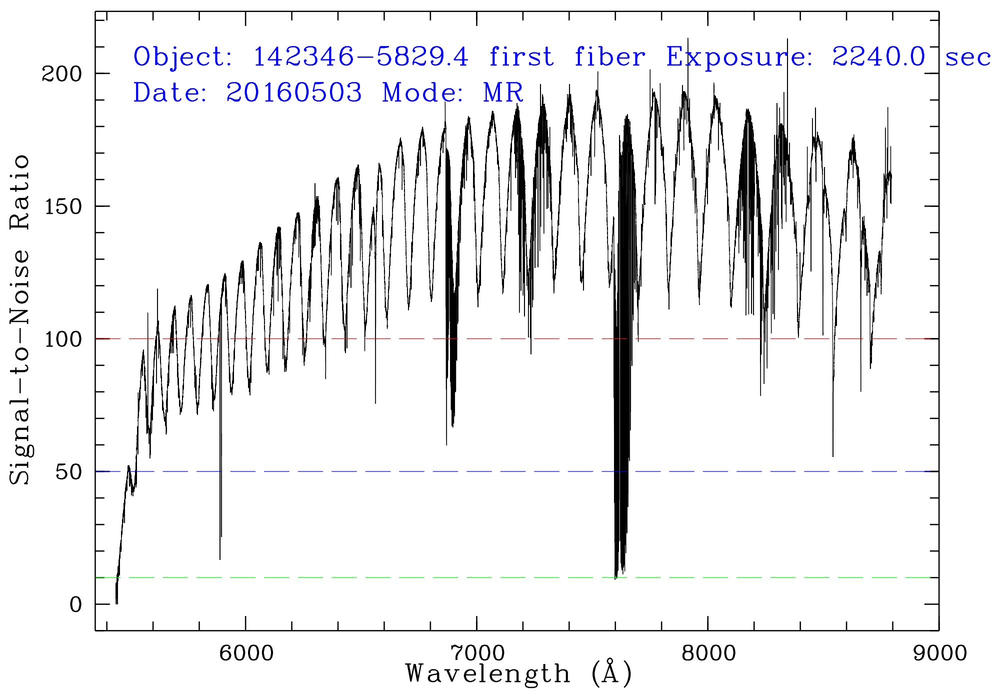


Figure 9: Merged spectra without flat-field correction. My standard procedure for estimation of SNR for observed spectrum.

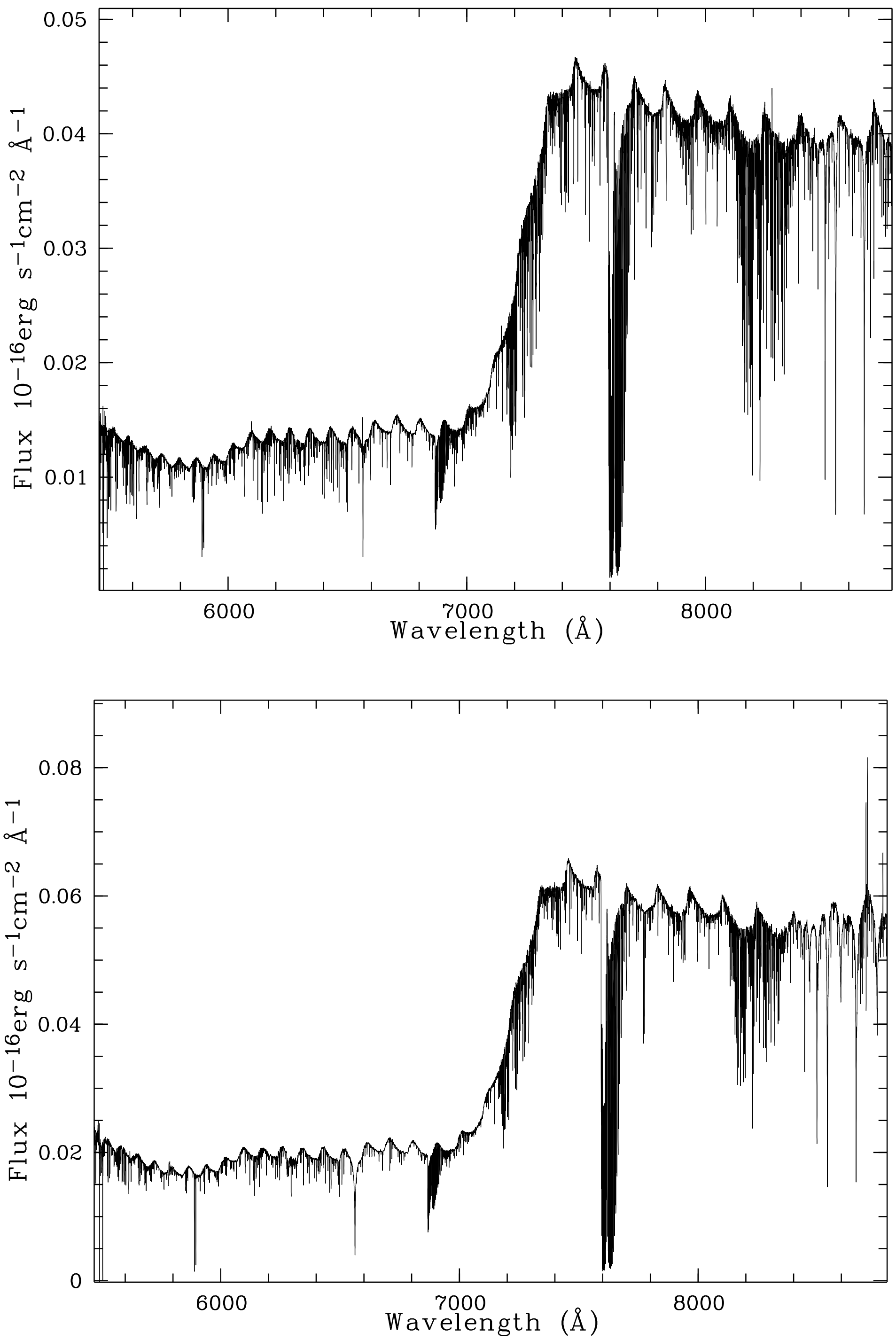


Figure 10: Examples of the final HRS data reduction for two previously shown stars, but after flat-field correction. Some waves are still visible in their continuum that means that our flat-fielding does not remove the blaze to better than about 10–15%.

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 9 and 10 show examples of the final reduction of two objects after all 33 orders were merged in one spectrum. Some waves are still visible in their continuum that means that our flat-fielding does not remove the blaze to better than about 10–15%. *Different reasons could be for that and this question needs to be studied carefully.*

2.7 The Final Sky Subtraction

The sky subtraction was done in the same manner as it was explained in the previous report. Figure 11 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 one of cepheid. 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 blue 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, practically in the reddest spectral region. All night sky lines were removed as well without any PCyg profiles. Unfortunately, *I can see some over-subtraction for some lines, so it is the field for the future study.*

3 MIDAS pipeline for HRS MR 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 $\sim$ 25 sec for FLAT reduction, $\sim$ 10 sec for ThAr reduction and $\sim$ 30 sec for one OBJ.

4 Conclusions

HRS pipeline for HRS MR red-arm data is created and works.

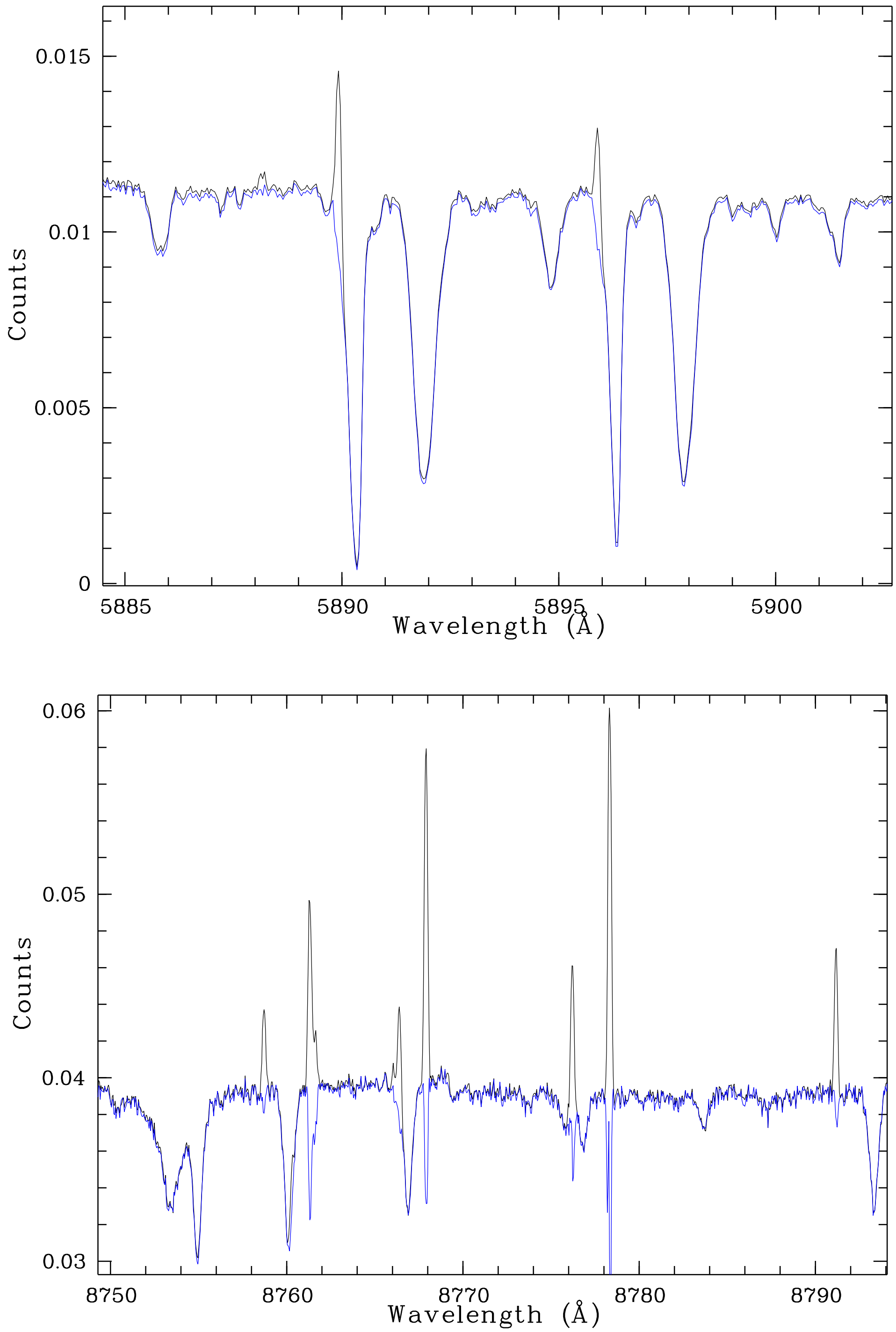


Figure 11: Examples of removing of night sky lines from HRS spectra after reduction with MIDAS. Both panels show result of the night sky removing in the HRS spectrum for one of cepheid from my program. The top panel shows such result in the very blue order, and the bottom panel shows such result in the very red order.