Comparison of Echelle Spectra Reduction Packages

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Abstract

The reduction of raw echelle data is a straightforward, although quite complicated task, where the reliability of the final result strongly depends on precise accomplishment of each step. Therefore the choice of reduction package best suited for the particular instrument is very important. We have tested several software packages commonly used for reduction of data from fiber-fed echelle spectrographs. We used them for processing of raw CCD echellegram of several early-type stars secured with HEROS fiber echelle spectrograph currently installed at Cassegrain focus of Ondřejov observatory 2m telescope. The main interest was focused on the methods and algorithms of determination of dispersion relation. The spectra were reduced until the individual one-dimensional lambda-calibrated orders were obtained. The precision of wavelength calibration was then checked measuring position of telluric lines.

Reduction recipe

Both basic principles and detailed cookbooks for reduction are described in a number of places (Hall et al. 1994; Hinkle et al. 2000; Churchill 1994; Erspamer & North 2002). Although quite complicated, the main part of echelle reduction is quite straightforward and the automatic pipelines can be used to reduce the data until the stage of individual extracted echelle orders with associated wavelength scale.

To check the quality of resulting spectra using different reduction packages, we have selected a single exposure of hot star ι Her secured by HEROS red channel with 2 flat fields and 2 comparison arcs bracketing the stellar exposure. The same raw data were reduced in three different reduction packages generally used for reduction of data from fiber-fed echelle spectrographs. The data had to be individually modified (mainly FITS keyword corrections). The basic strategy of reduction is the same. The reduction consists of

- averaging the 2 flat fields in 2D
- rotating all images to standard orientation (wavelength increases left to right and bottom to up)
- finding the echelle orders automatically using the fit of flat-field cross-order profiles in different columns and preparing the trace
- finding the background in the inter-order space and its smoothing by fitting of the 2D surface
- subtraction of the background surface from the all frames (still in 2D)
- extracting the flat-field and stellar orders along the given trace using the optimal extraction with cosmics cleaning
- removal of blaze function and fringes by division of extracted stellar orders by corresponding flat-field orders
- extraction of ThAr arc along the trace, manual identification of a number of lines and automatic follow-up using line list of about 150 selected lines.
- attaching the dispersion relation to the flat-fielded star including re-binning into equidistant wavelength difference and shift by the calculated heliocentric velocity.

Although the principles are almost identical the implementation of them in each packages is little different using unique algorithms.

Brief description of packages

Standard HEROS pipeline

This is a set o MIDAS procedures and custom C and Fortran functions written by A. Kaufer and O. Stahl as a customized version of standard MIDAS `echelle` context. The full description of a reduction procedure is published in Škoda & Šlechta (2002)

Before processing the bad columns and pixels are interpolated on 2D frame using the defect list.

It tries to be robust for orders with low flux by fitting the 2-dimensional polynomials of low degree through the Gaussian fitted cross-order profile maxima, but this makes a lot of troubles. Experience shows the necessity of tiny twiddling the parameters (mainly threshold, order width and order slope) to get correct order traces. Sometimes the algorithm is confused (creating even the loops and waves on traces) and such parts of low -flux data have to be removed before tracing.

The dispersion fitting is quite clever and robust using several manually marked lines to fit a 2D low-order polynomial than switches to order by order line identification automatically adding more lines from the list and again switching to 2D polynomials. The procedure is repeated several times rejecting lines outside the tolerance limit until the RMS is stable. The manual identification is done showing the 2D image of the echellegram so the constellation-like patterns may be easily remembered. Only about 20 lines spread over the whole frame is sufficient to allow the automatic identification.

The specific feature of the HEROS extension to the basic MIDAS echelle context is the application of global 7-parameter (only) rational-polynomial fit described by de Cuyper & Hensberge (1998) on the final dispersion calibration.

Hensberge's modified FEROS package

This is a custom package developed by H. Hensberge for reducing data from FEROS spectrograph. It uses the basic FEROS package but corrects a number of errors and strongly modifies the behavior of several procedures. It was partly modified for accepting data from HEROS by changing a number of parameters. Due to various reasons, however, the wavelength calibration was not successfully adapted to HEROS frames and so the dispersion relation from preceding HEROS pipeline was taken for this test. The order tracing is done using the cross-correlation with Gaussian-shaped template of a averaged cross-order profile beginning in the centre of frame and going to both end or until the trace is lost. The fit is then done order by order.

The background subtraction is very careful using the digital filter and noise statistics to fit 2D surface in inter-order space. The extraction is done twice - once with optimal variance weighting rejecting pixels deviating from normalized COP and once using the plain summing. By comparison of both results the cosmics and bad pixels are flagged and removed from optimal extracted data by interpolation.

This package has well-controlled behaviour and its precision had been well tested on the number of FEROS spectra.

IRAF dofoe task

For simulating the behaviour of preceding packages, the `dofoe` task was used separately on averaged flat field and stellar exposure and the extracted data were divided by `imarith`. The dispersion was then applied using `dispcorr` on flat-fielded extracted stellar orders taken from lambda calibrated extracted star. The main reason for this is the behaviour of standard `dofoe` that divides not by extracted flat-field but by `Flatnorm.ec` that is normalized to intensity about one. That preserves the amount of ADU but makes scales the data in comparison to MIDAS approach and makes the direct comparison difficult.

The tracing here is done using the automatic aperture finding in center of frame following the position of COP fits using the `fit1d` algorithm similar to cross-correlation. The extraction is optimal with cosmic cleaning and variable aperture with taking the certain level (in our case 0.001) of the COP peak as the background level. The background subtraction is using smoothed 2D surface obtained from inter-order space minima (method `scattered`).

The real challenge is the wavelength calibration with `ecidentify` task called from `dofoe` Only the 1D separate orders are seen and the number of lines required to get initial fit is quite high. After number of test we had to mark about 100 lines to get reliable result. Using the same lines as for MIDAS first estimate failed completely. The 2D Chebychev polynomials are too much flexible so in case of lack of lines can high-order fit obey positions of all lines and the good-looking graph of residuals (after interactive rejection of outliers) does not warrant the good fit. Mainly at the edges of orders and in IR orders (where is a lack of good Th lines and a number of overexposed Ar lines) can be the solution bad. This may be tested by over-plotting adjacent orders.

The wavelength calibration methods

As was said, the modified FEROS pipeline has to take the dispersion solution from HEROS pipeline, so we can compare only the different approaches of MIDAS and IRAF respectively. In both cases we used the linelist of 145 carefully selected lines of Th and Ar over the HEROS red channel range (5800 – 8400 Å). Then a number of lines was identified manually. For HEROS (MIDAS) package only 20 lines spread over the entire frame (see Fig. 1) was enough to be able to run the automatic finding procedure. In IRAF case of procedure `ecidentify` the usage of same 20 lines did not lead to correct solution (the automatic algorithm failed). We tried to follow the recommendations and have marked about 5 lines in every fifth order (i.e. about 35 lines). The results were promissing, but the further improvement using the automatic searching was not achieved. After a number of trials we had to manualy identified (as shown on Fig. 5) about 100 lines before runing the initial fitting procedure.

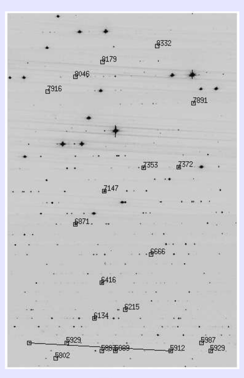

Figure 1

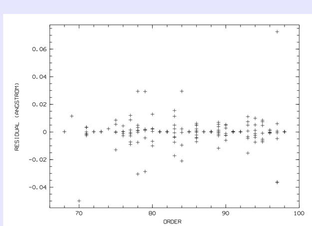

Figure 2

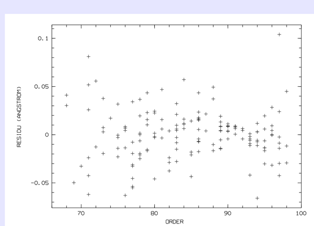

Figure 3

Then further lines were found succesfully and after some play with rejection and matching parameters and increasing the degree of 2D polynomials until the degree 6 (in x) and 5 in order coordinate (i.e. value xorder=7, yorder=6) we achieved the RMS about 0.008 Å as seen on Fig. 4. The residuals of fit in different orders from MIDAS for both order by order local fit (value RESIDUAL) and for global 7-parametric fit (RESIDU) are shown on Fig. 2 and Fig. 3 respectively. Here should be noted the smaller scatter of IRAF values. It requires however 56 coefficients in comparison to 7 and it is less reliable at the edges of frame or in orders contaminated by strong Ar lines (in near IR) as will be shown next. The extracted data is then rebinned to get equidistant intervals in wavelength.

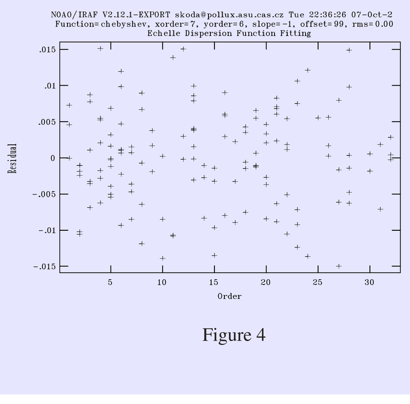

Figure 4

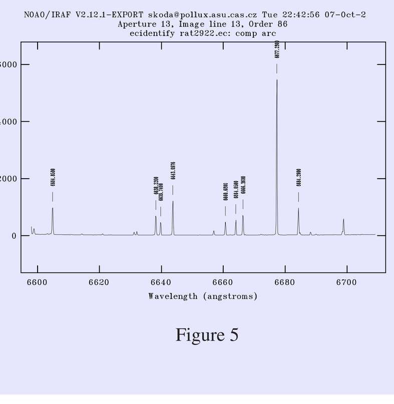

Figure 5

Comparison of reduced spectra

The resulting extracted echelle orders unblazed by division of extracted flats are compared on following pictures:. Every package is marked by one colour (HEROS pipeline–blue, modified FEROS–green and IRAF `dofoe` – red). In general the match is excellent. Some interesting differences are, however, seen on zoomed details that show, how the particular algorithm behaves.

The background subtraction and variable aperture (`resize=yes`) of IRAF is probably responsible for different slope of the order in bluer orders (Fig. 6 and Fig. 7) or for change in flux level (Fig. 8).

The optimal extraction with cosmics cleaning is very sensitive to parameters setup. When running over one bad column the digital filter together with flagging of bad pixels works quite well in Hensberge's procedures but fails in case of adjacent two and more bad columns (Fig. 9). The IRAF algorithm can be foolled by strong gradient of bad collumn and produces the sinusoidal bump. See Fig. 10.

Despite the small changes of line positions caused by different rebinning the dispersion calibration in IRAF case is not perfect and the problems of anchoring the polynomials at edges may cause the incorrect dispersion fit in orders with small number of usable lines as is shown at the edge of the frame in IR region (Fig. 11).

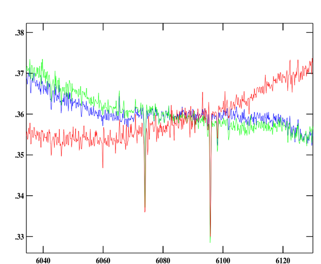

Figure 6

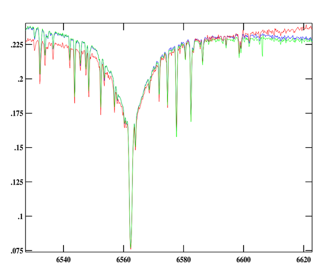

Figure 7

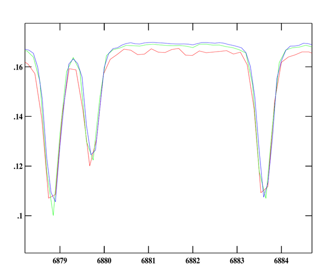

Figure 8

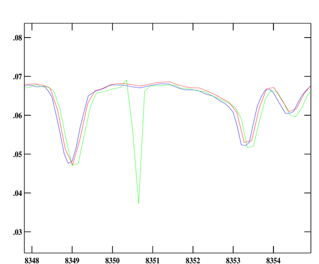

Figure 9

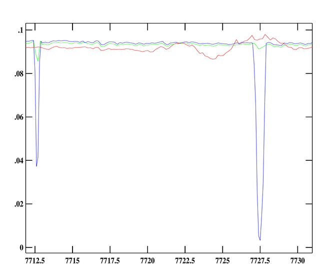

Figure 10

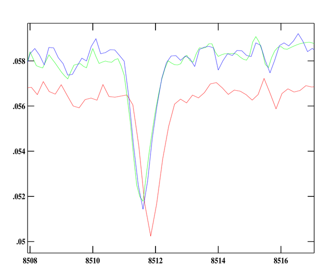

Figure 11

Conclusions

The tests have shown the good match of output from all three packages. The wavelength calibration procedure in MIDAS is much more comfortable and more robust. The IRAF approach requires many lines to be manually identified and the 2-dimensional polynomials have problems at the edges.

Despite the tiny differences, all packages may be used to produce reliable echelle spectra from fiber-fed instruments. The requirement of radial velocity stability is well obeyed in all cases but the precise flux level depends on a number of parameters and mainly on correct background subtraction. From the experience follows the idea that a simple robust package would be IRAF `dofoe` task calling completely different `ecidentify` procedure working like MIDAS `echiden` task and using the 2D manual representation and global 7-parametric fit by Hensberge.

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