

Spectangular - User Manual

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May 4, 2016

Abstract

Spectangular is a GUI program written in C++ for spectral disentangling of SB1 and SB2 systems. It is also capable of decomposing static (telluric) features.

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1 Introduction

Spectral disentangling is a self-consistent method to decompose spectra of multiple systems without information about the orbital parameters. Spectangular performs this method in the wavelength space and is capable of optimising the orbital parameters such that these parameters are also found from a set of observed spectra. This user manual provides all necessary information to run the program and gives some background information on the method. It is worth noting, that methods like direct or iterative subtraction are not understood as disentangling methods. They rely on a fully analytical approach which is, due to noise, not fulfilled by real data. Hence, the result is very sensitive to the SNR. See Hadrava (2009) for further information on Fourier-disentangling and separation techniques.

There are three principal differences to Fourier-based disentangling. In Fourier-space (1) all spectra need to have the same sampling, (2) each point has the same weight and (3) the output is a periodic function of wavelength. Spectangular is coded without the need of point (3). Hence, the wavelength coverage of the output spectra will be larger compared to the input by a value defined by the radial velocities of the observations. For a more detailed analysis of the code with artificial data as well as real-life data we refer to Sablowski & Weber (2016).

For efficient matrix and vector classes as well as routines for the SVD we use the Armadillo linear algebra library, Sanderson (2010). Furthermore, we use the OpenBLAS¹ library for parallel computing and the Qt² library for the GUI classes.

We collect all n observed spectra in

$$\vec{o} = (\vec{o}_1 \dots \vec{o}_n)^t \quad (1)$$

and the output spectra of the k components in

$$\vec{x} = (\vec{x}_1 \dots \vec{x}_k)^t. \quad (2)$$

If we assume that the spectral resolution is sufficient (in first-order approximation given by the rotational velocity of the slowest rotating component), we can treat the problem linearly. Hence, we have to solve

$$\underline{M} \vec{x} = \vec{o} \quad (3)$$

for the solution vector \vec{x} . The transformation matrix \underline{M} represents the radial velocities of each individual observation and images the solution to the observations. This (dense but large) matrix can be further separated to

$$\underline{M} = \begin{pmatrix} \underline{N}_{11} & \dots & \underline{N}_{k1} \\ \vdots & \ddots & \vdots \\ \underline{N}_{1n} & \dots & \underline{N}_{kn} \end{pmatrix}, \quad (4)$$

¹<http://www.openblas.net/>

²<https://www.qt.io/>

where

$$N_{ij} = \begin{pmatrix} \overbrace{0 \dots 1}^{v_{ij}} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 1 \end{pmatrix} \quad (5)$$

contains the velocity v_{ij} of observation j of component i . Singular value decomposition (SVD) is used to solve this system. SVD yields the solution of smallest residuum

$$r = \|\underline{M}\vec{x} - \vec{o}\| \quad (6)$$

as long as it is applied to overdetermined and rank-deficient systems. The system is overdetermined, obviously, if $n > k$. If telluric (static) lines are present, another column of matrices $N_{k+1,j}$ is added, hence $n > k+1$ is necessary. We note here, that the code does not apply heliocentric correction. Hence, in case of presence of static lines, no heliocentric correction has to be applied and the optimisation (if necessary) needs to be performed on the individual velocities $v_{ij} = RV_{ij} + h_j$, where RV_{ij} is the radial velocity of observation j of component i and h_j the heliocentric correction of observation j .

As already mentioned, Spectangular is capable of optimising the orbital parameters to find the best solution to the observations. An initial orbit needs to be set at the beginning as well as the number of iterations of the global optimisation algorithm. More details will follow in Sect. 3. The implemented algorithm is the Downhill-Simplex or Nelder and Meade algorithm, Nelder & Meade (1965). This is a multidimensional global optimisation algorithm and needs to be initiated first. In the case of a SB2 system, there are 8 free parameters. Hence, the algorithm will create a simplex with 9 points in the 8-dimensional space by varying the initial orbital parameters. The variation of these is not random, i.e., for a given data set and initiation the initiation of the optimisation will always be the same and does not need to be recalculated. The initiation is time-consuming since SVD needs to be performed 9 times. As already mentioned it is also possible to optimise on each individual velocity. However, if, e.g., $n = 10$ there are 20 variables in case of a SB2 system, i.e., initiation performs SVD 21 times. Obviously, in most cases optimisation on orbital parameters will provide faster convergence.

The procedure is (see Fig. 1): While the optimisation is initiating it solves the system multiple times for several sets of variables (as discussed above). The residuum is calculated for each of the solutions and used as the value to be minimised. During each iteration, different transformations of the simplex are used, i.e., SVD is performed multiple times in each iteration. The most time-consuming transformation is the total contraction of the simplex in direction of the best point (current set of variables which gives the smallest residuum).

We have defined a quality factor which helps to plan observations and to evaluate a given set of measurements. Let \widehat{RV} be the peak-to-peak value of the radial velocities and S_p the two-pixel resolution in the velocity space of the spectrum, then $N_{max} = \widehat{RV}/S_p$ is the maximum number of independent spectra.

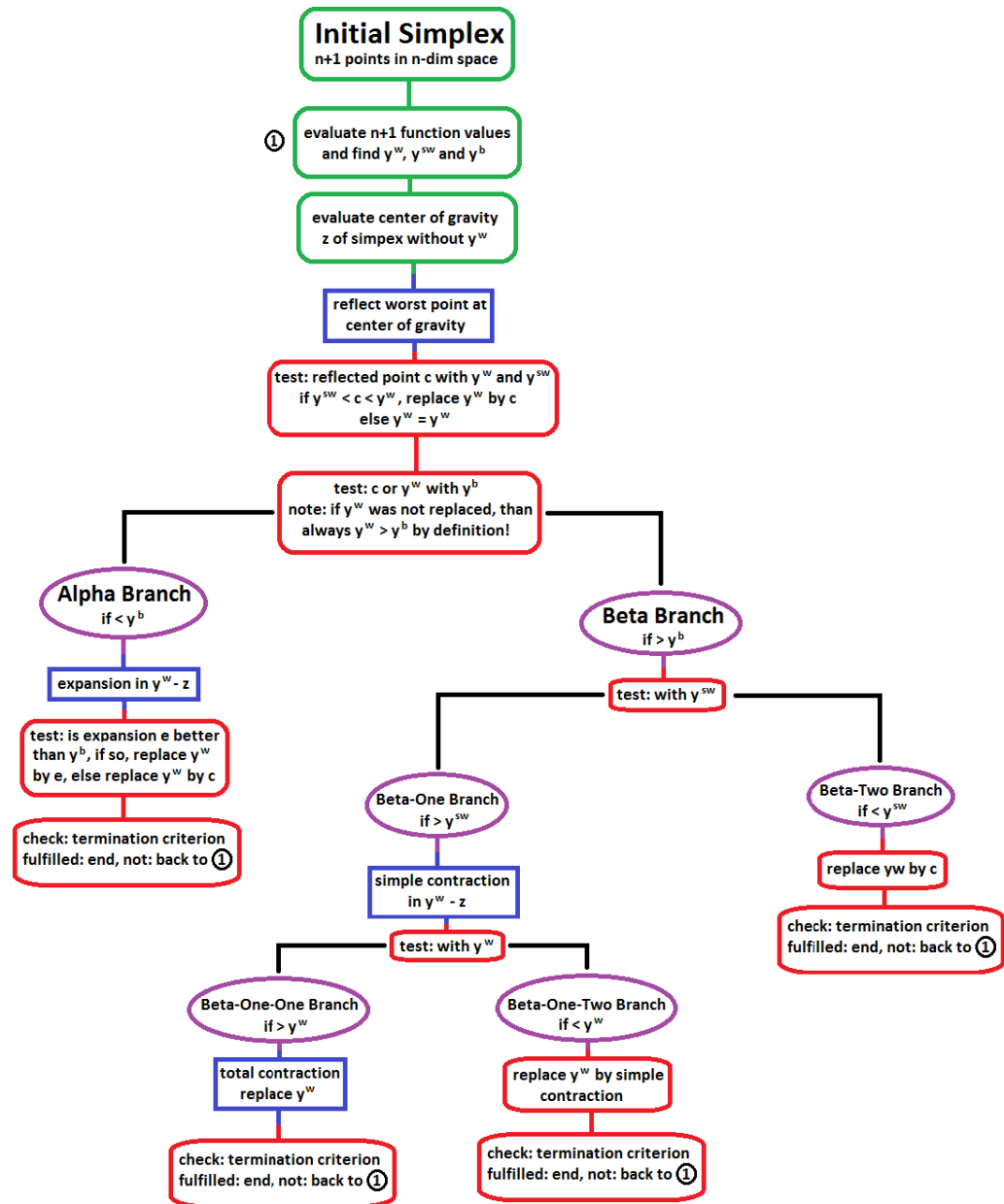


Figure 1: Downhill-Simplex-Algorithm

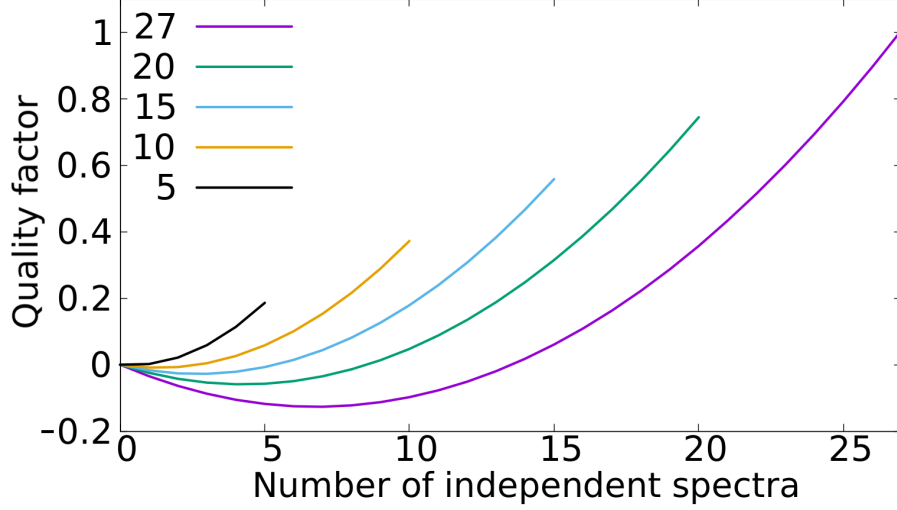


Figure 2: Quality Factor

The quality factor is thus defined as

$$Q_d = \frac{N_{IS}}{N_{max}} \left(1 - \frac{N_{RS}}{N_S} - \frac{N_{RS}}{N_{max}} \right), \quad (7)$$

where $N_{RS} = N_S - N_{IS}$ is the number of reproductions, N_{IS} the number of independent spectra and N_S the number of all spectra. This factor is plotted in Fig. 2 for $N_{max} = 27$ in dependence of the number of independent spectra and for different N_S . The factor is unity in case of $N_{IS} = N_{max}$ and redundant spectra are not counted. It is zero in the case that reproductions are compensated by independent spectra, $N_{IS} = N_{RS}$. The definition assumes only a small eccentricity of the system.

2 Observations and Input-Data Preparation

As described in the last section, the individual observations should be planned carefully in the sense of orbital sampling. In case that a rough orbital solution is known, the observations can be placed such that the radial velocities of the components differ by S_p from one to the next. As always, SNR should be high as possible and a compromise needs to be found for short period systems between exposure time and SNR to avoid smearing of the radial velocity information.

Care must be taken in data reduction by the wavelength calibration and continuum normalisation. All spectra need to be normalised equal and no differential deformations of the continuum is allowed. If the reduced spectra are provided by pipeline which does not allow any adjustments, bad spectra should

simply be removed. However, of course, there is always the possible of renormalisation of an “special favor” spectrum with standard data reduction packages (IRAF, MIDAS, etc.). There is also a cubic spline fit implemented to renormalise the output spectra. We will demonstrate this in Sect. 4.

An additional tool available is “CroCo”, which was written for 2-dimensional cross-correlation and logarithmic resampling of the spectra. This is necessary for all input spectra. Since the shift

$$\Delta\lambda = \lambda_0 \left(\frac{v}{c} \right) \quad (8)$$

on the wavelength axis for a given velocity depends on wavelength, we need to resample to a logarithmic grid. The new wavelength is

$$\lambda' = \lambda_0 \left(1 + \frac{v}{c} \right) \quad (9)$$

and on the logarithmic scale

$$\log(\lambda') = \log(\lambda_0) + \log(1 + v/c) \quad (10)$$

the velocity leads only to an additive constant. CroCo will look for the minimum sampling

$$\delta = \min[\log(\lambda_{i+1}) - \log(\lambda_i)] \quad (11)$$

between all bins in all spectra. The sampling δ' on the logarithmic scale is adjustable by the user, who can set the increment I such that $\delta' = I\delta$.

The main window of CroCo is shown in Fig. 3. To rebin the spectra need to be in the folder given in the line editor for the work path. All spectra need to be numbered starting at 0, e.g., spectra_0.fits ... spectra_10.fits. Currently allowed data format are fits tables and ASCII txt files (two columns, first wavelength second intensity). In case of fits tables the user can specify the name of the extension and the name of the columns for wavelength and intensity data. The user sets the number of spectra present in the folder (11 in our example), the common name of all spectra (spectra_) and the common name of the output. Furthermore, the user has two options to set the spectral region to be rebinned. The option, where all spectra will be cropped to equal wavelength range is the default. However, it is also possible defining a wavelength range to crop the data to a smaller region of interest, which of course will be faster and with less memory processable. All other fields and options are for the cross-correlation, which we will not describe here.

3 Run the Program

The main window is shown in Fig. 4. A short description of the numbered lines:

1. Check this box in case the RV data are generated by CroCo and an optimisation is done on individual velocities. In any case, the number of spectra to be used must be set in the two spin boxes.

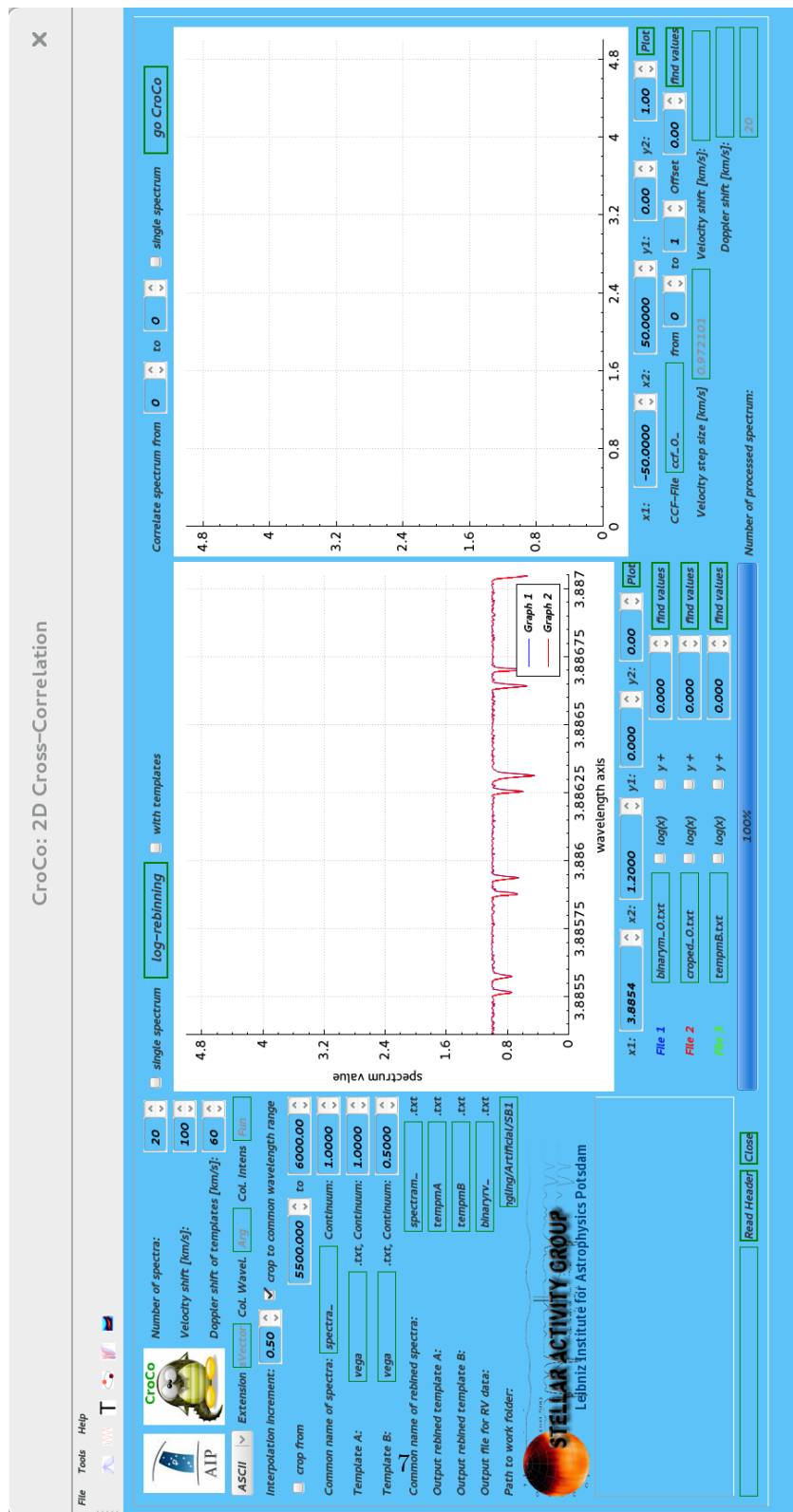


Figure 3: CroCo - main window

2. Check this box in case the RVs are listed in two (SB2) or one (SB1) columns in an ASCII file. The values have to be ordered as the spectra are. Hence, first line of values corresponds to the first spectrum.
3. Check this box in case the RVs are computed from provided orbital parameters set in the editor (later). If the period of the system is well known, some time may be saved when locking it.
4. Type in the common name and the file extension of all spectra, e.g, "spectra_" *. "fits(txt)" in case the file names are spectra_0.fits(txt) ... spectra_xxx.fits(txt).
5. You can set the flux-ratio of the components here. Constant over wavelength. However, since in most cases renormalization is necessary this correction can also be applied after the disentangling procedure.
6. Choose ASCII if data is stored in ASCII files, choose fits if data is stored in fits tables. Type in the name of the extension in case you are using fits tables.
7. Type in the name of the column for the wavelengths and for the intensity in case that fits tables are used.
8. Type in the path to your work folder.
9. Choose SB1 or SB2, static lines in case there are tellurics or other static features (nebula emission, CCD errors). The "Read Data" button can be used to display the RVs in the text field and check data size before starting the disentangling.
10. A single SVD can be performed. "SVD" for a full and slow SVD, "ECON" for economical SVD where one can choose between the divide-and-conquer and standard method.
11. The "Optimization" button starts the optimisation. The number of iterations the algorithm will perform can be set (without the necessary number of calculations for the initiation). If optimisation was performed already, the user can start from the "Initial" data or from the optimised "Continue" data. "New" needs to be checked in case that optimisation is performed the very first time.
12. The number of iterations and evaluations performed are shown. The user can choose whether to optimise on the mean residuum or the peak deviation.
13. Type in the name of the output file for component one and the static signal.
14. Type in the name of the output file for component two and the differences.

15. Type in the name for the initial data, first for values of the residuum, second for the values of the variables.
16. Same as 15 for optimised data
17. Computation time, mean residuum and the binning size in velocities is shown.

As soon as we have all the spectra rebinned, we need an additional ASCII file which list all times of the individual observations. Furthermore, we need to set the levels of the spectra and the initial orbit. This is done with the “Editor” found in the menu bar under “Tools” and is shown in Fig. 5. The tables will be filed with “1” as default when setting the number of spectra. If there are spectra from an eclipse, the relative values between the components need to be given. The data will be written to a local file when clicking the left “Apply” button. The coefficients (central field in the window) for the transformations in the optimisation algorithm are not changable at the moment. The orbital parameters are set in the right field and written to a local file by clicking the right “Apply” button. Some predefined orbits can be loaded and edited and applied. If there is a set of orbital parameters you want to have in that data base, contact the developer.

The three check boxes in the upper left corner of the main window are used to set the initial velocities. In case that CroCo was used for cross-correlation, the first box is checked. However, in any case, the number of the first spectrum and the last spectrum to be used for the disentangling need to be specified. If there is a custom ASCII file which lists the velocities (one column in case of SB1 and two columns in case of SB2), the second check box is used. Note that this file needs to contain as many rows as number of spectra are specified. These two options are used if one wants to optimise on the individual velocities. In case that an initial orbit is specified, the third check box is checked and the file name which contains the HJDs of each observation used is given. This file needs to be placed in the work folder and the path to that folder is given five lines further down. Currently, the user has the option to lock the period of the system, since it is sometimes precisely known.

The common name of all rebinned spectra is given in the next lines. Since the code is not able to get the flux ratio of the components, it can be set in the next line. However, it is also possible and sometimes necessary to adjust and renormalise the continuum of the output spectra. We will describe this in Sect. 4. If this ratio is not known “1” is the default. If data is present as txt ASCII file or fits table, set the necessary information in the next two lines. The “Read Data” button can be used to display the velocities in the text editor and observe the necessary memory (type “top” in a terminal under LINUX), the data addresses. Further check boxes are used to choose between SB1 and SB2 systems and to enable decomposing of static/telluric features. If there are CCD errors (dead pixels etc.) or fringing which appear in the same way in all spectra this option could also help to decompose these. The name for the output

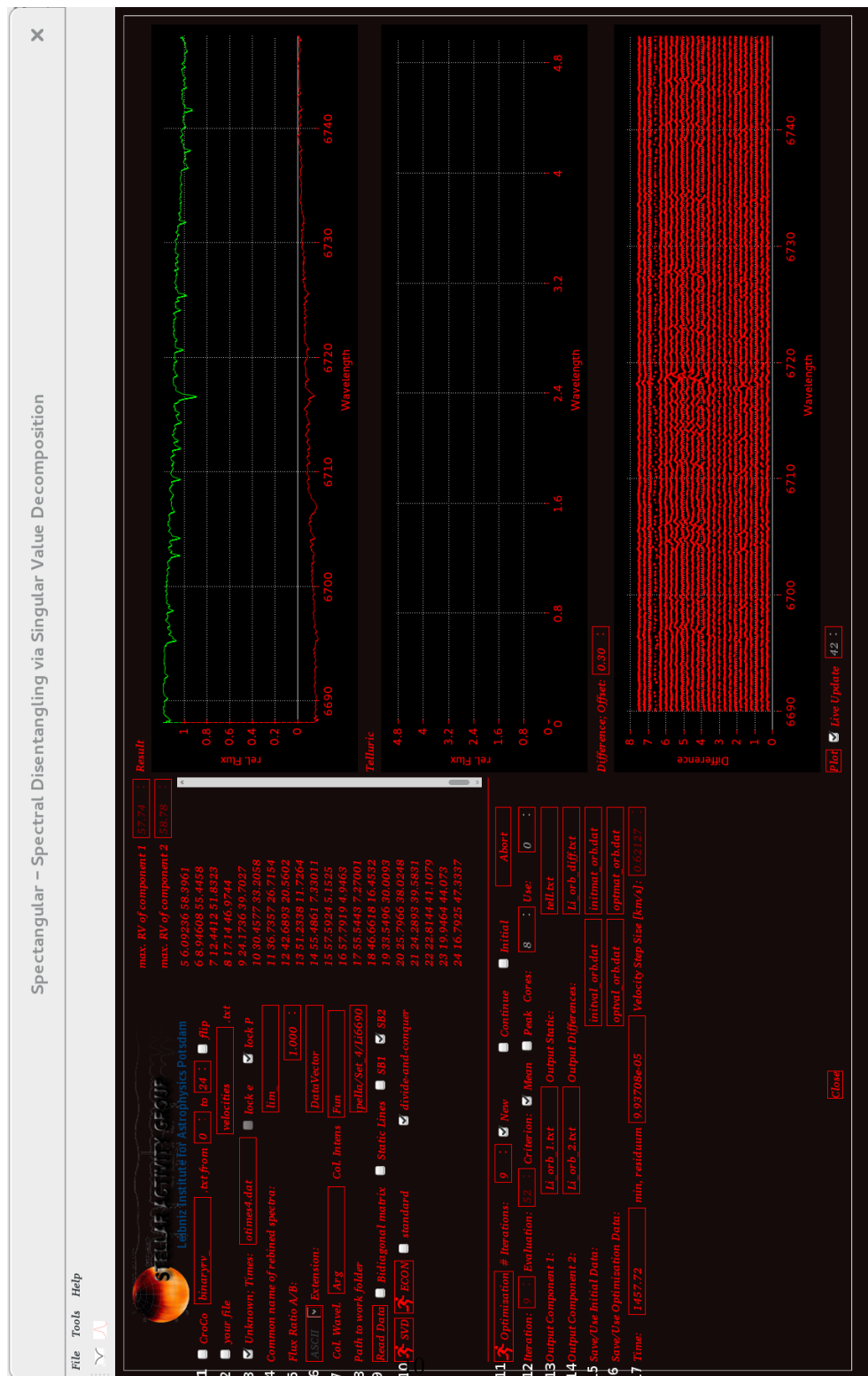


Figure 4: Spectangular - main window

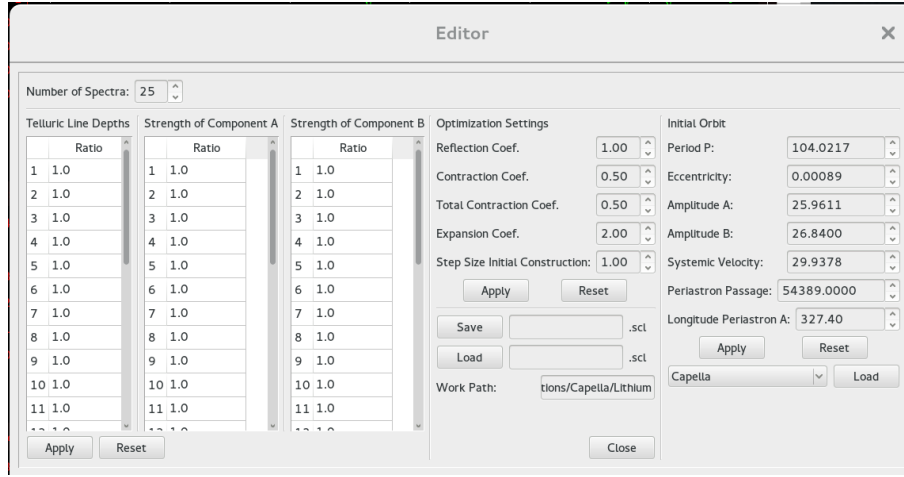


Figure 5: Editor

(both components, telluric and differences between results and observations) are specified in lines further down.

Full SVD (slowest option) is performed by clicking the “SVD” button. An economical version (standard or applied divide-and-conquer - fastest) can be performed by clicking the “ECON” button. This can be used in case that the orbital solution is precisely known and no optimisation is necessary.

If optimisation is necessary and done the first time with a given set of data, the check box “New” needs to be used. If there was already an optimisation run, the user can start either from the initiation data by checking the “Initial” or from the current optimisation status by checking the “Continue” box. Make sure that the correct file names for the optimisation data is given in the corresponding line edits further down. However, the code will check first if the file structure corresponds to the number of specified spectra and enabled optimisation strategy in case that there is a user-mistake. It will give a self-explaining error message. As already mentioned, the optimisation data is stored to files in the work folder and can be used in case that one wants to start from the initial data or wants to continue the optimisation. The criterion used for optimisation can be set to “Mean” (overall residuum) or “Peak” (largest difference of an individual bin between result and observation). In the last line, the time, overall residuum and the velocity sampling of the spectra are displayed. Since optimisation will be a very time-consuming job, only the divide-and-conquer SVD is implemented for that task.

Note that the GUI will update from time to time to user input (after each SVD). Hence, if you interact (even accidentally) with the interface, the command will be passed! The optimisation can be aborted by clicking the “Abort” button which will happen after the current SVD is finished. The optimisation data will be stored in this case and wont be lost. However, if you click (acciden-

tally) another button, this command will be processed after the optimisation is finished. Depending upon which button it was, the “Abort” button will not work. Force to quite the program if necessary.

4 Output Data

Since the output spectra are placed on continuum levels with the only constrained given to sum to the input level, they are not determined. Hence, it is not unusual that one component spectra is set to 1 while the other is at 0 in case of a continuum level of the input spectra of 1. To correct this as well as to account for the correct flux ratio between the components, we have implemented two dialog windows which we describe now.

The first window is to plot the results and to renormalise them with a cubic spline fit³. The dialog window is shown in Fig. 6. The two files can be plotted and shifted on both axis for visualisation reasons, font size adjusted, axis labels changed and the graph can be saved as pdf, png or jpg file. The commands for renormalisation is at the right side of the graph window. The functions to measure the equivalent width and the signal-to-noise ratio is not implemented yet. The points used for the spline are written to a local file, hence to delete old data the “Reset” button should be pushed. Only the data given in the “File 1” line will be used. A double mouse click into the graph window at the continuum position writes this point to the spline file. Note that the points need to be ordered starting at lower wavelength. Otherwise it will cause the program to crash. The “Apply” button divides the current displayed (File 1) by the spline fit if the “divide” check box is checked. The “Show” button can be used to overplot the spline fit. The result is saved as ASCII file by typing the file name into the field right to the “Save:” button. Note that in cases where the continuum of the output reaches values smaller than zero a proper value need to be added to avoid dividing by a small value. This can be done with the second dialog window. The spline data is saved to a temporary file. However, this data can be saved to local file and loaded later again. Note that this will overwrite the temporary spline file.

The “Arithmetic” dialog can be found under “Tools” and is used for basic mathematics on ASCII files with two columns. This dialog window is shown in Fig. 7 and should be self-explaining. It is possible to use the same file name for the output, hence the original file is overwritten.

5 Example with Test-Data

We provide test data located in the downloaded folder (Test). These are artificial data generated with CroCo of a SB2 system with telluric O₂ features and will need around 6 GB of memory. The 20 txt files are named spectra_0.txt ... spectra_19.txt. We use CroCo first to rebin the data. To do so, we set the

³We use the include “spline.h” from <http://kluge.in-chemnitz.de/opensource/spline/>

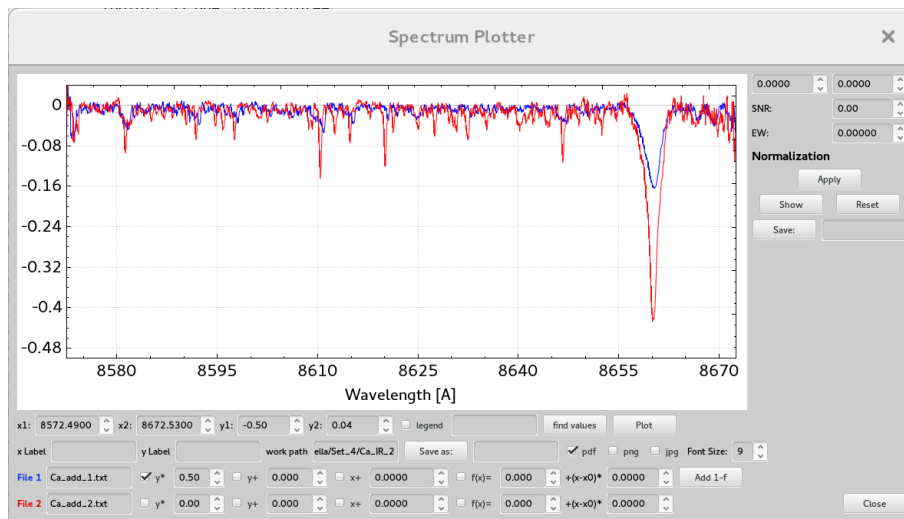


Figure 6: Plot window

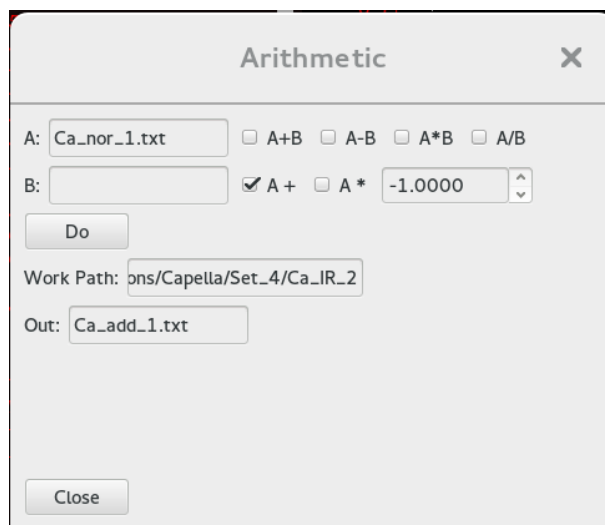


Figure 7: Arithmetic window

number of spectra to 20, choose ASCII in the combo box, check the box “crop to common wavelength range” and set a proper name in the field for the input (common name of spectra: spectra_) and output (common name of rebinned spectra: spectram_) and the work path to the folder wherever it was saved after download. Pushing the “log-rebinning” button starts the process, the progress bar will show the progress and the processed spectra will be displayed in the left graph. To display all spectra the “Sequence Plotter” under “Tools” can be used. Put in the common file name, the number of the first and last file to be plotted, the offset between each file on the y-axis and ASCII in the combo box. By pushing the “find values” button, the program looks for the largest and smallest value in y and x for all files and writes them to the corresponding boxes. Pushing the “Plot” button will plot the files in the region given in the forementioned boxes. The graph is savable as pdf, png and jpg, font size is adjustable as well as the labels.

After resampling we change to Spectangular and set the correct file names and number. Enable the third check box to use unknown RV option. The file with the times is also in the provided folder and named “otimes.dat”. Use again ASCII in the combo box and set the correct work path. We need to enable the “Static Lines” and the “SB2” check box. Set some proper file names for the output and optimisation data in the lower lines. Now we have to open the “Editor” window under “Tools” and set the number of spectra (20) apply the component strength of 1 for both components and telluric lines, load and apply the orbital data for Mizar. Now we can push the “ECON” button for a first run which will solve the system without any optimisation.

Optimisation can be started by checking the “New” check box. The number of iterations is set to 3 by default. Clicking the “Optimisation” button will start the optimisation on the orbital parameters. The program will now initiate the optimisation. One run will take around 2.7 min on a quad-core machine. After the run is finished the “New” checkbox will get unchecked and the “Continue” box is checked. This will avoid to accidentally overwrite the initial and already optimised data.

6 Example: WR Stars

Hot emission line stars can cause strong distortions of the result spectra near emission lines. We show an example in Fig. 8 top. For such non-constant deviations, the spline fit can be used to correct the continuum to a specified flux ratio. The spline fit is applied as described above and the check box “correct to ratio” is checked and the ratio given in the double spin box. Note that a value of 1 means equal flux of both components, i.e., the flux is corrected to a level of 0.5 for both components. The component which allows best identification is put in the line edit “File 1”, which will be used for the spline fit now. As soon as the points are set we can push the “Apply” button and the corrected file (File 1) will be plotted. However, it will apply the opposite correction for the file given in the line editor “File 2” since they add to the continuum level of the

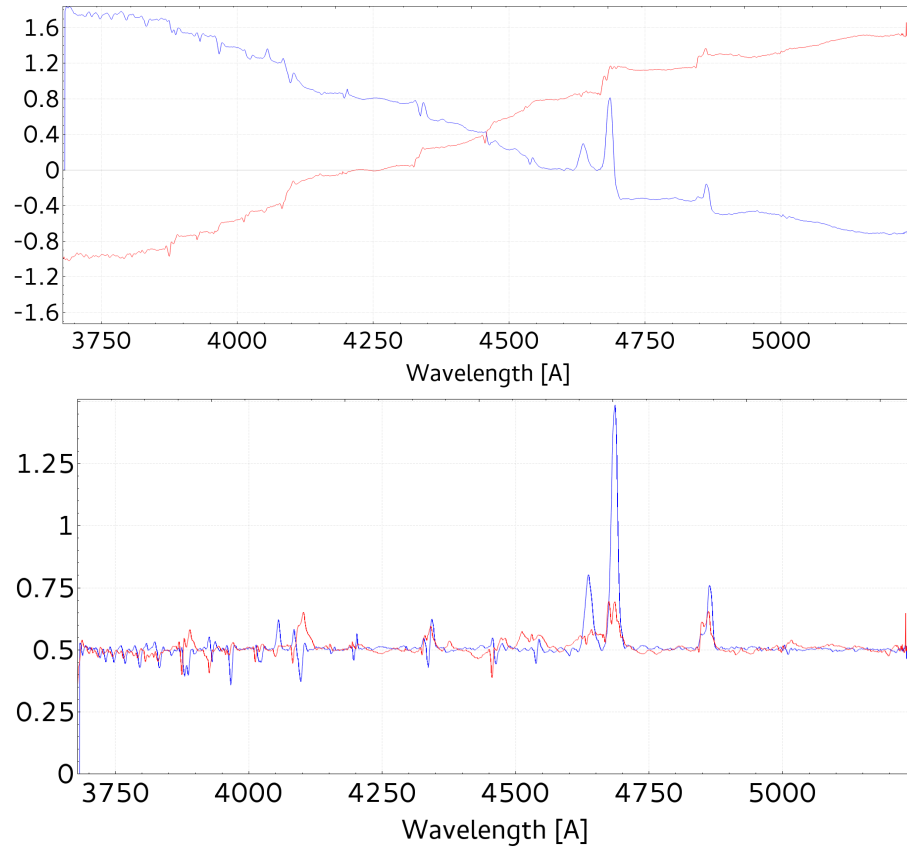


Figure 8: Output of for low-resolution data of a WR binary system.

input spectra. Type in some proper names for the corrected data in the right line editors and save the result. To show the result, type these names to “File 1” and “File 2” and plot it. In our case where we applied a flux ratio of 1, both components are set to a level in the continuum of 0.5, Fig. 8 bottom.

7 Troubleshooting and Contact

1. **After pushing the “Optimization” button, data is loaded but optimisation is not performed.**

This is a known and unresolved bug. Push the button again.

2. **Program crushes**

Most possible this happens in case that data storage exceeds available memory or data is in wrong or disordered format. Check all files and check the used RAM of the process (under Linux type “top” in a terminal

and observe “RES” as well as “VIRT”. If VIRT exceeds the physical + swap, use a machine with more memory).

3. Normalization leads to crash

Push the “Reset” button and/or make sure that data points are ordered with increasing wavelength.

This manual should always be consulted first. It contains all information necessary to run the program and with all references it gives all information to step into the method of spectral disentangling. Please do not contact the developer in case you have questions on the basics. However, if you have tried to solve an issue without any success by reading this manual and the cross-references contact dsablowski@aip.de. In case that you have found another reproducible bug, please send a mail to dsablowski@aip.de.

Furthermore, the developer will be happy to receive suggestions of making Spectangular more convenient.

References

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Sanderson, C. 2010, in NICTA, Australia