# A USER'S GUIDE TO VCROSS

# A CROSS-CORRELATION VELOCITY MEASURING PROGRAM

BY

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## Contents

# I. INTRODUCTION

VCROSS is a program which uses wavelength linearized and rectified data (over a restricted wavelength range) or a $\ln\lambda$ linearized scale to measure radial velocity differences between stars, by cross-correlating one stellar spectrum with another. The tool used in this analysis is FOURT (Brenner 1967). The choice of the reference spectrum is arbitrary and can therefore be a velocity standard of similar spectral type or it can be the program star itself. The linearized data must have been processed by REDUCE to a rectified form and recorded on Disk in FITS format.

The rectification is very important in that the sharpness of the resultant cross-correlation function (or c.c.f.) is critically dependent on the presence of trends in the continuum. Other techniques needed to enhance this peak are taken from Simkin (1974) and include the initial adding of data to each end of the spectrum (this prevents information being lost when the tapering occurs -- see later), normalizing the spectrum to the average intensity and tapering each end of the spectrum by a cosine bell function. After this zeroes are added to each end of the spectrum to increase the number of data points even more.

We are also able to select those wavelengths of interest to us. For example, trying to detect a weak secondary in the wings of a broad hydrogen line is likely to be a futile task and it would best be accomplished by the use of narrower lines. Hence, in this case, the hydrogen lines must be suppressed in both the program and comparison star spectra.

Once the c.c.f. is displayed the velocity measurement may be made in a number of ways.

i) fit a parabola to the peak.

ii) fit a Gaussian or Lorentzian to the profile.

iii) fit a number of Gaussian or Lorentzian profiles using VLINE as a subroutine (see Appendix 1).

In the event that the profile shape is not suitable for fitting by either a Gaussian or Lorentzian then a standard profile may be generated (see Appendix 2) and stored in digital form (one-dimensional version of a point-spread function).

## GETTING STARTED

As noted above, VCROSS (and its relation RETCROSS) relies on the FITS output from REDUCE. (Read the Reduce manual or Paper III in the Reduction of spectra series). It also needs a file, which I term the cross-correlation file, that controls the initial display of the c.c.f. and which also contains the wavelength regions to be used in the cross-correlation. The creation of this file is mandatory but another file is optional, that which I term as the Master File. The Master File would contain lists of FITS files that one wants to measure with VCROSS. The use of such files enables VCROSS to be run automatically, including a hard copy of the screen if desired. When the VAX is not busy the measuring process may take 10 seconds and the recording about 30 seconds. It is a beautiful and powerful way to measure spectra but still fraught with subtle pitfalls, notably caused by the mismatching of program and comparison spectra.

## THE CROSS-CORRELATION FILE

A single data file, the cross-correlation file, is needed to specify the initial velocity range over which the data are to be displayed and a series of wavelength intervals defining the data to be used in the cross-correlation. These entries are in free format. Line 1. Two velocities (low and high limit). Line 2. Two wavelengths (low and high limits). Line 3. Two more wavelength limits, ...

If one wanted to restrict a cross-correlation calculation to a narrow $\lambda$ and display ± 100 km/s the file would look like

-100. +100.
4300. 4340.

if the file was to exclude hydrogen lines then it would look like

-100. +100.
4000. 4080.
4120. 4320.
4360. 4380.

Once underway the radial velocity display limits can be freely changed but the data, the results of two Fourier transforms, their manipulation, and their product, cannot be altered without returning to the beginning of the program.

## IV. THE MASTER FILE

Another file, termed the Master File may be established which contains the names of FITS files to be processed by VCROSS. These files may be W, I, R or U FITS files. The normal entries in the master file are the names of processed FITS data files, but other commands may be included that change the status of the program. These commands are:

NOAUTO; will stop automatic measuring

HARD; will initiate hard copy after a measurement is made.

NOHARD; will halt automatic hard copy.

AUTO: initiates automatic measurement. This command must be followed by a keyboard entry that will (ultimately) establish whether either peak or window fitting will be performed.

STOP: disengages the program from the master file and restarts it at the first step. The master file will not be engaged at the next record until START is entered manually in the data reading step (Steps 2 and 3).

DELAY: If VCROSS is operating in the automatic mode with no hard copy then a delay is needed to prevent immediate screen erasure. This command must be followed by a keyboard entry giving the time before screen erasure in seconds.

EXIT: Ends program execution.

Samples:

| | |
|---|---|
| NOHARD<br>DELAY<br>R0001.FTS | No hard copy and a delay before screen erasure. |
| HARD<br>AUTO<br>R0001.FTS<br>STOP | Hard copy, measuring automatically file R0001.FTS and restart at Step 1. |

## V. RUNNING VCROSS

VCROSS is executed from the directory DISK1:[HILL] by the command procedure @VCROSS. At this time the following assignments are made

```
$ASS SYS$COMMAND  FOR013
$ASS SYS$COMMAND  FOR012
$ASS LPA0:  FOR003
$ASS TT TEX
```

If you do no want line printer output and want to write to a file instead make the above assignments (or run the command procedure VCROSS, abort it after the assignments are made) and then reassign FORTRAN unit 3 (e.g. $ASS DUMMY.OUT FOR003), then run the program VCROSS.

$R DISK1:[HILL]VCROSS otherwise: $@DISK1:[HILL]VCROSS. If you abort the program for some reason or another remember that the assignments have been made and you can restart by

$R DISK1:[HILL]VCROSS.

## VI. THE PROGRAM

Upon execution the following steps must be followed. Note that I have not described all of the prompts in detail. As far as possible (remember it is not a refresh screen) I've attempted to have VCROSS let you know what is happening.

**STEP 1.**

Here the file that defines the initial range of RV to be plotted and the wavelength range(s) to be used is entered. The program status may also be altered here. A testing option involving RV shifts of single stars, the creating of synthetic binaries and the addition of noise to spectra may be invoked here. Enter TEST to allow the program star spectrum to be shifted by a number of data points (of known RV/point). Enter BINARY to later create a synthetic binary of given separation and luminosity ratio. Enter NOISE to subject the program star to various amounts of noise either dependent or independent of the signal. While these 3 options are invoked here their parameters are set later at the end of STEP 3. Note that these entries must be made before the cross-correlation file name.

PROMPT: Give FILE NAME for cross-correlation lambda data. The testing options may be invoked here by entering TEST, BINARY or RANDOM.

REPLY: Enter TEST, BINARY or RANDOM first if you need them, otherwise enter the file name.

STEP 2.

Fetch comparison star FITS data file and set some options. Here one is prompted for a FITS file name. This linearized file, preferably rectified and in log$\lambda$ is the reference or comparison spectrum. One can invoke a master file of FITS data files to bypass these manual entries. One can also change the status of the program here. Choices are:

i) W,I,R or U FITS data file

ii) HARD; will make a hard copy of the screen after a measurement is made.

iii) NOHARD; will defeat the hard copy option (NOHARD is the default option).

iv) AUTO; will initiate automatic measurement. AUTO must be followed by a keyboard entry to establish either peak or window fit. Enter % level above which a parabola will be fitted to the c.c.f. If a -ve number is entered then a profile will be fitted to data within a RV window. Once the cross-correlation function (c.c.f.) is displayed this window is defined later by two cursor placements.

v) DELAY: will delay screen clearing once the c.c.f. has been measured. This is needed if one is measuring the Master File and automatic measuring. One makes a keyboard entry after DELAY.

vi) NOAUTO; will stop automatic measurement.

vii) MASTER: will enable a master file to be opened. Respond to the request for a master file name.

viii) START; will reengage the master file at the record following the STOP command.

ix) EXIT: completes execution.

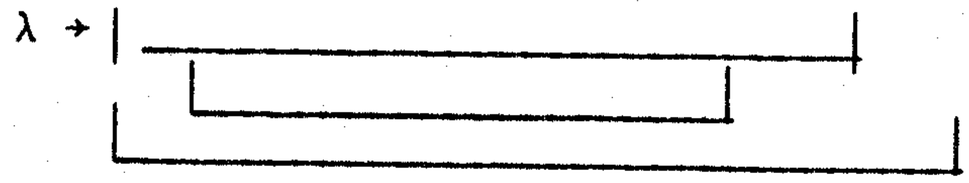
Following the data entry one is prompted for the radial velocity of the comparison star.

STEP 3.

Enter the Program star FITS file and set any options that weren't invoked in STEP 2. Note that the program and comparison star data must be

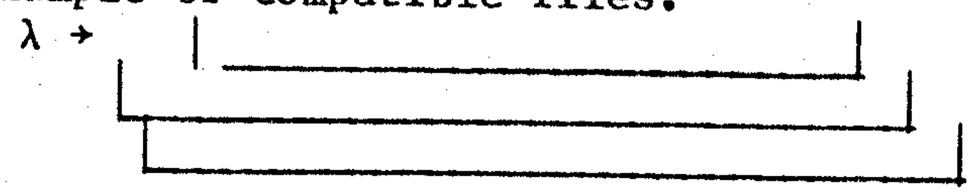
identical in wavelength increment and both must be defined over the limits specified in the file opened in STEP 1.

Example of an incompatible set of files




Cross-correlation file Comparison Program

Example of compatible files.




c.c. file Comparison Program

If one is not testing VCROSS by the commands BINARY, TEST, RANDOM described in STEP 1 then skip to STEP 4.

TEST; Enter a data point offset here. A +ve number for +ve RV

BINARY Enter the FITS file name for the secondary star, followed by the velocity offset, in data points, of the secondary w.r.t. the primary. A +ve number for a +ve velocity shift of the secondary w.r.t. the primary. One also must enter a luminosity ratio (primary/secondary).

RANDOM: Enter the noise level, either as a % of the signal, or independent of the signal as a % of the continuum assumed to be at unity. This latter option is accomplished by entering a -ve number.

**STEP 4.**

Once the data have been acquired and selected in wavelength according to the data file specified in STEP 1, the resultant c.c.f. is displayed on the screen. If no automatic measuring is invoked (by entering AUTO in STEP 2 OR 3) then measurements can now be made in three ways.

i) Make two cursor placements using the space bar, setting from left to right. Once the measures are made a parabola will be fitted to the data within this window and the fitted curve drawn through the data. An arrowhead will show the mean position, and the results will be written to the screen.

ii) Measure the peak with a single cursor placement (move the cursor and hit the T key).

iii) Fit one or more functions (Gaussian, Lorentzian or std profiles) to the c.c.f. using a subroutine taken from VLINE. Refer to the VLINE manual, or Appendix 1.

iv) One can fit either a Gaussian or a Lorentzian function to a window, defined by 2 cursor placements. Enter a 1 or 2 on the first placement to define either a Gaussian or Lorentzian fit. By entering an A on the rightmost placement all the data, centred on the peak will be used.

v) Alternatively, one may use the displayed c.c.f. as a standard profile. Once defined, and stored, this standard profile can be fitted to subsequent c.c.f. results by using the VLINE (or function) part of the program. Instructions for creating a standard profile are given in Appendix 2.

If AUTO has been invoked and VCROSS is fitting above some % level then this measure will occur automatically here and the result displayed.

If a window has been invoked in RV (a -ve number following AUTO in STEPS 2 or 3) then one will be prompted for a definition of the window at this point, as well as the type of profile to be fitted. To fit a single Gaussian (code=1) or Lorentzian (code=2) place the cursor on the left hand side and strike either the 1(=G), or 2(=L) key. If you want to fit the whole screen image strike an A on the rightmost setting. Later, as the program operates in this mode this window is retained and the c.c.f. will be centred automatically so a narrow window can be used with safety.

PROMPT: Measure: TFDC, fit function G, form std profile P, next step J, E end.

Fit function to window: 1=Gauss, 2=Lorentz; End with A for all data.

REPLY. Measure peak with 2 cursor placements

Measure window with two cursor placements. Enter 1 or 2 to define profile type on 1st setting. Enter A on last setting to accept full window centred on peak.

T measure RV with one cursor placement.

F return to STEP 1

C return to STEP 2 for a new comparison spectrum

D return to STEP 3 for a new program star spectrum

G fit one or more function to the c.c.f. using VLINE.

P form std profile and store it.

J skip to next step.

STEP 5.

This is a branching step. Here one can modify the screen image, skip to VLINE, form a std profile, or branch to previous steps.

PROMPT: OPTIONS: <X>S% WHFCDTGP M = measure anew, E = End.

REPLY. < Shifts the data 20% (default value) to the left (presents longer λ data)

> Shifts the data 20% to the right.

X Expands the amount of data displayed by 40% (2 x 20%).

S Shrinks the amount of data displayed by 40%.

% Allows one to alter this % amount

PROMPT: ENTER % INCREASE FOR PLOT (INTEGER)

W Allows one to alter width (default is 900) of graph is display.

PROMPT: ENTER NEW WIDTH (max 900) — current value _____.

H Allows one to alter height of graphics display (default is 500).

PROMPT: ENTER NEW HEIGHT (max 600) — current value _____.

F Returns to STEP 1.

C Returns to read in new comparison and program spectra at STEPS 2 and 3.

D Returns to read new program spectrum at STEP 3.

T measure RV with one cursor placement

G fit one or more functions using VLINE.

P form STD profile and store it.

M Return to STEP 4 to make another measure.

E to End program.

COMMENTS

An all-purpose program cannot fulfill everyone's needs. If you want VCROSS to be changed, or discover a bug, document it (copy the screen) and I'll see what can be done. If there is some specialized use for the analysis that VCROSS just doesn't meet, but could, talk to me. RETCROSS came out of such a circumstance and the improvements contained in it have been incorporated back in VCROSS.

Remember that the Tektronix hard copy will fade so either Xerox it or keep it light-free.

I've enclosed a sample run. Note that because VCROSS is continually evolving the instructions shown here may differ from what VCROSS currently gives.

# APPENDIX 1.

## Fitting multiple functions to data

This subroutine is a slightly modified version of that used in VLINE. It enables the user to select parts of data to be fitted by a function, or combination of functions. The analytical forms available are Gaussian, Lorentzian or rotational, along with non-analytical profile (two max), see Appendix 2. Up to 12 profiles can be fitted to the data with starting values for each profile (depth, mean position, FWHM) being encoded from a series of X and Y cursor placements. A linear continuum is fitted simultaneously with these profiles. Parameters can be fixed to any value or fixed to each other; i.e. the FWHM of all lines may be set to one (unknown) value.

The program steps are as follows:

1. Make initial selection of data, all or part of a screen image.
2. Make a further selection within these data if you choose. You may want to eliminate parts spoiled by gliches for example.
3. Use cursors to establish the starting parameters.
4. Fix parameters to each other, or to a particular value.
5. Display fit and results. Choose a branching option.

**STEP 1.**

Data selection. Here one has the choice of accepting the whole range of data or taking out part of it. This selection is made by moving the X-cursor to two places and striking the space bar each time. Hitting other keys will direct the program to other steps or to the main program.

PROMPT: Select? NESB@

REPLY: Initiate fixing of parameters by striking @. The program will not encode the cursor and returns to the above PROMPT.

Make 2 cursor placements (using space bar) setting from left to right selecting the part of the data you want to work with.

Enter E on first placement to accept <u>all</u> of the data and skip to STEP 3.

Enter E on last placement to select <u>part</u> of the data and skip to STEP 3.

Enter N on first placement to accept <u>all</u> of the data and to go to the next step.

Enter S to return to main program.

Enter B to restart at this step.

STEP 2.

Selection of discontinuous pieces-of data (optional step). Here we select pieces of the data by making pairs of cursor setting (from left to right). The end of this selection is signalled by an E on the last (rightmost) setting.

PROMPT: Delimit profile BSNE

REPLY: Make pairs of settings ending with an E on the final rightmost setting.

Enter B to return to STEP 1.

Enter N to restart this step.

Enter S to skip to main program.

STEP 3.

Establishing starting values. Here we measure the starting values by using the X-cursor, and occasionally the Y-cursor. We can also initiate the fixed parameter mode here if it has not been done at STEP 1. These measures are made by making two continuum settings with the X-cursor (first and last placements in the sequence) and three settings for each profile in order to define the FWHM, mean position and line depth. As an example the complete settings for two profiles are:

left continuum (LC), left FWHM (LH), center (C), right FWHM (RH)

left FWHM (LH), centre(C), right FWHM (RH), right continuum (RC).

Normally the y value is taken to be that y datum nearest the X-cursor but it can be measured by striking the T key. The only Y values that are used are in the continuum and line centre measures. The type of profile to be used in the fit is governed by the key that is struck on either the left FWHM setting or the central setting. The end of the settings (rightmost continuum placement) is signalled by an E key or by a T if the continuum height is being fixed. Ending the data entries in this way removes the necessity for counting the number of placements. A sample sequence for a Gaussian and Lorentzian with a central Gaussian line depth defined by the Y-cursor would be:

space bar (LC), G (LH), T (C), space bar (RH), space bar (LH),

L (C), space bar (RH), space bar (RC)

Some of the keyboard options (S,B,N,@) have already been described and we now discuss them in more detail.

PROMPT: Fit GLR45 BNA@

REPLY: Initiate fix parameter mode by enter @. Then begin your cursor placements.

Placement 1. Left-hand continuum (can accept nearest y datum by hitting space bar or encode the Y-cursor height by striking the T key).

Placement 2. Set on left-hand side of profile at half-intensity point. Can define the profile type here by entering G=Gaussian, L=Lorentzian, R=rotational, 4=one standard profile, 5=different standard profile.

Placement 3. Set on minimum or maximum profile. Identify profile type if not encoding the Y-cursor with the T key.

Placement 4. Set on right side of profile at half-intensity point.

Placement 5. If more profiles are to be defined repeat STEPS 2-4, otherwise make the final continuum placement now. This placement must be signified by entering an E, or a T if the continuum height is to be defined by a Y-cursor setting. Ending the sequence of entries with the E or T removes the necessity for counting the entries.

The branching options are as before except the A command that will return you to the beginning of this step. (STEP 3)

Enter B to return to STEP 1.

Enter N to return to STEP 2.

Enter A to restart this step.

STEP 4.

Fixing parameters. If you have chosen to fix some parameters by entering a @ in STEPS 1 or 3 then the screen will be erased and the current starting values displayed. If the fixed parameter mode has not been initiated this step will be bypassed and you will be at the following STEP (5). Once the current values are displayed you are prompted to enter those values to be fixed, either to each other or to a given value. Enter the index of the parameter to be fixed, followed by the value. If this parameter is to be fixed to another enter a negative index. You will be prompted for the index of this other parameter. The value, in this case, will be determined by the solution. These entries are terminated by the entry of a zero. The screen will clear, the data plotted anew and the fit graphed through the data.

STEP 5.

Display of results. Here the fit is displayed, and the results are written to the screen. One has the choice of redoing the fit, or returning to the main program.

PROMPT: Rerun B; Delimit N; 4 new std file; 5 new std file; S to main.
F new c.c. lam file; C new comp spectrum;
D new program spectrum

REPLY: Enter B to return to STEP 1.
Enter N to return to STEP 2.
Enter S to return to main program.
Enter 4 or 5 to enable new standard profiles to be defined leaving you still at this step.
F skips to fetch a new cross-correlation lambda file in the main program.
C Skips to fetch a new comparison spectrum in the main program.
D Skips to fetch a new program spectrum in the main program.

## APPENDIX 2

## FORM A STANDARD PROFILE FROM C.C.F. DATA.

Not all shapes resulting from a c.c.f. calculation can be fitted by Gaussian or Lorentzian functions. Differences from these shapes may only be small but they may become significant when one is trying to measure a weak secondary velocity component in the wings of the principal c.c.f. In this appendix we describe the creation of such a standard profile. These profiles, which may be rendered symmetric (by folding), are defined in units of the FWHM and therefore look very much the same to VCROSS as the analytic functions identified above.

The program steps are as follows:

1. Measure background level, line positions, strength and FWHM.
2. Manipulate image if more data are needed.
3. Check the derived parameters.
4. Normalize the final profile and store it.

**STEP 1**

The same image seen in VCROSS is displayed and one may select a part of this to generate a std profile. Measurements of the line centre must be done now. This measurement is made by fitting a parabola to the peak in just the same way as is done in VCROSS (STEP 4, i)).

PROMPT: Measure <x>, <d>, <c>; TBJELRDCPF

REPLY: Make two cursor placements with the thumbwheel and the spacebar.

Enter T to measure the mean position with the cursor. These measures if made first will leave you at STEP 2.

The following commands will (ultimately) result in the data being replotted, but not until an F has been struck.

Define new window by a left (L) and right (R) cursor placement.

C encodes the Y cursor to define a new background level.

D encodes the Y cursor for a new maximum height.

End these changes with an F. The screen will clear and the data will be replotted leaving you again at STEP 1.

The following commands cause the program to branch.

B return to the beginning of this subroutine, and negate any current measures.

J skips to next step.

P skips to STEP 3 where the std profile is finally formed.

E returns the user to VCROSS main.

STEP 2

This is a branching step. Once can begin anew, branch to STEP 1 or move on to define the standard profile.

PROMPT: OPTIONS: BP M=measure anew, E=end

REPLY: B to re-initialize all the measures and return to STEP 1.

M returns to STEP 1 for another series of measures.

P continue to next step

E abort process and return to VCROSS main.

STEP 3.

Here you have a final chance to alter the values of the background height, line position and depth prior to the final derivation of the FWHM and the creation of a normalized profile p(x(units of FWHM), intensity). After these questions are answered the displayed profile may be folded, inverted and stored.

The questions invite the user to either adopt the current parameter or alter the value by making a setting with the X and Y cursors and encoding the position by striking the T key. At the end of these questions the following prompt appears.

PROMPT: Fold profile; invert, store I; adopt, store A; E=end

REPLY: If you are happy with the profile as is enter A.

Fold the profile with an F. The resultant profile will be plotted in squares. Store it with an A command. Invert the profile (to an absorption line) and store it with an I.

Skip to main program with an E.

If you elected to store the profile you will be prompted for a file name. I suggest that you append .ccf to this name so that you know later what operation this file resulted from.

STEP 4.

Here one can return to the beginning of the step or to the main program.

PROMPT: What next? B=restart, E=end.

REPLY: B to reset all the current measures to zero and begin anew at STEP 1.

E returns to VCROSS main.