B A Step-by-Step Guide to Spectral-Line Data Analysis in $\mathcal{AIPS}$

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In this guide, we assume that the reader is familiar with the basic tools of $\mathcal{AIPS}$; *e.g.*, `MCAT` (§ 3.3), `GETN` (§ 3.3.1), `IMHEAD` (§ 3.3.4) and other $\mathcal{AIPS}$ tools involving the manipulation of the data catalog are not mentioned. This guide contains three main sections covering editing and calibration of spectral-line data, making and Cleaning of map cubes, and moment analysis and rotation curves of galaxies. *It is assumed through these sections that all sources in the data set were observed at the same frequency; the final section of this guide describes what you should do before beginning data reduction if this is not the case.*

This is an outline of a typical reduction procedure for spectral-line data from the VLA; different users may use slightly different approaches. This guide is a supplement to the $\mathcal{AIPS}$ `EXPLAIN` and `ABOUT` verbs (§ 3.8) and the $\mathcal{AIPS}$ $\mathcal{C}ook\mathcal{B}ook$. Some of the less obvious or more important parameters for each task will be mentioned, but the user should *always* check to ensure that the rest of the parameters are specified correctly. When in doubt, the defaults are usually fairly safe. Words in boldface or typewriter fonts represent $\mathcal{AIPS}$ tasks and their inputs. When you see a phrase enclosed in brackets, replace the phrase and the brackets with the correct input. For example, to specify the source 0134+329

`SOURCE '`$< source_name >$`'` would be typed as

`SOURCE '0134+329'` The text below is in a three-column format, showing a step number on the left, a descriptive paragraph in the center, the name of the $\mathcal{AIPS}$ task or verb on the right.

B.1 Editing and calibrating spectral-line data

B.1.1 Loading the data

(1) Go to the VLA archive web page at

`https://data.nrao.edu/`

log in wih your `my.nrao.edu` account and locate the desired data set using the basic retrieval tool. Use the observing date, program code, or observer's name to locate the data. If the data are within the proprietary period (usually 6 months), you will be allowed access only if your login is recognized as an owner. Select the data file(s) desired and ask for them with $\mathcal{AIPS}$-friendly names. Wait for the e-mail notification that the files are ready and then follow the supplied advice to copy the data files to your computer.

(2) Before starting `AIPS`, create an environment variable pointing at the disk directory containing the data files. Use `cd` $< data_area >$ followed by `setenv MYDATA` ‘`pwd`‘ if you use C-shell or its variants or `export MYDATA=`‘`pwd`‘ if you use the bash shell. (Note the back tick marks surrounding the `pwd`.) Then start `AIPS`.

(3) Load the data from the archive file(s) to *AIPS* data areas. Use the defaults to load the data without further averaging. The m disk files will be named $< program_name > _i$ for $i = n+1, \ldots, n+m$. **FILLM**

```
VLAOBS '< program_name >' ; DOWEIGHT 1
NFILES n ; NCOUNT m
DATAIN 'MYDATA:< program_name > _'
```

The data loaded to disk will normally be in two parts: One will have the class "CH0" and the other will have the class "LINE." The names of the files are thus

```
DATE.CH0
DATE.LINE
```

where "DATE" is the date the observations began. Each file is a multi-source file, containing observations for all your sources: flux calibrators, phase calibrators, and target sources. Your spectral-line data are contained in the LINE file, while the CH0 file is a "pseudo-continuum" file; it is the average of the inner 75% of the bandpass and will be used for gain and phase calibration.

(4) List the "scan summaries" from the CH0 data. *Keep the output for future reference.* Note that the frequency in the header of a multi-source file is always the sky frequency in the center of the band of the first scan of the observation (see § B.4). **LISTR**

```
OPTYPE 'SCAN' ; DOCRT -1 ; OUTPRINT ' '
```

to print on the line printer. To make a text file instead

```
OUTPRINT 'MYDATA:< filename_in_all_caps >'
```

(5) Print the antenna configuration file. *Keep the output for future reference.* **PRTAN**

B.1.2 Inspecting and editing the data

There are a number of different ways to isolate and edit bad *uv* points from your data set. The method described below is typical. Other tasks of interest can be found by typing ABOUT EDITING and ABOUT UV and by consulting § 4.3.5, § O.1.6, § 4.3.11, § 5.5.2, § 10.2.2, and § 4.3.13 in the *AIPS CookBook*.

(6) Plot amplitude versus baseline length for your flux and phase calibrators. Inspect each source, Stokes, and IF separately. Set XINC so there are only a few thousand visibilities on the output plot (the total number of visibilities is listed on the scan summary sheets from Step 4). Use the TV to save trees. **UVPLT**

```
BPARM 0 ; DOTV 1
```

If there are anomalous amplitude points, continue to the next step. If your data points have a small scatter, you may not need to edit and can skip to calibration (Step 10).

(7) Determine if the anomalous data points are from a particular baseline, antenna, Stokes, or IF, inspecting each Stokes and IF separately. The output of this task will be all points that have anomalous amplitudes, based on your selection criteria. **UVFND**

```
OPCODE 'CLIP' ; APARM(1) < max_flux >
APARM(3) < min_flux >
```

(8) Once you have determined which data points to flag with UVFND, flag them with UVFLG. You can flag by time-range, baseline, or antenna and you can flag any or all of the Stokes parameters or IFs. To assist in undoing flags, set a REASON. **UVFLG**

```
OPCODE 'FLAG' ; OUTFGVER 1
```

(9) Examine the *uv* data for your calibrators on the TV to check for any obvious problems which you might have missed; see § O.1.6. Check each IF and each Stokes separately and edit the data more carefully, if necessary, before continuing. **TVFLG**

```
DOCAL -1 ; CALCODE '*' ; FLAGVER 1
```

B.1.3 Calibrating the data

Steps 10–15 should be applied to the CH0 data alone, not to the LINE data. To ensure that all inputs are set to their defaults before continuing, type

```
RESTORE 0
```

Then, when you are satisfied with your editing, type

```
RUN VLAPROCS
```

to set up VLA-specific parameters and procedures for calibration. You may turn all adverbs for a specific $< task >$ to their default values with

```
DEFAULT < task >
```

If you have multi-frequency data, each frequency must be calibrated separately; this can be done by specifying the FREQID *parameter in each task (see § B.4).* More information on calibrating your data can be found by typing ABOUT CALIBRAT and HELP CALIBRAT and consulting Chapter 4.

(10) Calculate the flux of the primary flux calibrator for the channel zero (CH0) data. **SETJY**

```
SOURCE '< flux_calibrator >' , ' ' ; OPTYPE 'CALC
```

(11) Calculate gain and phase solutions for *all* of the calibrators. In this case, you must run this procedure once for each source. Check for the presence of an appropriate model with CALDIR. For those sources having a model **VLACALIB**

```
DOCALIB 1 ; UVRANGE 0 ; ANTENNAS 0
CALSOUR '< flux_calibrator_1 >' , ' '
```

For sources without a model, choose a UVRANGE according to the tables in the *VLA Calibration Manual*. You may do more than one source at a time, if they have the same UVRANGE. The output of this procedure is a solution (SN) extension table, which is printed automatically. Select a reference antenna (REFANT) which did not have any problems during the observing run and which is located near the center of the array.

```
DOCALIB 1 ; UVRANGE < uv_min > , < uv_max >
CALSOUR '< calibrator_1 >' , ... , '< calibrator_n >'
DOPRINT 1; OUTPRINT '< filename_in_all_caps >'
```

The output from VLACALIB will include a list of closure errors. If there are too many large errors, edit your data carefully using UVFND, TVFLG, or LISTR as described above. *Destroy old SN tables with* EXTDEST and then re-run VLACALIB until the solutions are satisfactory. The output will include amplitudes and phases for each baseline; for each calibrator, the amplitudes should be approximately constant and the phases should vary smoothly over time.

(12) Calculate the flux densities of the secondary (phase) calibrators from the primary (flux) calibrator, based upon the flux densities in the source (SU) table and the antenna gain solutions in the solution (SN) table. *Destroy bad or redundant versions of the* SN *tables before using this task.* Compare the computed fluxes with those listed in the *VLA Calibration Manual*. **GETJY**

```
SOURCES '< phase_cal_1 >' , ... , '< phase_cal_n >'
CALSOUR '< flux_cal >' , ' '
```

(13) This procedure interpolates the solutions derived from the calibrators into the calibration (CL) table for *all* sources. Run this procedure once for each phase calibrator (which may be used to calibrate multiple sources). **VLACLCAL**

```
SOURCES '< phase_cal >' ,'< source_1 >' , ... , '< source_n >'
CALSOUR '< phase_cal >' , ' '
OPCODE 'CALI' ; INTERPOL '2PT'
OUTPRINT '< filename_in_all_caps >'
```

Note: if you are observing at low frequencies or there are gaps in your observations of phase calibrators, you may want to use SAMPTYPE 'BOX' and review the other inputs carefully. They have changed.

(14) Apply the calibration to the phase calibrators and examine the amplitudes, which should be nearly constant, and the phases, which should be nearly zero. **LISTR**

```
SOURCES ' ' ; CALCODE '*'          ⇐ print results for all calibrators
OPTYPE 'MATX' ; DOCALIB 2 ; GAINUSE 2; DPARM 5, 1, 0
UVRANGE 0 ; DOCRT -1 ; OUTPRINT '< filename_in_all_caps >'
```

(15) Examine the *uv* data for your *sources* on the TV to check for any obvious problems which you may have missed. Re-edit the data (Steps 6–9) if necessary. **TVFLG**

```
DOCAL 2 ; GAINUSE 2 ; CALCOD '-CAL'
```

If you have too many visibilities to fit on the TV screen, you may want to set TIMERANG, SOURCES or DPARM(6) (the input averaging time) to limit the amount of data displayed. There are also interactive options to set the on-screen averaging time and the time range currently displayed.

(16) To calibrate the spectral-line data, simply copy the calibration (CL) table from the CH0 to the LINE data. **TACOP**

```
INEXT 'CL' ; NCOUNT 1 ; INVERS 2
```

Also be sure to copy the flagging (FG) table

```
INEXT 'FG' ; INVERS 1
```

Steps 17 and 18 should be applied to the LINE data alone, not to the CH0 data

(17) Calibrate the bandpass for the LINE data using the primary (flux) calibrator. The output from this task is a table (BP) of the bandpass spectrum. **BPASS**

```
GET3NAME < CH0data >
CALSOUR '< flux_cal >' , ' '; CALCODE '*'
DOCALIB -1 ; FLAGVER 1
```

(18) Examine the bandpass for each of the antennas on the TV. **POSSM**

```
APARM(8) 2 ; DOTV 1 ; STOKES 'RR'
ANTENNAS 0 ; NCOUNT 4              ⇐plot 4 antennas at a time
```

Then do the LL Stokes. After this, generate a plot (PL) file of the total bandpass for each Stokes.

```
NCOUNT 0 ; DOTV -1
```

Plot the bandpass on the laser printer; specify PLVER for each Stokes. **LWPLA**

(19) Now that the calibration is completed, write the calibrated CH0 and LINE data to tape. **FITTP**

Print the contents of the tape(s) for your data. **PRTTP**

(20) Apply the calibration and editing tables, writing single-source *uv* files for imaging. **SPLIT**

```
CALCODE '-CAL'                    ⇐write uv for all non-calibrator sources
DOCALIB 2; GAINVER 2 ; DOBAND 1; BPVER 1
```

B.2 Making and Cleaning image cubes

(21) Determine the imaging parameters needed for a full-field image of the continuum. Set the BPARMs to cover the full single-dish beam area (or more at 21-cm wavelength). **SETFC**

```
IMSIZE 0 ; CELLSIZE 0
BOXFILE 'MYDATA:< source_name >.BOX'
```

Delete the output BOXFILE and re-run the task with your chosen (more congenial or exact) CELLSIZE.

(22) Make a CH0 image with a large field (set by IMSIZE and CELLSIZE returned by SETFC) to look for strong continuum sources. Use uniform weighting (UVWTFN ' ') with ROBUST of 0 or -1 if resolution is more important than detecting significantly extended sources; set ROBUST to 2 or more if the converse is true. **IMAGR**

```
STOKES 'I' ; NITER 0
```

Then make a dirty image cube of your LINE data in the center field only (unless more are needed for the line source).

```
NFIELD 1 ; BCHAN 1 ; ECHAN 0
```

(23) Examine the cube on the TV to determine which channels are free of line emission. **TVMOVIE**

(24) Calculate the noise in a few of the line-free channels.

Display a channel on the TV **TVALL**

```
TBLC = 0 , 0 , < channel_number > ; TTRC 0
```

Select a large window that contains no continuum sources. **TVWIN**

Calculate the RMS noise inside the window. The verb TVSTAT is helpful if there are no large rectangular windows free of continuum emission. **IMSTAT**

Having an initial guess of the signal-free RMS, you may attempt to refine that estimate (see message generated) and also produce a histogram plot. **IMEAN**

```
BLC 0 ; TRC 0; DOTV 1; DOHIST 1; NBOXES 256
```

(25) Remove the continuum emission by fitting a baseline in the *uv* plane to the line-free channels; see EXPLAIN UVLSF and § 8.3. If you don't want this task for flagging, but only for continuum subtraction, the important parameters are **UVLSF**

```
ORDER 1 ; DOOUT 1 ; FLUX 0 ; CUTOFF 0
```

Choose your line-free channels, normally avoiding the channels at the edges of your bandpass since they are usually quite noisy.

```
ICHANSEL < begin_1 >,< end_1 >,, 0, 0, < begin_2 >,< end_2 >
```

This task will also write a new continuum data set which is a better estimate of the continuum than the CH0 file which contains contributions from the line signals. If there is a bright continuum source far away from the phase center, you *will* want to use SHIFT to center it while running UVLSF. Multiple interfering sources might even require UVSUB with a good continuum model rather than UVLSF.

(26) Make a dirty cube containing only the line emission. Use the same parameters as in Step 22, including usually only one field — but consider multi-scale Clean. **IMAGR**

(27) Calculate the noise in the line-free channels as in Step 24.

(28) Make a contour plot of the beam.
Display a channel on the TV. **TVALL**

```
TBLC = 0, 0, < channel_number > ; TTRC 0
```

Select a window containing the source (or beam) you want to plot. **TVWIN**
Display the contour plot on the TV. For a beam plot, good parameters are **KNTR**

```
PLEV 10 ; LEVS -3,-1,1,3,5,7,9 DOTV 1
```

When you are happy with the plot, generate a plot (PL) extension file.

```
DOTV -1
```

Send the plot file to the default printer. **LWPLA**
Measure the beam diameter at half-power (FWHP) to get beam parameters (BMAJ, BMIN, BPA) for the Cleaning process. If you do not specify these, IMAGR will choose them automatically by fitting a Gaussian beam with an elliptical cross-section. This is usually fine for uniformly-weighted images (ROBUST around 0), but may not be desirable for naturally-weighted images for which the beam is often rather non-Gaussian.

(29) Select boxes containing all of the line emission in the cube. Use as many boxes as necessary (up to 50). The better that you constrain the locations of real emission, the faster the Cleaning process will go. Note that IMAGR allows you to set the boxes interactively when you run with DOTV 1, which is important when Cleaning reveals emission initially lost in the sidelobes of the stronger objects. **TVBOX**

(30) Make a Clean cube of the line emission. Start by Cleaning just one or two channels (set with BCHAN and ECHAN) to ensure that your inputs are set correctly. If you don't want to waste time, it is a good idea to Clean only those channels with emission that is ≥ 4 times the RMS noise (Step 20). Use SUBIM and MCUBE to construct a full cube of the images later. Use the same parameters as in previous runs of IMAGR, but specify the beam parameters (BMAJ, BMIN, BPA) and control the Cleaning depth with FLUX and NITER. **IMAGR**

(31) Examine the Cleaned cube and do progressively deeper cleaning with IMAGR until you are satisfied with the result. The DOTV 1 option in IMAGR will help you reach this state more quickly. You can examine the Clean components with PRTCC. You should Clean until the total Cleaned flux converges. **TVMOVIE**

(32) Correct for attenuation away from the center of the primary beam. Use your Cleaned cube as the input, the default parameters should be adequate, and the output is a corrected cube. **PBCOR**

(33) Back up the Cleaned cubes and the cubes after PBCOR to tape. **FITTP**
Print the contents of the tapes for your records. **PRTTP**

B.3 Moment analysis and rotation curve of galaxies

After correcting for primary beam attenuation with PBCOR, the noise in the images will depend upon position. Because of this, you should use the uncorrected line cube for moment analysis.

(34) The frequency axis can be labeled in either frequency or velocity units. Make sure that the desired units are chosen; use IMHEAD to check. Velocity is recommended for moment analysis. **ALTSW**

(35) Transpose the axes to VEL-RA-DEC (or FREQ-RA-DEC) order. **TRANS**

```
TRANSCOD '312'
```

(36) Generate images of the total emission (MOM0), the velocity field (MOM1), and the line width (MOM2) using the transposed cube as input. Be sure to exclude the end channels as they generally are very noisy. Try various values for the flux cutoff FLUX and the width of the smoothing functions (set by CELLSIZE) until you are satisfied with the results. **MOMNT**

(37) Correct for the attenuation away from the center of the primary beam in the MOM0 image, as in Step 28. If you computed the moment images with a velocity axis, use ALTSW to change to a frequency axis before running PBCOR. **PBCOR**

(38) Make contour plots of the MOM0 and MOM1 images; see Step 24. Note that KNTR can superpose contour and grey-scale plots as in Figure 8.4. **KNTR**

(39) The task GAL allows you to generate a "tilted-ring" model rotation curve of two types from a galaxy's velocity field or to fit single-parameter rotation curves to annuli of a specified width. The EXPLAIN file for this task describes all of the parameters in detail and contains general advice on how to obtain an optimum fit. **GAL**

The task CUBIT, written by Judith Irwin, allows you to fit a rotating galaxy model to the full Cleaned image cube. The EXPLAIN file for this task describes all of the parameters in detail and contains general advice on how to obtain an optimum fit. **CUBIT**

B.4 Multi-frequency observations

B.4.1 General frequency information

For any *uv* data file, the frequency listed in the header information is the sky frequency of the center of the band (LINE or CH0) during the first scan of the observation. This is true regardless of whether you observed at a single frequency or multiple frequencies. After you SPLIT a multi-source file into single-source files, the frequency in the header refers to the sky frequency at the center of the band during the first scan *on that source*.

Corrections for the Doppler shift due to the rotation of the Earth can be taken into account within *AIPS*, if the data were observed at fixed frequency. Task CVEL may be used, but it requires that the spectra be well sampled in frequency.

B.4.2 Multi-frequency *uv* files

A simple rule of thumb: If you want to calibrate sources together, load the data with the same value of FREQID in FILLM. If you want to calibrate sources separately, give them different FREQIDs. For multi-frequency files, you should be sure to assign a different qualifier (QUAL) to each observing frequency (or velocity) with the OBSERVE program *before taking the observations*. There are essentially two types of multi-frequency observations:

1. Standard multi-frequency observations in which you want to do the entire calibration process separately for each frequency. When reading in such data with FILLM, set CPARM(7) = 0. This sets a different value of FREQID to data that differ by more than the maximum Doppler shift in a source in a day. During calibration, you can control which data you process by choosing the appropriate values for FREQID and QUAL. After calibration of each source/frequency, you may destroy the SN table to avoid using it to calibrate sources with different FREQIDs. For each source/frequency, you should create a new version of the calibration (CL) and bandpass (BP) tables (*e.g.*, for the second source/frequency, you will create version 3 of the CL table and version 2 of the BP table). (It principle, FREQIDs may co-exist in single tables without interference, but if they are in carefully specified separate tables they cannot interfere with each other.)
2. Observations of, or affected by, Galactic emission or absorption, in which you want to combine data at different frequencies to do the calibration. Normally, these are observations in which the calibrator sources themselves are absorbed by Galactic HI around 0 velocity. It is *extremely important* that you assign a different qualifier to each frequency with the OBSERVE program. Then load the data with FILLM forcing a single value of FREQID by setting CPARM(7) = -1. In this case, the information that two observations with the same FREQID have different frequencies will be contained only in the qualifiers. Whatever data are loaded with the same value of FREQID will have the same reference frequency; it should be possible to average over the observing frequencies using the appropriate programs in *AIPS* (CLCAL and BPASS).

B.5 Additional recipes

B.5.1 Banana breeze pie

1. In a small saucepan, melt 1/3 cup **butter** or **margarine**. Add 1/4 cup **sugar** and 1/2 teaspoon **cinnamon**. Stir constantly over low heat until bubbles form around the edges of pan.
2. Remove from heat, add 1 cup **corn flake cereal** crumbs and mix well. Press mixture evenly into a 9-inch pie pan to form crust. Chill.
3. Beat 8 ounces softened **cream cheese** until light and fluffy. Add 1 15-ounce can **condensed milk** and blend thoroughly. Add 1/3 cup **lemon juice** and 1 teaspoon **vanilla**. Stir until thickened.
4. Slice 3 ripe **bananas** and line crust. Pour filling into crust and refrigerate for 2–3 hours or until firm. Do not freeze.
5. Slice 2 ripe **bananas**, dip in lemon juice and arrange on top of pie. Note. for a change of pace, use lime juice.

B.5.2 Banana cutlets

1. Peel 6 medium-ripe **bananas** and halve them crosswise.
2. Dip them in 1/3 cup **lemon juice** and then roll in 1 cup crushed **corn flake crumbs**.
3. Saute them in 3 tablespoons **butter** until a golden brown.
4. Serve on lettuce.