B A STEP-BY-STEP GUIDE TO SPECTRAL-LINE DATA ANALYSIS IN *AIPS*

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In this guide, we assume that the reader is familiar with the basic tools of *AIPS*; *e.g.*, `MCAT` (§ 3.3), `GETN` (§ 3.3.1), `IMHEAD` (§ 3.3.4) and other *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 *AIPS* `EXPLAIN` and `ABOUT` verbs (§ 3.8) and the *AIPS CookBook*. 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 *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 *AIPS* task or verb on the right.

B.1 Editing and calibrating spectral-line data

B.1.1 Loading the data

(1) Copy the Observer's log and find the number of the tape containing your data. Check the listing of the files on the tape (in a binder labeled `PRTTP` in the tape archive room) and determine in which file number your observations are located.

(2) Allocate and mount a tape drive. Use `DENSITY 6250` for the regular archival Exabyte tapes and `DENSITY 22500` for the high-density archival Exabytes. **MOUNT**

(3) Advance the tape to the appropriate file. *You must do this; if the task* `FILLM` *(below) doesn't find data from your observing program after checking two files, it quits and doesn't search further.* **AVTP**

`OPCODE 'AVFI' ; NFILES` $<$ *file_number* $- 1>$

(4) Load the data from the tape to disk. If you used the default averaging time for the VLA, you may want to save disk space by using a higher averaging time for your target sources; if you plan to use self-calibration, it is recommended that you set `CPARM(8)` to a few minutes. **FILLM**

`VLAOBS` '$< program_name >$' ; `NFILES 0`

`CPARM(1)` $< averaging\_time\_for\_sources >$

`CPARM(10)` $< averaging\_time\_for\_calibrators >$

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.

(5) 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 '`< *filename_in_all_caps* >`'`

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

(7) Assuming that all the data were read in successfully, rewind and dismount the tape. **DISMOUNT**

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 § 4.3.1, § 4.4.3, § 4.4.2, § 5.5.2, and § 10.2.2 in the *AIPS CookBook*.

(8) 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 5). 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 12). **UVPLT**

(9) 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* >

(10) 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. **UVFLG**

`OPCODE 'FLAG' ; FLAGVER 1`

(11) Examine the *uv* data for your calibrators on the TV to check for any obvious problems which you might have missed; see § 4.4.3. 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 12–17 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. *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.

(12) Calculate the flux of the primary flux calibrator for the channel zero (CH0) data. Choose the `UVRANGE` according to the tables in the *VLA Calibration Manual.* **SETJY**

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

(13) Calculate gain and phase solutions for *all* of the calibrators. In this case, you must run this task once for each `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. **VLACALIB**

```
DOCALIB -1 ; UVRANGE <uv_min> , <uv_max>
CALSOUR '<calibrator_1>' , ... , '<calibrator_n>'
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.

(14) 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>' , ' '
```

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

```
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 `INTERPOL 'BOX'`.

(16) 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 1 ; GAINUSE 2; DPARM 5, 1, 0`

`UVRANGE 0 ; DOCRT -1 ; OUTPRINT '`< *filename_in_all_caps* >`'`

(17) 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 8–11) if necessary. **TVFLG**

`DOCAL 1 ; GAINUSE 2 ; CALCOD '-CAL'`

If you have too many visibilities to fit on the TV screen, you may want to set `TIMERANGE`, `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.

(18) 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 19 and 20 should be applied to the LINE data alone, not to the CH0 data

(19) 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`

(20) 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**

(21) 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**

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

`CALCODE '-CAL'` ⇐*write uv for all non-calibrator sources*

`DOCALIB 1; GAINVER 2 ; DOBAND 1; BPVER 1`

B.2 Making and Cleaning image cubes

(23) Make a CH0 image with a large field (set by IMSIZE) 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. Choose `CELLSIZE` so that you have 3–4 pixels per synthesized beam. If you don't do this, you will get a warning message. **IMAGR**

```
STOKES 'I' ; NFIELD 1 ; NITER 0
```

Then make a dirty image cube of your LINE data

```
BCHAN 1 ; ECHAN 0
```

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

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

Display a channel of 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
```

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

`DOCONT -1 ; FLUX` $< high_{v}alue >$

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

`NBOXES 2 ; BOX` $< begin_1 >, < end_1 >, < begin_2 >, < end_2 >$

`IMLIN` is the equivalent task for subtracting continuum emission in the image plane, but is not recommended for large fields or when Cleaning. If there is a bright continuum source far away from the image center, you may want to run `UVSUB` before running `UVLIN` or `IMLIN`.

(27) Make a dirty cube containing only the line emission. Use the same parameters as in Step 23. **IMAGR**

(28) Calculate the noise in the line-free channels as in Step 22.

(29) 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 PL 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.

(30) 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**

(31) 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 22). 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**

(32) 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**

(33) 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**

(34) 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.

(35) 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**

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

```
TRANSCOD '312'
```

(37) 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**

(38) Correct for the attenuation away from the center of the primary beam in the MOM0 image, as in Step 29. If you computed the moment images with a velocity axis, use `ALTSW` to change to a frequency axis before running `PBCOR`. **PBCOR**

(39) Make contour plots of the MOM0 and MOM1 images; see Step 25. Note that `KNTR` can superpose contour and grey-scale plots as in Figure 8.4. **KNTR**

(40) 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**

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 are taken into account automatically within *AIPS*.

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 `FREQID`s. 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) = -1`. 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 each source/frequency, you must destroy the SN table, so that it is not used to calibrate sources with different `FREQID`s. For each source/frequency, you must 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).
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. The load the data with `FILLM` forcing a single value of `FREQID` by setting `CPARM(7) = 0`. 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`).