C A Step-by-Step Recipe for VLBA Data Calibration in $\mathcal{AIPS}$

This appendix provides a step-by-step guide to calibrating many types of VLBA and HSA (High Sensitivity Array or Effelsberg, Arecibo, GBT, and phased VLA) experiments. Continuum strong-source or phase-referencing observations are included, as are simple spectral-line observations. This appendix applies specifically to data sets with full calibration transfer. There is an addendum (§ C.10) describing issues with flagging for non-VLBA data sets and other matters for cases in which not all calibration data are loaded by `FITLD`. It may often be used (with some modifications in loading amplitude data) for data sets containing other antennas. Simple VLBA utilities that go all the way up to and including fringe-fitting are described.

C.1 Quick Guide

This section is meant as a reminder for people who have some idea how to reduce straightforward VLBI data and a familiarity with $\mathcal{AIPS}$. For further details see the rest of this appendix and/or Chapter 9. This section does not include things like `CVEL` or `AVSPEC` that might be useful for spectral line observations. Also, this section refers to procedures that can loaded by typing `RUN VLBAUTIL`. All these steps are also performed by the VLBARUN (section § C.5) pipeline procedure.

1. `VLBALOAD` — load the data
2. `VLBAFIX` — fix the data (separate frequencies, merge tables, create index table, etc.)
3. `VLBAEOPS` — correct earth orientation parameters
4. `VLBATECR` — (if frequency < 10 GHz) remove dispersive delay from ionosphere
5. `VLBACCOR` — correct sampler threshold errors from correlator
6. `VLBAPCOR` or `VLBAMPCL` — (if more than 1 IF) correct instrumental delays, use `POSSM` to inspect correction
7. `VLBABPSS` — calibrate bandpass, use `POSSM` to inspect bandpass solutions
8. `VLBAAMP` — corrects any auto-correlation departure from unity caused by previous steps and performs a-priori amplitude calibration, use `SNPLT` to check that nothing has gone wrong in the amplitude calibration.
9. `VLBAPANG` — correct parallactic angle
10. `VLBAFRNG` or `VLBAFRGP` — fringe fit data
11. `SPLIT` — apply all calibration and possibly average data spectrally
12. `IMAGR` — image data

C.2 Table Philosophy

AIPS follows an incremental calibration process on multi-source data sets. Calibration solutions are written to `SN` ("Solution") tables, which can be inspected in various ways. `CLCAL` is used to apply an `SN` table and write a new `CL` ("Calibration") table, which stores the cumulative calibrations. If the procedure in VLBAUTIL is used, much of this is hidden, however most procedures will report the new SN andor CL that are produced. The actual visibilities are not altered until the final calibration is applied using `SPLIT` (or `SPLAT`), which produces single-source (or multi-source) data sets that can be imaged. With this philosophy, it is easy to back up a step or two if errors are made in processing. Users should keep track of which tables contain which solutions and calibrations as they go through the calibration process.

A key verb to be aware of is `EXTDEST`, which can delete any unwanted table. For example, to delete `SN` version 3 from the data set cataloged as data set 1 on disk 1, type `INDISK 1; GETNAME 1; INEXT 'SN'; INVER 3; INP EXTDEST; EXTDEST`. *Beware of the fact that once a table is deleted, there is no 'undelete' function.*

C.3 Data set assumed in this Appendix

This appendix assumes a VLBA-only data set observed at several frequency bands (*e.g.*, 1.6, 2.3, and 5.0 GHz). To include data from the non-VLBA antennas see § C.10. It is also assumed that phase-referencing programs have been observed according to the philosophy discussed in detail in VLBA Scientific Memo No. 24. The hypothetical observation considered here contains the following sources:

- 'CAL-BAND' — fringe-search and bandpass calibrator
- 'CAL-AMP' — amplitude-check source
- 'CAL-POL' — polarization position angle calibrator
- 'STRONG' — strong target source
- 'CAL-PHASE' — phase-reference source
- 'TARGET' — weak target source, to be calibrated with CAL-PHASE

In the text below, table versions, such as `SN` version 1, are referred to as `SN` 1.

C.4 VLBA Utilities

Note that there are simple VLBA procedures ("front ends" to standard tasks) that will take the user all the way from data loading up to and including fringe-fitting. These are tremendous labor-savers for those working with reasonably straightforward data sets. For spectral line, use the procedures to calibrate a lower spectral resolution version of the spectral line data and copy the final calibration to the line set. To access the utilities, type `RUN VLBAUTIL` from inside *AIPS*. The procedures that we will use in this appendix are:

- `VLBALOAD`: loads VLBA data with simplified inputs
- `VLBASUMM`: makes summary listings of your data set
- `VLBAFIX`: Fixes VLBA data
- `VLBATECR`: automatically downloads and applies ionospheric corrections
- `VLBAEOPS`: automatically downloads and applies corrections to the Earth Orientation Parameters used by the correlator

- VLBACCOR: determines amplitude corrections caused by errors in sampler thresholds
- VLBAPANG: determines phase corrections for parallactic angles
- VLBAPCOR: determines instrumental phase corrections using pulse cals
- VLBAMPCL: determines instrumental phase corrections using FRING
- VLBACPOL: calibrates cross polarization delays
- VLBABPSS: does bandpass calibration
- VLBAAMP: does adjustment due to normalization errors and a-priori amplitude calibration
- VLBAFRNG: does global fringe fit using FRING
- VLBAFRGP: does global fringe fit for phase referenced experiments using FRING
- VLBASNPL: plots the SN or CL tables versus time
- VLBACRPL: plots the cross-correlation spectrum

There are two additional procedures that can make life easier, called ANTNUM and SCANTIME. ANTNUM will return the antenna number of the antenna corresponding to a certain character string. For example, in many data sets, typing REFANT = ANTNUM ('BR') will be the equivalent of typing REFANT = 1. SCANTIME will return the time range of a given scan number, for use in various programs. Typing TIMERANG = SCANTIME(4) will fill the eight-element array TIMERANG with the start and stop times of the 4^{th} scan of a given data set.

Note that all of the VLBAUTIL procedures have HELP files with good discussions about when to use the simple procedures and when to use the tasks directly. Also, note that the procedures do not include data editing, which should be performed at appropriate points in the calibration process. You only need to RUN VLBAUTIL once to access all of the procedures. If you run it again for any reason, it is a good idea to type COMPRESS immediately afterward to avoid overflowing AIPS's symbol memory.

C.5 VLBA Pipeline

VLBARUN is a procedure which uses the VLBA calibration procedures (from VLBAUTIL) and some logic to calibrate and image VLBA data. VLBARUN attempts to make intelligent decisions on defaults, so it can be run fairly automatically if the names of the sources are known. If desired, VLBARUN will produce diagnostic plot files and write them to disk, creating an HTML file to ease examination of these files. Images will be produced, but no self-cal is done, so the images should be considered diagnostic in nature.

VLBARUN does all the calibration steps described in § C.1 and the next few sections. It does not do polarization calibration. It offers options to use CLIP and/or RFLAG to do flagging. It also offers options to flag data at low elevations and to try to clean up bad values in the system temperature table. Although VLBARUN is intended for simple VLBI observations, the addition of non-VLBA antennas should work if all the non-VLBA system temperature and gain curve information are loaded into the first TY and GC tables.

Sample inputs for procedure VLBARUN are:

> RUN VLBAUTIL C_R	to acquire the procedures used by VLBARUN.
> RUN VLBARUN C_R	to acquire VLBARUN.
> INDISK *n* ; GETN *ctn* C_R	to specify the input data file.
> OPTYPE 'CONT' C_R	to say this is a continuum data set.
> CLINT 0 C_R	to use default.
> CHREFANT 'FD' C_R	to set reference antenna to Fort Davis.

> CHINC -1 C_R	to have the procedure determine an appropriate channel increment for FRING.
> TIMERANG 0 C_R	to have VLBARUN determine a good instrumental delay calibration scan.
> INVER 0 C_R	PC table to use, -1 if you want to force manual phase cal.
> CALSOUR 'CAL-BAND', 'CAL-PHASE', 'CAL-AMP' C_R	to list calibrators, bandpass calibrator *must* be first.
> SOURCES 'CAL-PHASE', 'TARGET', ... C_R	to list phase referencing and target pairs.
> INFILE '' C_R	set if you want to apply a zenith delay file produced by DELZN.
> SOLINT 0 C_R	to use default.
> IMSIZE 512 C_R	to make images and specify size of target images.
> FACTOR 0 C_R	to make calibrator images 128x128.
> DOCLIP fp, fc C_R	to run CLIP to flag a sample when the parallel-hand flux is above $\|fp\|$ or the cross-hand flux is above $\|fc\|$. If fp is positive, the clip is done after amplitude calibration; if negative, it is done before the bandpass and amplitude calibration. The appropriate values for fp and fc are different in these two cases.
> DOFLAG 1 C_R	to run RFLAG on each source individually.
> TYSMOLEV 100 C_R	to clip system temperatures above 100 K with median-window filtering at 10 K and replacing the clipped values with nearby good ones.
> ELEVLIM 15 C_R	to flag out all data for which the elevation is < 15 degrees.
> BPASS5 -2 C_R	to normalize bandpass scans before the fit. Default is +1 to normalize the bandpass functions themselves without normalization of the data.
> BPSOLINT 0 C_R	to make a solution for each calibration scan. BPSOLINT=-1 averages all calibration scans.
> DOBAND 3 C_R	to interpolate the bandpass over time. DOBAND=1 (the default) averages all bandpass records.
> CALTASK 'CALIBS' C_R	to use FRING for the initial time series calibration but use CALIB for any self-cal. Other choices are 'CALIB' and 'FRING' (the default) to use the specified task for all time series calibrations.
> DOPLOT 1 C_R	to make some diagnostic plots. Use level 2 only if there are serious issues; it generates a lot of plots.
> OUTFILE '*/directory/name* C_R	to specify directory for output plots. If this is set, plots are written out from AIPS and organized in an HTML file for easy viewing. The plots, HTML file, and message file contents are put in a dated subdirectory below the specified directory.
> OUTTEXT '*email@somewhere.edu* C_R	to specify an e-mail address if the user wants to be notified when the pipeline is done.
> BADDISK 0 C_R	to specify which disks to avoid for scratch.
> VLBARUN C_R	to run the procedure.

It is a good idea to examine your TY table with SNPLT before running VLBARUN; this will tell you what a reasonble upper limit to $T_{\rm sys}$ will be and whether there are bad values in need of correction. SNRMS provides a summary of the statistics of tables such as the TY table. It's maxima and rmses will make problems with the table very clear. Note that editing with CLIP is always a good idea. RFLAG appears to work well at low frequencies but to be overly enthusiastic at C-band and above. Note that the flagging is done after all calibration steps, so you may examine your data with and without the new flags to determine their correctness. `RFLAG` is run using baseline-dependent clip levels and so should work with arrays containing high-sensitivity telescopes as well as the VLBA. You may wish to use `VLBARUN` without `RFLAG` (or to discard the flags produced by `RFLAG`) and then run `SPFLG` to flag the visibility data interactively. Then use `VLBARUN` over again applying the manually produced flags.

`VLBARUN` will then run and produce the requested number of diagnostic plots. For details on the plots produced for each level of `DOPLOT` see `EXPLAIN VLBARUN`. If an e-mail address is specified then a `VLBARUN DONE` or `VLBARUN FAILED` message will be sent. However, the `VLBARUN FAILED` message will only be sent if `VLBARUN` failed because of problems with the inputs, if `VLBARUN` failed because a task it was running failed this message is not sent. It is highly recommended that the user read the explain file for `VLBARUN`.

A similar `RUN` file named `VLBAMPHC` is available to calibrate, flag, and image data sets for secondary phase stopping centers when DiFX has been used to correlate multiple centers from a single pointing. A pipeline called `VLBARFI` appeared in `31DEC21`. It calibrates a data set concentrating on the autocorrelation data on which it performs a statistical analysis.

C.6 Data Loading and Inspection

1. Load the data using `VLBALOAD` (which is a very simplified `FITLD`). `CLINT` should be set so that there are several `CL` table entries for each self-calibration or fringe-fitting interval anticipated; this will minimize interpolation error during the calibration process. However, setting `CLINT` too short will result in a needlessly large table. Somewhere between `CLINT = 0.25` and `CLINT = 1.0` is about right. A `FITLD` parameter that is set automatically in `VLBALOAD` is `WTTHRESH = 0.7`, which results in irrevocable discarding of all data with playback weight less than 0.7. The only way around this is to use `FITLD` explicitly. The data will be assigned weights that reflect the playback weight plus the integration time and channel bandwidth. If you run `FITLD` explicitly you may turn this off with `DOWEIGHT <= 0`.

2. Correct data with `VLBAFIX`. *If necessary*, `VLBAFIX` sorts (with `MSORT`), splits into different frequencies (with `UVCOP`), fixes the polarization structure (with `FXPOL`), and indexes (with `INDXR`) the data. `VLBAFIX` will also correct for subarrays (with `USUBA`), but you must tell it to do so. There are only 2 inputs of interest in `VLBAFIX`, `CLINT`, the CL table interval, and `SUBARRAY` which should be set to 1 if there are subarrays and 0 if not. This is a very benign procedure, it can be run on every data set read into AIPS and will only perform the necessary fixes. Note that, if the data are split into different frequencies, the flag table is applied and deleted.

3. At this point it is a good idea to get a listing of the antennas and scans in your data by running `VLBASUMM`. `VLBASUMM` runs `PRTAN` over all antenna tables and `LISTR` with `OPTYPE='SCAN'` and gives a choice of writing a text file to disk or sending the listing to a printer.

4. Apply corrections to the Earth Orientation Parameters (EOPs). VLBI correlators must use measurements of the Earth Orientation Parameters (EOPs) to take them out of the observations. These change slowly with time and therefore the EOPs used by the correlator must be continually updated, and they are generally best two weeks or more after the observation. Since we try to correlate observations as quickly as possible, it is likely that the EOPs used are not the most accurate. Therefore it is recommended that all phase-referencing experiments be corrected for this possible error. The procedure`VLBAEOPS` will do this correction. `VLBAEOPS` automatically downloads a file with correct EOPs and runs `CLCOR` to correct the EOPs. If the automatic download does not work, `VLBAEOPS` can use a file which you have downloaded. *Warning: this procedure does not work well over concatenated data sets containing multiple days; uss* `CLCOR` *explicitly and set* `CLCORPRM(2)`.

5. Apply ionospheric corrections, if desired, with VLBATECR. This procedure automatically downloads Global Positioning System (GPS) models of the electron content in the ionosphere and uses them to correct the dispersive delays and Faraday rotation caused by the ionosphere. If the automatic download does not work, VLBATECR can also use a file which you have downloaded, This is particularly important for phase referencing and polarization experiments at low frequency. We recommend VLBATECR for all experiments at 8 GHz or lower. VLBATECR is only as good as the ionospheric model, so it is a very good idea to compare the corrected and uncorrected phases using VPLOT. To inspect the phases using VPLOT, use options BPARM = 0, 2; APARM=0; DOCAL=1; GAINUSE=*highest* CL *table*. The phases should not wind as much (although they will probably not be completely flattened), when the corrected CL table is applied. To see the corrections themselves, use SNPLT on the new CL table setting OPTYPE = 'DDLY'. In 31DEC23, tasks MFIMG and TEPLT may be of interest after running TECOR.

6. For a simple spectral-line data set, or any data set with high spectral resolution, it is a very good idea to average the data set to a smaller number of channels before deriving the calibration parameters. Otherwise, the calibration tasks may take forever to run. It is recommended that you quickly inspect the channels of interest for your line data (*e.g.*, with UVPLT) for high points. Remove obviously high amplitudes with CLIP (or *e.g.*, UVMLN, SPFLG) before averaging. Inspect the full resolution data also for high delays and fringe rates. Spectral averaging in such cases may not be acceptable. Continue calibration on the averaged data set as if it were a continuum set. There is a better method to calibrate spectral line data described in § 9.5.6 and § 9.5.7.10, but the one used here is simpler and will usually give acceptable results. To reduce the data-set size, run the task AVSPC with AVOPTION = 'SUBS'. For example, to average IFs with $N_{\rm chan}$ down to 32 channels, set the adverb CHANNEL = $N_{\rm chan}/32$ (*e.g.*, to average from 2048 to 32 channels, use CHANNEL = 64).

C.7 Amplitude and Delay Calibration

Amplitude calibration uses measured antenna gains and system temperatures ($T_{\rm sys}$), as well as finding a correction for voltage offsets in the samplers. Even though this is substantially still the case, we now recommend a somewhat different amplitude calibration procedure than in the past based on VLBA Scientific Memo #37 (Walker 2015).

Before amplitude calibration is done, there must be information for all antennas in the gain curve (GC), system temperature (TY), and weather (WX) tables (weather tables are needed for the opacity correction in APCAL). Missing $T_{\rm sys}$ and gain curve information can usually be obtained in ANTAB format and loaded with the AIPS task ANTAB. § C.10 has information on including non-VLBA calibration information, if they are not already included in the data. § C.11 has details on how to incorporate the pre-EVLA VLA $T_{\rm sys}$ and gain curves. Otherwise consult § 9.5.2.3.

1. Correct sampler offsets and apply amplitude calibration by running VLBACCOR. The procedure VLBACCOR runs ACCOR, SNSMO, and CLCAL. ACCOR uses the autocorrelation to correct the sampler voltage offsets. After ACCOR creates an SN table, SNSMO smooths the table in order to remove any outlying points. Then the SN table is applied to the highest CL table using CLCAL (using INTERPOL='2PT'), and a new CL table is created.

2. Next, the instrumental delay residuals must be removed. These offsets or "instrumental single-band delays" are caused by the passage of the signal through the electronics of the VLBA baseband converters or MkIII/MkIV video converter units. There are two different methods to remove these instrumental delays, one for the case where you have pulse-cal information for some, but not necessarily all, of your antennas; and one for the case where you have no pulse-cal information at all. Note that the preferred method for continuum experiments is to use the pulse-cals, since they

correct the instrumental delay over the whole experiment, rather than on a short scan. Spectral-line observers would have switched off the pulse-cals as they interfere with line observations, so they are forced to use the second (strong source) method. For VLBA continuum experiments before April 1999, you can load the pulse-cal data using PCLOD; consult the § 9.5.2.

- For the case where you have some pulse-cal information, run VLBAPCOR. VLBAPCOR is another procedure which runs quite a few tasks, PCCOR, CLCAL, FRING (sometimes) and CLCAL again (sometimes). PCCOR extracts pulse-cal information from the PC table and creates an SN table. Then CLCAL is run to apply that SN table to the highest CL table, creating a new CL table. If there are antennas that do not have information in the PC table, or their PC entries are wrong, then VLBAPCOR can run FRING on a short calibrator scan (input TIMERANG). The SN table from FRING contains corrections for the antennas left out of the PC table, and is applied to CL table without corrections from PCCOR, and added to the CL table with the PC corrections. For the simplest case of all VLBA antennas, the inputs for VLBAPCOR should be TIMER=*time range on* CAL-BAND *with good fringes for all baselines*; REFANT=n; SUBARRAY=0; CALSOUR='CAL-BAND''; GAINUSE=0; OPCODE=''; ANTENNAS=0. For the case where you have the VLA (in this example antenna 11), which does not have pulse-cals, your inputs should be the same as above except OPCODE='CALP'; ANTENNAS=11,0. For the second case it is important that there are no "Failed" solutions from FRING; if there are failed solutions, then you should delete the tables that were created and find another TIMERANG with good fringes to the REFANT. Also see EXPLAIN VLBAPCOR for a detailed description of the steps involved with using pulse-cals and FRING without using VLBAPCOR.
- The alternate method is to solve for the phase cals "manually" with VLBAMPCL. This method uses the fringes on a strong source to compute the delay and phase residuals for each antenna and IF. VLBAMPCL runs FRING to find the corrections and then CLCAL to apply them. If there is no calibrator scan that includes all antennas then there is an option to run FRING and CLCAL again on another source and/or time range in order to correct the antenna(s) not corrected by the first scan. For the simplest case where all antennas have strong fringes to CAL-BAND, set TIMERANG = *time range of scan on calibrator with strong fringes to all antennas*; REFANT = n; CALSOUR = 'CAL-BAND'; GAINUSE = *highest* CL *table*; OPCODE = ''. There must be no "Failed" solutions from FRING, if there are any failed solutions the data from that antenna/IF will be completely deleted from the data set.
- Now you *must* check the results of correcting your instrumental delays using VLBACRPL or POSSM. Set GAINUSE=*highest* CL *table*, and plot cross-correlations (VLBACRPL will do this for you). The plotted cross-correlations should show the phase slope removed from each IF and there should no longer be a phase jump between IFs, although the phase does not have to be at 0°. If you do a "manual" instrumental delay correction (*i.e.*, you used FRING, not PCCOR); then the phases far in time from the scan on which FRING was performed may have a small slope and a small phase jump between the IFs. Also non-zero phase slopes still may be seen at low elevations, where the atmosphere causes additional delay residuals, or for low-frequency observations where the ionospheric delay varies. If you see significant phase slopes, or phase jumps between IFs on *any* baseline, then the instrumental phase corrections have not worked and you need to figure out why and start again.

3. Next you must calibrate the bandpass shapes. To do this, run VLBABPSS on the bandpass calibrator, CAL-BAND. Make sure that the spectral line data for the bandpass calibrator are clean and devoid of high points, using UVPLT or SPFLG. Inputs for VLBABPSS are CALSOUR = 'CAL-BAND' and a model for your calibrator if you have one. Then you must examine the BP table using POSSM by setting APARM(8)=2.

4. Now it is time to finish the amplitude calibration by running VLBAAMP. This procedure runs several tasks: ACSCL, SNSMO, CLCAL, APCAL and CLCAL. After the previous steps the calibrated autocorrelation amplitudes will be offset from unity; ACSCL corrects this offset. ACSCL creates an SN which is then smoothed by SNSMO and CLCAL is run to apply the calibration to the next CL table. Then to finalize the amplitude calibration, APCAL is run on the highest TY and GC tables, and a new SN table is created.

Adverb DOFIT controls whether APCAL also uses the weather tables to fit and correct for opacity. It is desirable to perform an atmospheric opacity correction at high frequencies, particularly if very accurate source fluxes are needed. See § 9.5.4.6 for a more detailed discussion of APCAL. Lastly, VLBAAMP runs CLCAL to apply the amplitude calibration SN table to the CL created by the last run on CLCAL. VLBAAMP will print messages telling you about the new tables it has created. To keep track of your tables, it is important to copy these messages.

5. At this point it is a *very* good idea to examine your calibration.

   - Run the task SNPLT or procedure VLBASNPL (which is a very simplified SNPLT) to examine the tables created by ACCOR. Use INEXT='CL'; OPTYPE= 'AMP'; INVERS=CL-*table-with-sampler-offsets*; DOTV=1 (to display to the TV; for a hardcopy use DOTV=-1 and LWPLA to print the plot files). The solutions that SNPLT plots should be close to 1000 milligain or 1 gain.
   - Run SNPLT or VLBASNPL to examine the amplitude calibration. This time look at the SN table that APCAL created. Use INEXT='SN'; OPTYPE= 'AMP'; INVERS=*highest* SN *table*; DOTV=1 for VLBASNPL; or to inspect IF m, use BIF = m; EIF = m; OPTYP = 'AMP'; INVER = 0; INEXT = 'SN'; OPCODE = ' '; NPLOT = 10; DOTV = 1; GO SNPLT. For a hard copy, use DOTV = -1; GO SNPLT; GO LWPLA. Plotted amplitudes are the square-roots of the system-equivalent flux densities (SEFDs), in Jansky, where the SEFD is the flux density of a source that would double the system temperature. (Low numbers are good!) At centimeter wavelengths, VLBA antennas have SEFDs near 300 Jy, so gains above $30°$ elevation should be near 17–18 and should vary slowly and smoothly with time (*i.e.*, change in elevation) for an individual source. To look at the input system temperatures, run SNPLT with OPTYP = 'TSYS'; INEXT = 'TY'; INVER = 0. On rare occasions, you might find clearly discrepant points that have leaked in from a different frequency band. In that case, you can use task SNEDT, or the clipping option of SNSMO, to get rid of the bad points. You may notice that at low elevations the gains on individual antennas are high. All data below a given elevation can be flagged by running UVFLG; *e.g.*, to flag all data below $10°$, run UVFLG with APARM(4)=0 and APARM(5) = 10. Note that FG tables are not applied to tables, so flagged data still may have points plotted by SNPLT. The $T_{\rm sys}$ measurements are also a very good diagnostic of bad data from poor weather, equipment failures, *etc.*. If there are time ranges of unusually high or low $T_{\rm sys}$ you may consider flagging those time ranges using UVFLG or EDITA. Be particularly suspicious of patches of unusual gains at only one IF or STOKES of an antenna. Remember, one of the best things you can do for your final result is to get rid of bad data.
   - You may wish to use your favorite method of inspecting data for flagging (*e.g.*, EDITR, SPFLG, TVFLG, IBLED). On-line flags are already included in FG 1 unless they were applied as the data were split into separate frequencies. For example, run EDITR with inputs SOURCES= 'CAL-BAND','' (do each source separately); DOCAL=1; GAINUSE=*highest* CL *table*; FLAGVER=0; OUTFGVER=0; DOTWO=1; ANTUSE=1,2,3,4,5,6,7,8,9,10. Once you gain experience you might want to set CROWDED=2 ; DO3COL=1 which allows 3-color displays of all polarizations and IFs in one plot with a faster method for the TV displays; this can speed up editing significantly. Look for anomalously high or low amplitudes, remember there can be a slow change in amplitude with time due to source structure. Some people do no additional flagging at this stage, but later use the results of fringe-fitting and visibility plots of calibrated data to point the way to bad data.

6. For spectral-line experiments needing velocity accuracy better than 1 km/s, a Doppler correction should be performed. Use CVEL; see § 9.5.4.5 and § 9.5.5 for details.

7. This is a useful time to run TASAV to save all your ancillary tables to another file. If you foul up the calibration, the relevant tables can be copied back using TACOP.

C.8 Rate and Phase Calibration

Now that the data have calibrated amplitudes, the next step is to do the calibration of the antenna rates and phases. This section describes that process.

1. Correct the antenna parallactic angles, if desired, using VLBAPANG. The RCP and LCP feeds on alt-az antennas will rotate in position angle with respect to the source during the course of the observation (all VLBA and VLA antennas are alt-az). Since this rotation is a simple geometric effect, it can be corrected by adjusting the phases without looking at the data. You *must* do this correction for polarization experiments and phase referencing experiments. Parallactic angles are important for phase referencing because the parallactic angle difference between calibrator and target is different at different stations which leads to an extra phase error which can be corrected. VLBAPANG copies the highest numbered CL table with TACOP and then runs CLCOR (OPCODE = 'PANG'; CLCORPRM = 1,0). VLBAPANG has no inputs that require discussion. Be sure to correct the parallactic angles before any of the following steps. Again keep track of which CL tables add which correction.

2. Now you must remove global frequency- and time-dependent phase errors using FRING or one of the procedures which use this task, VLBAFRNG or VLBAFRGP. This cannot be done simply for spectral-line sources, so the practice here is to determine delay and rate solutions from the (continuum) phase-reference sources and interpolate them over the spectral line observations. The procedures run FRING along with CLCAL. VLBAFRNG and VLBAFRGP use FRING, with VLBAFRGP specifically for phase referencing. For all these procedures, if the SOURCES adverb is set, then CLCAL is run once for each source in SOURCES. For the phase-referencing procedure (VLBAFRGP), any source that is in the SOURCES list that is *not* in the CALSOUR list will be phase referenced to the *first* source in the CALSOUR list. These procedures will produce new (highest numbered) SN and CL tables. Since it is probably best to run CLCAL on each source separately, SOURCES should always be set. To use VLBAFRGP for a simple phase referencing experiment (remember that CAL-PHASE is the phase reference calibrator), set CALSOUR='CAL-PHASE','CAL-BAND','CAL-AMP','CAL-POL','STRONG'; GAINUSE=*highest* CL *table*; REFANT=n; SEARCH 9 4 1 3 5 6 7 8 10; SOLINT=*coherence time*; DPARM(7)=1 *(if a polarization experiment)*; SOURCES='CAL-PHASE', 'CAL-BAND', 'CAL-AMP', 'CAL-POL', 'STRONG','TARGET'; INTERPOL='SIMP'. For this example, FRING will be run on the sources in CALSOUR and then CLCAL will be run 6 times, with all of the sources except TARGET referenced to themselves and TARGET referenced to CAL-PHASE, using interpolation method SIMP. For a non-phase-referencing experiment you would use VLBAFRNG with inputs the same as above except for SOURCES, which would not contain TARGET. The results will be the highest SN and CL tables. The INTERPOL to use is a personal preference. You might want to restrict the channel range slightly using BCHAN and ECHAN, since the channels at the high end of each IF will have lower SNR, due to the cutoffs in the bandpass filters. For a data set with 16 channels per IF, numbered from 1 to 16, setting ECHAN to 14 or 15 may be worth trying. Note that some people like to run CALIB rather than FRING or KRING for this stage of phase-referencing observations, but fringe fitting is recommended, as it solves for rates.

   The above fringe fit may take a bit of time, depending on the computer and the spectral resolution. Then, use SNPLT or VLBASNPL to inspect the solutions in the SN table. It's not totally out of the question that some data will be found that need flagging, which can be done with UVFLG. In that case, it's a good idea to delete the last SN and CL table and re-run VLBAFRGP or VLBAFRNG.

   This fringe-fitting stage is the most likely place where things can go wrong, for reasons that are not immediately apparent to the observer. Below, a few common examples are listed.

   - **Many solutions failed.** The source may be too weak, or the coherence time too short. Try increasing or decreasing SOLINT. Or narrow the search window. For most VLBA data, DPARM(2) = 400 and DPARM(3) = 60 should be a good first step, though the rate window specified in DPARM(3) is proportional to the observing frequency, and may need to be larger at 22 GHz and above. For more options you could try running FRING and reduce the SNR threshold with

APARM(7) or averaging the RR and LL (APARM(3)=1). One last thing to try is to abandon FRING and solve for the phases in CALIB, obviously not ideal since you will not get rates or delays, but it is a hit worth taking if the the calibration can be salvaged.

- **Some antenna has low SNR, and may cause an entire set of solutions to go bad.** This typically happens because an antenna should have been flagged. A common cause is when OV is looking at the White Mountains, and neither the on-line system nor the astronomer has flagged the data. Then, you need to run UVFLG and re-run VLBAFRGP or VLBAFRNG.
- **There are discrepant delay/rate solutions.** Look at the solutions you believe, and try VLBAFRGP or VLBAFRNG again with DPARM(2) and DPARM(3) specified appropriately. Full widths are specified, so if the good solutions fall between $+15$ mHz and -15 mHz, use DPARM(3) = 30. (Actually, you should use a value somewhat larger to allow some margin.) It may be that an antenna is suffering from radio-frequency interference, so some channels and/or IFs will need to be flagged.
- **Some solutions are outside the specified delay/rate range.** This can happen because the initial coarse fringe search uses the range specified by DPARM(2) and DPARM(3), but the least-squares solution can take off from there and go elsewhere.
- **Delays and rates for some station change rapidly near the beginning or end of the observation.** This may be caused by low elevation at the relevant station. Depending on how desperate you are to include low-SNR data, you may wish to flag some time range, or flag all data at elevations below 5°, 10° or even 20° (particularly at high frequencies or for phase referencing) with UVFLG.
- **Phases wrap rapidly, particularly on the phase-reference source, CAL-PHASE.** There may not be a lot you can do about this initially, because it's possible that the tropospheric delay just changed too fast for the cycle time used in the observation, especially at low elevation. However, you may wish to note the times and antennas when the phase connection is best (typically the southwestern antennas near transit). Later, when imaging the program source, it can be helpful to image with a subset of antennas and time ranges, then use that initial image to self-calibrate the rest of the data.

3. Use SNPLT or VLBASNPL to inspect the interpolation of the phases in the CL table. When you inspect the CL table notice any phase wraps that seem out of place. The human eye is better at pattern matching than a computer and these phases may be in error. You can use SNBLP to examine the phase solutions on a baseline basis (as they actually affect the visibilities). This may make problems more apparent. If so you might want to run CLCAL independently and try another interpolation method or you might want to edit the CL table. Remember that this is your last calibration table; you want to get rid of any bad calibration now before applying it to the data. Getting rid of spurious wraps in the final CL table (SNEDT) or flagging the data associated with fast changing phases (SNFLG) will improve your final image more consistently than anything else, *particularly* for phase referencing.

C.9 Final Calibration Steps

1. If you used AVSPC to reduce the size of the data set used in determining calibration, you must copy your final calibration tables back to the full-size data set. This can be done with task TACOP. For bookkeeping purposes, it may be best to copy over all the CL tables with the same table numbers in both the averaged and un-averaged data sets. Copy the FG table as well, since any data which are bad in the averaged data set will be bad in the full resolution data set. After inspecting the data with UVPLT or VPLOT, run EDITR, TVFLG, CLIP, SPFLG, or other data editor to edit the bad data from the calibrated spectral-line data set.

2. After you have corrected the bandpass for spectral line data, you may want to correct for the change in frequency by the motion of the antennas with respect to the Sun *etc.*. This is done with CVEL, after the source velocities are entered in the SU table with SETJY. For a detailed description see § 9.5.5.

3. Polarization calibration still remains, if desired, and if all the appropriate calibration sources were observed. This can be done in a variety of ways; see § 9.5.7 for details.

4. Finally, apply the calibration to the visibility data and make single-source data sets using SPLIT. (Some people might wish to use SPLAT to average over time as well as spectral channel.) Inputs for a continuum observation are SOURCES = ' '; BIF = 0; EIF = 0; DOPOL = -1 (or 1 if polarization calibration was attempted); DOBAND = 1; DOUVCOMP = 1; NCHAV = 0; APARM = 2,0; DOCALIB = 1; GAINUSE = *highest* CL *table*. For a spectral-line observation, set APARM = 0, because you don't want to average over frequency. Use OUTDISK and OUTCLASS as appropriate for your computer and record-keeping purposes.

The single-source data sets are now ready for imaging and possible self-calibration. At this point, it is a good idea to look at the amplitude check source 'CAL-AMP' using tasks such as UVPLT, WIPER or VPLOT in order to see if there are any antenna gain calibrations that must be adjusted. Doing a WIPER for each target source is a good idea also, because there may be discrepant amplitude points due to interference or poor fringe fits (among other things). The task WIPER makes UVPLT like plots but is designed to do flagging.

C.10 Incorporating non-VLBA antennas

Many non-VLBA telescopes have their amplitude calibration incorporated in the tables loaded by FITLD. We retain the following sections for the case where some telescopes are not included in calibration tables for whatever reason.

The phased-EVLA came on-line in February 2013. Its calibration is very different from the old VLA. With the phased-EVLA either an ANTAB style file was provided to the observer or the calibration information is attached to the data. This calibration is generated from the switched power measurements attached to the EVLA only data. There is no need for special calibration steps. However, the observer may wish to improve the calibration by editing the switched power and recreating the ANTAB style file. More information on this can be found in § 9.5.2.4. There is a separate section (§ C.11) dealing with pre-EVLA VLA data.

C.10.1 Loading $T_{\rm sys}$ and Gain Curves

Most telescopes that do not have $T_{\rm sys}$ and gain curve information attached to the data will provide the user with a text ANTAB format file that can be loaded with ANTAB. Please see EXPLAIN ANTAB for more information on the ANTAB format. Follow the steps below to load calibration information and amplitude calibrate the data.

1. To prevent any chance of having to re-run FITLD, first save the VLBA TY and GC (and all your other) tables by running TASAV. Then run ANTAB with CALIN set to the ANTAB file and setting TYVER and GCVER to the highest numbered tables (usually 1). You don't want to leave TYVER and GCVER equal to 0 because that causes ANTAB to create new TY and GC tables with only the antennas in the file you are loading. If ANTAB fails, it is most likely caused by the input file not being formatted correctly. Perhaps you needed to add an INDEX entry or the file wasn't in true ANTAB format. Also, if ANTAB fails check that the TY and GC tables have not been corrupted. If they have you should delete the tables and copy the original tables from the TASAV'ed file with TACOP.

2. Now, run VLBAAMP as described in § C.7 to combine the gain and system temperature information for all antennas into the appropriate SN and CL tables. Then, use SNPLT or VLBASNPL as described in § C.7 to make sure that the resulting SN now contains amplitude calibration for all the antennas and IFs included in the project.

C.10.2 Pointing Flags

The VLA, GBT, AR and possibly other telescope's on-line systems produce only recorder-related flags, not pointing flags. Thus, for example, there are no flags for when the telescope is not on-source. This can lead to a large amount of bad data especially if you are changing source frequently. However, the VLBI scheduling program SCHED creates a *.flag file which contains estimates of how long it takes these antennas to slew. The *.flag file will also contain flags for all antennas in the experiment, so it is best to remove the flags that pertain to the VLBA antennas. The flag file can be read in with UVFLG using the INTEXT adverb.

C.11 Pre-EVLA VLA data

The method described in this section is only meant for VLA data from before February 2013 (before the phased-EVLA came on-line). The observation being calibrated may have incorporated either a single VLA antenna or the phased VLA, but the amplitude calibration parameters for the VLA were not transferred automatically. You will need to obtain an input text file for the VLA then run ANTAB before APCAL. Before February 2013, the gains and system temperatures for this file, in an appropriate format, were supplied in a file called *xxxxx*cal.y.gz', where '*xxxxx*' is the observation code (*e.g.*, 'bm120'), located at http://www.vlba.nrao.edu/astro/VOBS/astronomy/mmmyy/xxxxx/. That file contains instructions on editing the file to get correct inputs. For a phased array or a 1.3-cm observation in which 3 antennas are used, follow the instructions in § C.11.2; for a single antenna, use § C.11.1.

C.11.1 Single VLA Antenna

The method described in this section is only meant for VLA data from before February 2013. Depending on the age of your observation, you may have to add an INDEX entry within the TSYS card (**Do not separate the INDEX entry from the TSYS entry by a "/" !!!**), un-comment the GAIN line for your particular observing frequency, and un-comment the TSYS line. There are examples of INDEX entries in the comments at the head of the file.

Beginning in June 2003, the INDEX, GAIN, and TSYS information in this table are reformatted to be directly acceptable to *AIPS*. You should check the times in the text file to make sure that your observation has been properly described. Only a few special cases will require editing of the file; in most cases you are able to invoke ANTAB with no editing. Once you are satisfied with the ANTAB file, load the data following the directions in § C.10.1.

C.11.2 Phased VLA

The method described in this section is only meant for phased-VLA data from before February 2013. The VLA may be phased on a program source ('STRONG'), or may be phased on a phase-reference source ('CAL-PHASE'), with the resulting solutions applied to the program source ('TARGET'). Rather than recording a system temperature, the VLA system will record a ratio of antenna temperature to system temperature, which will vary as the array phases up. In order to convert the ratio of antenna and system temperatures to a usable gain, the flux density of some source will be needed.

1. Load and calibrate the VLA data by standard means (see Chapter 4 and Appendix O). Determine the flux density of a relevant strong source, usually either 'STRONG' or 'CAL-PHASE'. Then, on the VLBI data set, insert the flux density of this source into the `SU` table using `SETJY`. For example, if the source is 'CAL-PHASE' and its flux density is 0.432 Jy, run `SETJY` with `SOURCES = 'CAL-PHASE'; BIF = 0; EIF = 0; ZEROSP = 0.432,0; OPTYPE = ' '`.

2. Edit the input file as indicated above for a single VLA antenna. Again, an `INDEX` line, a `GAIN` line, and a `TSYS` line must be checked (after June 2003) or be created or un-commented. The `GAIN` line is independent of observing band (the source flux is used to determine the gain), and the `TSYS` line should include the parameter `'SRC/SYS'`, indicating that the ratio of antenna temperature to system temperature is being supplied.

3. Run `ANTAB` to read in the input file of amplitude calibration parameters. Then run `VLBACALA` to put this in an `SN` table. Both steps are essentially the same as for a single VLA antenna (see § C.11.1). The most likely problem is that `APCAL` in `VLBACALA` will fail because you forgot to enter a source flux density using `SETJY`, although the error message may not always make this obvious.

4. Run `VLBASNPL` or `SNPLT` to inspect the resulting `SN` table, as for the single VLA antenna. In this instance, you should see that the phased VLA is very sensitive. If the phasing worked well at centimeter wavelengths, the amplitude should be near 4 or 5 instead of the value of 17 or 18 seen for a single VLBA antenna. At the start of scans where the VLA is being phased, you may see a rapid change in the amplitude gain (toward smaller numbers) as the antenna phases are brought into alignment. The `SN` table should be inspected very carefully, because there may be data that should be flagged when the VLA phasing did not work well. Three possible reasons for poor phasing are (1) the source is too weak; (2) the troposphere is misbehaving; or (3) there was radio-frequency interference at the VLA.

C.12 Summary for non-VLBA antennas

Following the insertion of the amplitude solutions for the non-VLBA antennas, you can return to follow the standard path for calibration of VLBA data. Although the procedures from here on are identical to the VLBA-only case, the observer may wish to pay attention to several issues.

1. Many non-VLBA antennas are more sensitive than a single VLBA antenna, it can be a good idea to use the most sensitive antenna as the reference antenna for fringe-fitting.

2. Non-VLBA antennas may have a larger delay offset than VLBA antennas. The user should pay close attention to the fringe fits, and be aware of the possibility that non-VLBA antennas may have larger residual delays and rates than a VLBA antenna.

3. Many non-VLBA antennas do not slew as rapidly as the VLBA. The `FG` table supplied by calibration transfer may not include all the on-line flags, and may not incorporate information about the pointing of non-VLBA antennas, and when they arrive on source. Therefore, some judicious flagging by the user may be necessary. See § C.10.2 for a discussion of applying flags produced by the scheduling software SCHED.

4. The elevation limit for non-VLBA antennas is generally different and usually higher than the VLBA's limit ($> 2°$) which may cause sources to rise and set at different antennas at different times. For example, the VLA has an elevation limit of 8°, this means that a source will rise later and set earlier at the VLA than it does at Pie Town or Los Alamos.

C.13 Some Useful References

1. Chatterjee, S., "Recipes for Low Frequency VLBI Phase-referencing and GPS Ionospheric Correction," VLBA Scientific Memo No. 22, May 1999.
`http://www.vlba.nrao.edu/memos/sci/`

2. Ulvestad, Jim, "VLBA Calibration Transfer with External Telescopes, Version 1.1," VLBA Operations Memo No. 34, July 30, 1999. `http://www.vlba.nrao.edu/memos/vlba/vba.oper.txt`

3. Ulvestad, Jim, "A Step-By-Step Recipe for VLBA Data Calibration in *AIPS* Version 1.3" VLBA Scientific Memo No. 25 (the basis of this appendix), January 2, 2001.
`http://www.vlba.nrao.edu/memos/sci/`

4. Ulvestad, Jim, Greisen, Eric W., Mioduszewski, Amy "*AIPS* Procedures for Initial VLBA Data Reduction, Version 2.0" *AIPS* Memo No. 105 April 26, 2001.
`http://www.aips.nrao.edu/aipsdoc.html # MEMOS`

5. Wrobel, J. M., Walker, R. C., Benson, J. M., & Beasley, A. J., "Strategies for Phase Referencing with the VLBA," VLBA Scientific Memo No. 24, June 2000.
`http://www.vlba.nrao.edu/memos/sci/`

C.14 Additional recipes

C.14.1 Orange baked bananas

1. Mix in a saucepan 1/2 cup firmly packed **brown sugar**, 1 tablespoon **cornstarch**, 1/8 teaspoon **cinnamon**, and a few grains **salt**.
2. Add gradually, blending in 3/4 cup boiling water.
3. Bring rapidly to boiling and cook about 5 minutes or until sauce is thickened, stirring constantly.
4. Remove from heat and blend in $1\frac{1}{2}$ teaspoons grated **orange peel**, 1/4 cup **orange juice**, 1 teaspoon **lemon juice**, and 2 tablespoons **butter**.
5. Peel and cut into halves lengthwise 6 **bananas** with all-yellow or green-tipped peel.
6. Arrange halves cut side down in baking dish and brush with about 2 tablespoons melted **butter**.
7. Sprinkle 1/2 teaspoon **salt** over bananas and then pour the orange sauce over bananas.
8. Bake at 375° F for 10 to 20 minutes.