LWA Memo 228:
The LWA Swarm Interferometry Guide

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Introduction

This guide is to help in the calibration of interferometry data taken using the LWA Swarm Interferometer. Calibration is done using the Astronomical Imaging Processing Software (AIPS), and we assume that the user has been introduced to the basics of AIPS martial arts.

The LWA is an interferometer array telescope collaboration comprised of 'stations' distributed across the Southwestern United States. These stations observe over a frequency range of 3-88 MHz and are composed of a pseudo-random distribution of dual-polarization dipole antennas spread across a ∼100m aperture G. B. Taylor et al. (2012). Each station is a digital beamforming aperture array capable of targeted observing and all-sky imaging on its own, or in cooperation with other LWA stations to form an interferometer. Continued improvement in radio astronomy technology since the construction of the first LWA station in 2012 has allowed subsequent stations to incorporate more features and flexibility. For this reason, each LWA station is slightly different in its construction, but fundamentally is maintained and operated using the LWA Software Library(`lsl`; J. Dowell et al. (2012)). LWA1, located near the Very Large Array (VLA) control building, and LWA-SV, located at the Sevilleta National Wildlife Refuge, are both 256-element stations. OVRO-LWA, hosted at the Owens Valley Radio Observatory, is a 352-element station with a core of 243 elements and an additional 109 elements with long baselines up to ∼2.4 km for arc-minute scale imaging. The newest station commissioned is the LWA-NA station located near the end of the VLA North arm is a smaller 64-element 'swarm' station (C. A. Taylor et al., 2025). LWA Swarm observations utilize at least 3 active LWA stations to make interferometry observations (Although using fewer stations is possible, one cannot image target fields).

Observing Strategy

The first step for conducting LWA Swarm interferometry is to select a set of calibrators for your observation, starting with a strong calibrator from Table 1. This calibrator will provide tracking delay and rate solutions for your science field and should be observed for ~ 6 minutes every 1-2 hours. This calibrator will also be used to perform bandpass calibration for the observation. Preferably, this strong calibrator should be within 20 degrees of the target, but that is not always possible with the current calibrator coverage, so the closer the better. Next, try to identify additional calibrators with a peak flux ≥ 20 Jy at 74 MHz, that are closer to the target field for additional delay and phase calibration. Choosing several secondary calibrators, ideally $< 3^\circ$ from the science field, will provide additional support to primarily the phase calibration. These additional calibrators should be observed for approximately ~ 6 minutes per 30 minutes.

Observing is better at night compared to day, given the dynamic ionosphere at these frequencies. However, results from a preliminary survey of calibrators indicate that the worst observing windows include sunrise and sunset, so these times should be avoided if possible. Observations should be a minimum of 5 hours duration to obtain the best possible (u,v)-coverage, and elevations below 20 degrees should be avoided. Ideal conditions would be at night while the source is transiting. Typically, we use an integration time of 1 second

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Table 1. LWA Swarm Calibrator Survey Sources

Source ID	Quality	RA (J2000)	DEC (J2000)	S (Jy)	σ_{rms} (mJy)
3C 20	B	00 43 08.71	+52 03 29.1	21	22
3C 48	A	01 37 41.41	+33 09 38.2	92	181
3C 123	A	04 37 04.46	+29 40 15.3	59	129
3C 147	A	05 42 36.04	+49 51 07.9	51	76
3C 154	A	06 13 49.81	+26 04 38.6	17	70
3C 161	A	06 27 10.1	-05 53 06	61	102
3C 196	A	08 13 36.22	+48 13 02.5	89	109
3C 208	A	08 53 08.57	+13 52 54.3	20	33
3C 216	A	09 09 33.50	+42 53 48.3	47	86
3C 234	A	10 01 48.69	+28 47 07.3	20	60
3C 254	A	11 14 38.02	+40 37 17.6	30	93
3C 268.1	A	12 00 22.55	+73 00 48.6	22	50
3C 280	A	12 56 57.16	+47 20 21.7	28	47
3C 286	A	13 31 08.28	+30 30 32.96	29	55
3C 295	A	14 11 20.24	+52 12 06.6	112	107
3C 298	A	14 19 08.18	+06 28 34.80	93	112
3C 309.1	A	14 59 08.39	+71 40 20.6	32	41
3C 330	A	16 09 36.56	+65 56 43.3	18	29
3C 368.0	B	18 05 06.60	+11 01 31.3	28	90
3C 380	A	18 29 31.78	+48 44 46.16	80	124
3C 388	B	18 44 02.38	+45 33 29.62	15	69
3C 394	B	18 59 23.64	+12 59 08.4	20	39
3C 409	A	20 14 27.62	+23 34 55.8	85	117
3C 427.1	B	21 04 07.89	+76 33 09.7	34	81
3C 438	B	21 55 52.23	+38 00 27.9	42	101

Note. — 66 MHz flux densities in this table were from the first LWA Swarm Calibrator Survey and used the calibration framework described here **?**. Flux values are not robustly calibrated, but will be updated after the next survey. Quality factors indicate $\geq 98\%$ (A) and $\geq 95\%$ (B) fringe fitting success fraction.

and 1024 channels ($\sim$ 19 kHz/ch) across the 19.6 MHz bandwidth tuning. This high time resolution is good for rejecting narrow-band and sporadic RFI, and Time average smearing is not an issue for integration times less than 15 seconds. Bandwidth smearing is a more significant issue even at the minimum suggested frequency resolution of 512 ($\sim$ 0.04 MHz/ch). While it is possible to use finer frequency resolution than recommended here, computation times will increase significantly with channel resolution scaling.

The observing files themselves should be constructed using the LWA Software Library SwarmGUI tool from the session_schedules repository. You can further use the search functionality in the GUI to help with finding calibration sources beyond those provided in Table 1. To provide an example, if you wanted to image the source 3C 41 (01h26m44.3s, +33d13m11.1s), you might pick the nearby strong calibrator 3C48 (01h37m41.3s, +33d09m35.1s), and use the closer, but fainter 4C 32.07 (01h28m00.5s, +32d44m29.2s) as a secondary calibrator (11 Jy at 74 MHz) for phase-only corrections.

Table 2. LWA-NM Interferometry Ampl. Coeffs after 8/6/24

Antenna	Tuning1	Tuning2
Linear (XX/YY)		
51 (LWA1)	20	33
52 (LWA-SV)	55	67
53 (LWA-NA)	111	110
Circular (RR/LL)		
51 (LWA1)	16	25
52 (LWA-SV)	42	50
53 (LWA-NA)	95	95

Note. — Amplitude coefficients used to calibrate LWA Swarm Interferometry runs. Using only 3 stations we cannot self-calibrate for amplitude errors, instead, we use this fixed scale to help normalize the amplitudes for each station. As more Swarm stations come online, this set may become obsolete. Scale is referenced to 110 Jy for 3C298 at 65 MHz, for observing in the 45-84 MHz band.

Calibration Steps

The following are instructions for basic calibration of LWA Swarm Interferometry observations. Individual steps are named after the primary AIPS task used for that particular set of reduction, and each will have to be manually configured according to the brief here. For each task, we identify important input parameters that need to be adjusted to appropriately apply the calibration for LWA observations. These inputs are listed immediately following the step/task name. **Users are encouraged to explicitly pay close attention to the adverbs before running commands to avoid making mistakes and to check their work after each step using LISTR and POSSM.** Try to get in the habit of checking your inputs using 'inp' before running each step, paying special attention to filenames and version number. Use 'uc', 'mc', and the 'getn #' commands to more safely input and output your data using tasks.

For any steps where we have defined one of the sources as '*YourCal*', you would replace the field with the name of the primary calibrator used in the observation as it appears in AIPS. *For example, If I have observed the calibrator source 3C380 during an observation, I would replace '*YourCal*' with '3C380'.* In this guide, quotation marks are strictly used for the inputs so the software knows the input is a string. AIPS may complain or things could go wrong if these are forgotten. Sometimes we also use the equal sign (=) to indicate values when variables are set to a given value, but they are not strictly required in most cases when working in the terminal(For example, typing *docal=-1* is equivalent to *docal -1*.) There are many aspects to AIPS that have redundancy, such as this equal sign example, so pay attention and reference the AIPS help pages often.

Don't give up! Ask questions! You got this!

AIPS Calibration Instructions:

Loading in your data

1. **FITLD**: **DATAIN '*filehandle*.FITS_', outname '*your choice*', CLINT=10/60, ncount=*value***. Set input using new observation files and be sure to assign it a new name (otherwise this will try to concatenate observations). Setting CLINT will give us 10 second entries in the CL table, and remember to reset the ncount for the number of data files produced by the LWA Correlator for your observation.

   If there is a BP table created by FITLD you will want to delete that using:
   >>> inext 'bp'; invers 0; extdest;

2. **LISTR**: Use **optype 'SCAN'** to show the observed times.

   LISTR is also used with the optype 'GAIN' to view coefficients saved into the SN and CL tables. This can be done by using optype 'GAIN', inext='CL' or 'SN', invers=*table_version*, and changing dparm(1) to the desired value according to the description in the inp menu.

Removing the Bulk Delay Offset

For these steps, use LWA1 for the reference antenna. This means **refant=1** (or for data before October 2024, **refant=51**).

3. **FRING**: **calsour='*YourCal*' '', timer=*choose 2 min from a scan*, docal -1, doband -1, solint 2, aparm(6)=2, dparm 1 8000 800 1, snver 0**. The rest are pretty much defaults (zeros or blank). Remember here to pick a scan in the middle of the observation with our fringe-fitting calibrator source, somewhere that the rates look low and the SNR is high as the task runs. This step captures the large delay offset for each baseline, using the brightest source to find a bulk value. Later, we will make a fine correction to these solutions.

   After running, then use 'save clocks'. You can get a head start on inputs by invoking 'get clocks' (but only if you previously had the foresight to 'save clocks' after this step). If you don't get solutions for all antennas then try another scan or calibrator. You might also try a larger delay window. If the delay is beyond 10,000 nsec then consider asking for recorrelation.

4. **SNCOR**: **stokes ' ', bif,eif = 0, timer 0, antennas 0, snver = 1, opcode 'mula', sncorprm 10 0**. To increase the amplitude of our data for easier viewing in plots, we apply this first stage of amplification with a factor of 10. This scaling will compound with later amplitude normalization, so it is important to include this step to reach the appropriate flux scale. *Do not apply this 10x multiplier to VLA antennas in eLWA runs*

5. **CLCAL**: **sources=' ', calsour=' ', timer 0, opcode='calp', snver 2, invers 2, gainver=1; gainuse=2, 2pt interpolation**. Here we are applying the bulk fringe fit offsets acquired in the FRING step and the 10x from SNCOR to a single calibration table.

Next we fit the fine geometric delay corrections to the bulk offset already applied.

6. **FRING**: **calsour='*YourCal*' , timer 0, docalib 1, gainuse 2, solint 2, aparm(6)=2, dparm 1 2000 200 1 (use smaller search window), snver 3**. Alternatively run on each calibrator source making sure output all goes into the same SN table (leaving snver 3 for all sources will accomplish this). This step imposes our Fringe solutions from clcal Table 2 back onto the input sources and removing the bulk offsets in the data. The remaining residuals will be fit in this step and are due to small inaccuracies geometry and ionospheric effects. For each source you should attempt to fringe fit on it's own, assigning calsour to each target in your observation and monitor the successful solutions reported at the end of FRING. Ideally you do not want to self-calibrate sources that have a poor fringe fit solution rate, instead try to iterpolate the solutions in the following step.

7. **CLCAL**: **sources=' ', calsour=' ', snver 3, invers 3, gainver 2, gainuse 3**. Table 2 here should have all of those bulk offsets to apply onto the rest of our calibrators and targets. If each source had a satisfactory fringe fit sucess rate, then use **interp 'self'** to not interpolate solutions between

sources, only onto themselves. If one or more sources had poor success rate and needs to have solutions transfered, then change calsour to the name of your calibrator and set to **interp '2pt'**.

8. **LISTR**: **optype 'GAIN', inext 'CL', invers 3, dparm #**. At this point it is a good idea to do a LISTR of your CL table 3 to make sure that all calibrators and targets have amplitudes of 10 (**dparm 0**) and delays for all antennas and times (**dparm 6 0**).

Next we are going to do some quick and dirty rfi flagging. Using POSSM and making a cross power spectrum on a short sequence of data we inspect the band using bchan/echan. If there is RFI we can excise it using UVFLG, remember to double check after in possm too.

9. **POSSM**: **timer=choose 2 minutes, docal=1, gainuse=3, aparm 0, bparm 0**. This will make several PL (plot) files for you to inspect, plotting PL file number # with the following:
   >>> plver #; go tvpl;

   If there are any RFI spikes in the band you can use the task UVFLG to select which IF, Baseline, and Frequency channels to mask. You can also use the SPFLG tool to edit manually in the AIPS TV window. This will write to a flag table (FG) that you can use for future tasks that ask for an FG table. You can use this step several times for a single FG table as long as you pay attention to the OUTFGVER being written. We have a lot of flexibility when flagging in difmap later, so the most important things to flag here is emission that will distort the bandpass spectrum in calibration.

Bandpass Fitting

10. **BPASS**: **calsour='*YourCal*', timer 0, docalib 1, gainuse 3, flagver 1, solint -1, soltyp='L1R', bpassprm(10) 3, doscale=-1**. This will perform the bandpass calibration on your observation.

11. **POSSM**: **bpver=1, aparm(8)=2** to plot the bandpass. Again, *plver #* to choose PL table, *go tvpl* to view. Make sure bandpass for all antennas looks smooth. Should roll off gently at both ends. If you see spikes then use UVFLG to get rid of bad ant/chan/pol combinations and make a new BP table with the updated flagging. Pay attention to BP versions if you need to iterate, and **use the final BP table in the following step for bpver**.

12. **SPLAT**: **sources=' ', bchan=81, echan=961, docalib=1, gainuse=3, doband 1, bpver #, outname=inname, outcl 'SPLAT', outseq=0, aparm(1)=3, channel=22, chinc=22, solint 0**. This is going to average our 1024 frequency channels into 40× $\sim$ 1MHZ channels. Using the calibration in CL table 3 and your best BP table, in this step we lock in the timing corrections to our interferometry data.

After this splat is where we will put in the coefficients that we have solved for to normalize amplitudes to a reference level using observations of 3C196. To do this we used the following steps:

13. **CALIB**: **calsour='*YourCal*', timer = 2 minutes only, docalib -1, doband=-1, solint 0.5, aparm 0, aparm(9) 1, cparm 0, solmode='P', snver 1**. We will keep this bad solution, don't panic, but do make sure that there are entries in the SN table for all antennas and polarizations.

14. **SNCOR**: **bif/eif = #, timer = 0, antenna=# 0, opcode 'mula', sncorprm=*value* 0**. Here you have to run through antennas 1, 2 and 3, and IFs 1 and 2 so you will make 6 new SN tables. The values come from the table. Make sure you increment SNVER every time you run it. Be sure to run LISTR with aparm 0 to make sure that your final SN table has the right values for every antenna and IF. For example, the first call of this would apply (linear) coefficients to LWA1 using: *task 'sncor'; bif 1; eif 1; anten 1; snver 1; sncorprm 20 0; go sncor;*. And so on, incrementing through all values in the table.

15. **CLCAL**: **sources=' ', calsour=' ',interp='2pt', snver 7, gainver 1, gainuse 2, inclass 'SPLAT'**. Assuming you have successfully populated the final SN table with all coefficients, this step helps to normalize the amplitudes across all baselines (as best as we can without access to amplitude selfcal).

16. **LISTR** **optype ‘gain’, inext ’CL’, invers 2, dparm 0**. Make sure that the desired values got placed in the CL table for each source/antenna/IF.

NOTE: As an alternative to steps 13-16 you can use SWCAL(N) where N is the catalog number of the SPLAT file used in step 14. To use it you first have to type in the terminal: vers=‘runfil’, then type “RUN SWCAL”. This will print out the manual steps described above. Calling SWCAL(N) on the catalog number you would like to amplitude scale, N, will perform the above calibration table steps.

17. **SPLAT**: **bchan=1, echan=0, docalib=1, gainuse 2; doband=-1, outname=inname, outcl=’SPLAT’, oseq=0, aparm=0, chinc=1, channel 1; solint 0**. Again here, we are locking in the amplitude scaling using a SPLAT file.

18. **MORIF**: **bif=1, eif=0, npiece=20, outname=inname, outcl=’MORIF’**. Here we will split the observation into more intermediate frequencies instead of many channels which is helpful when imaging the data.

19. **SPLIT**: **sources=‘SrcName’, aparm 2 0, nchav=0, chinc=0, bchan=0, echan=0, gainuse 1, outcl=’SPLIT’**. This task is used to separate single sources from multi-source uv data, so you will change ‘SrcName’ and write a .SPLIT file for each source.

20. **FITTP**: **dataout ‘HOME:*filename*.UVF** (for your home directory). Save the split files out to your machine, changing dataout to where you want to save each file to. You did it!

References

Dowell, J., Wood, D., Stovall, K., et al. 2012, The Long Wavelength Array Software Library, Journal of Astronomical Instrumentation, 01, 1250006, doi: `10.1142/S2251171712500067`

Taylor, C. A., Dowell, J., Taylor, G. B., et al. 2025, Design and Commissioning of an LWA Swarm Station: The Long Wavelength Array – North Arm, Journal of Astronomical Instrumentation, 14, 2550003, doi: `10.1142/S2251171725500035`

Taylor, G. B., Ellingson, S. W., Kassim, N. E., et al. 2012, First Light for the First Station of the Long Wavelength Array, arXiv. `http://arxiv.org/abs/1206.6733`