Practical 2: Make a VLA interferometric image

**Starting data: Raw imaging data from VLA.**

**Objective: Reconstruct the sky image**

This pipeline constitutes of ***three*** main processes:

1. Flagging and Demixing
2. Calibration
3. Imaging

We have finished the first part of the practical and this exercise will be focussed on the rest two.

*This is the minimum we will try to achieve within the first practical*

**Few tips before we start:**

* Fix an output file header which you can consistently use in the whole practical.
For example if the input visibility file name in our case is ‘3Cw91\_file.ms’ we can say all gaintables and figures should be saved with a header

‘3Cw91’+ ‘plot/gaintable\_information’+ ‘corresponding\_extension’

* Field of the amplitude calibrator
* Field of the phase calibrator if used then polarization calibrator as well

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# **Part 4 - calibration**

Post imaging if there are no calibrations, we might end up with an image which has many artefacts. These artefacts can be like side lobes, grating and various error patterns and

in order to obtain a clean image we need to correct for various effects.

The calibration equation from Michael’s lecture :

## $\hat{V}\_{ij }(t)= G\_{i} (t)G^{\*}\_{j}(t) V^{true}\_{ij}+E\_{ij}(t)+η\_{ij}(t)$

Where, $\hat{V}\_{ij }$is the observed complex visibility,

 $G\_{ij }$is the complex calibration term which we will compute.

 $V\_{ij }$is the true visibility measured between antennae i and j ,

 $E\_{ij }$is the correlator offset

 $η\_{ij}$ is the noise

We will now look into every effect and corrections thus required due to them this will help us in obtaining the term $G\_{ij } $. We will then apply all these calibrations or correction at the end.

## Antenna Position

1. State why and how do you think errors in antenna position can introduce an error in imaging? If the change in each position $(Δx\_{i}=0.1 m ,$$Δy\_{i }= 0.1 m$) for the Westerbork Telescope’s simulation Part 1 in the last excercise *‘Simulate your own interferometer’* , open a new python notebook and in it obtain the new sky brightness image and copare it with the one from previous excercise. (~ref: slide 9 Lec. 7)
2. Now, to correct for antenna position errors we will use *‘gencal’* task in CASA which generates a table of correction values manually and we can then apply these to the data.
We pass the options caltype = ‘antpos’, if it’s VLA type antenna position correction in VLA’s frame we do caltype = *‘antposvla’.* In CASA type:
gencal(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',caltable='3c391\_ctm\_mosaic\_10s\_spw0.antpos',caltype='antpos',spw="",antenna="",pol="",parameter=[])

1. Please refer, <http://casaguides.nrao.edu/index.php?title=Gencal> and find out what the various options you have provided do. List them here.
2. This will generate a caltable with correction values that you can view in log. Here, study the table carefully, find out a) what the different fields stand for? b) minimal and maximal values for offsets?

##  b. Flux Density calibration

The true flux density can be affected by the presence of noise and thus to obtain it we need to correct for system noise $T\_{sys}$ or System Equivalent Flux Density(SEFD). This is done by using a model source as a flux calibrator i.e since we know the observed flux density for the model source we can scale the visibilities with visibilities for this source to get the flux density scale and arrive at true flux.

1. Various model sources are available and these have in turn been calculated by using 3C295 as the primary calibrator. You can see which are the available models through following command:
setjy(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms', listmodels=T)
Setjy will list all the available models \*.mod and the images therefore given by extension \*.im.
2. Refer to the listobs output in the last excercise, and here figure out the model thats is used by comparing with the setjy outputs in the last step
3. You can try different setjy options from: <http://casa.nrao.edu/docs/TaskRef/setjy-task.html>
After figuring out the model used, we need to find the amplitude calibrator that was used in the observation. Refer to setjy link above and cross correlate with fields observed in listobs.
4. Now, try the following command :setjy(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',field='ampl\_calib\_name',standard='Perley-Butler 2010',model= ‘model\_name.im',usescratch=False,scalebychan=True,spw='')
5. Study the output of this:

	1. find out what is the flux density for channel 0 for every Stoke’s parameter?
	2. Find out which spectral window is used? For this window an output of scaling values for every channel corresponding to the Stoke’s parameter is given. Here, what is the maximum and minimum flux density scale ?
	3. Find the phase offset of image w.r.t amplitude calibrator.

## c. Phase Calibration

Tracking calibrator sources at regular intervals (~10 mins) reveals a wealth of information particularly the phase and gain tracking for an instrument and studying jumps in phases, atmospheric and ionospheric phase variations. These gains and variations also depend on the frequency and configuration used. Obtaining these gains and phase variations and calibrating for initial phase can help in improving data quality.

1. Refer to the calibrator’s manual for VLA and list what are the conditions for a good phase calibrator source.
<https://science.nrao.edu/facilities/vla/docs/manuals/cal/referencemanual-all-pages>
2. To calibrate for the phase using n number of source calibrators type the following command in CASA. Here the n calibrators fields can again be checked from listobs.:
gaincal(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',caltable='o/p\_caltable.G0all', field='the field numbers for n calibrators for example --’0,1,2’ ', refant='reference antenna number obtained from plotants earlier', spw='0:27~36', gaintype='G', calmode='p', solint='int', minsnr=5, gaintable=['gaintable\_name.antpos'])

If you don’t want to use any gain table type option as = ‘ ‘(none);
Use the following documentation to study options for gaincal and understand them.<http://casa.nrao.edu/docs/TaskRef/gaincal-task.html>
3. When you run the above command see what is the flagging SNR.
4. To see what is going on do the following :
plotcal(caltable='o/p\_caltable\_from\_prev\_command.G0all',xaxis='time',yaxis='phase', poln='R',iteration='antenna',plotrange=[-1,-1,-180,180])
This command loops over every antenna’s r polarization and plots the gain phases. To see various antennas just press next.
5. Check if for any antennas instead of a smooth variation of phase gains you see sudden jumps. These will look like presence of multiple states.
Use command:
plotcal(caltable='o/p\_caltable\_from\_prev\_command.G0all',xaxis='time',yaxis='phase', antenna=’antenna name’ ,poln='R', iteration='antenna', plotrange=[-1,-1,-180,180], figfile='plotcal\_name\_for\_given\_antenna.png’')
6. We can’t use these antennas to calibrate and therefore it is wise to remove them.
flagdata(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms', flagbackup=T, mode='manual', antenna = 'antenna\_name\_to\_be\_flagged')
7. Repeat the above three steps for L polarization.
8. Now, run the iteration command again as given in 3 see what happens to phase gains for antennas you flagged?
9. Now, after we have flagged the data,
gaincal(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms', caltable='only\_for\_the\_bandpass.G0', field='ampl\_calib\_name', refant='reference antenna number obtained from plotants earlier', spw='0:27~36', calmode='p', solint='int', minsnr=5, gaintable=['gaintable\_name.antpos'])
10. Inspect the o/p of above with plotcal as we did in step 3 , but add the options of field and time range to it.

## d. Delay Calibration

This calibration helps in removing the phase ramp across frequency channel in every spectral window. This is an antenna based local delay obtained per spectral window per polarization.

1. To obtain the calibration table for this delay using CASA, we reuse the *‘gaincal task’* which has a K gain that can yield relative delay for each antenna w.r.t a reference antenna. The command to do it is gaincal(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',caltable='o/p\_caltable.K0', field='ampl\_calbr', refant='reference antenna number obtained from plotants earlier', spw='0:5~58', gaintype='K', solint='inf', combine='scan', minsnr=5, gaintable=['gaintable\_name.antpos','gaintable\_name.G0'])
2. We can plot these delays for each antenna using :
plotcal(caltable='O/P caltable.K0',xaxis='antenna',yaxis='delay', figfile='plotcal\_3c391-K0-delay.png')

##  e.Bandpass Calibration

 The process of correcting for the frequency dependent gains is the bandpass calibration.

Bandpass amplitude errors are similar to the changes in line structure with frequency and the bandpass phase errors may give false positional offsets of spectral features. Therefore, especially for weak broad features the bandpass calibration becomes significant.

1. Find out if a synthesized beam size is given what will be the positional uncertainty for spectral feature?
2. Now, to form a bandpass, in CASA do: bandpass(vis='3c391\_ctm\_mosaic\_10s\_spw0ms',caltable='O/P\_caltable.B0',field='Ampl\_calib',spw='',refant='reference antenna number obtained from plotants earlier', solnorm=True, combine='scan', solint='inf', bandtype='B', gaintable=['gaintable\_name.antpos', 'gaintable\_name.G0', 'gaintable\_name.K0'])
3. Now using plotcal we can plot four plots:
	1. Ampl - R polarization, L polarization
	2. Phase - R polarization , L polarization

 Command to do it is :

 plotcal(caltable= 'O/P\_caltable.B0',poln='L/R as needed', xaxis='chan',

yaxis='amp/phase as needed', field= 'Ampl\_calib', subplot=221,iteration='antenna',figfile='O/P\_figname\_with\_polarization\_mention.png')

##  f. Gain Calibration

 Next, we will need to calculate the complex antenna gains by using a standard flux density calibrator.

For this pick up a phase calibrator close to the observing target of interest to remove the atmospheric effects introduced by difference in the line of sight. Obtaining the relative gains in amplitude in the phase and amplitude can be done as follows:

1. In CASA to obtain complex amplitude gains do the follwing:
gaincal(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',caltable='O/P\_caltable\_name.G1', field='Ampl\_calib',spw='0:5~58', solint='inf', refant=’reference antenna number obtained from plotants earlier', gaintype='G',calmode='ap',solnorm=F,gaintable=['gaintable.antpos','gaintable.K0', 'gaintable.B0'])
2. Now, we pick up our selected phase calibrator and using it we get the complex gain for the direction in the sky. We add the calibrations from this to the caltable in previous step by selcting append = True.
gaincal(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',caltable='O/P\_caltable\_name.G1', field='phase\_calib',spw='0:5~58', solint='inf', refant=’reference antenna number obtained from plotants earlier', gaintype='G',calmode='ap',solnorm=F,gaintable=['gaintable.antpos','gaintable.K0', 'gaintable.B0'], append = True)
3. Now, to get the polarization calibration repeat step 2 by changing the field to the polarization calibrator name.
4. Lastly, plot the phase and amplitude by selecting ‘amp’/’phase’ for L and R polarization using following command : plotcal(caltable='O/P\_caltable.G1',xaxis='time',yaxis='amp’ or ‘phase',poln='L’ or ‘R’, plotrange=[-1,-1,-180,180],figfile='O/P\_figname-amp/phase-L/R.png')

##  g. Scaling the amplitude gains

We knew the primary amplitude calibrator’s flux density but for the phase calibrator and the polarization calibrator used in last step we need to compute it. To find flux density of these secondary calibrators we assume that the mean gain amplitudes of the primary calibrator remain same for the phase calibrator. Using this and a task called ***‘fluxscale’*** we can find out the calibration table for amplitudes scaled for the secondary calibrator.

1. To check out how flixcal works see:
http://casa.nrao.edu/docs/TaskRef/fluxscale-task.html
2. In CASA to get the calibration table do:
myscale = fluxscale(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',caltable='O/P\_caltable\_obtained from gain calibration (last step).G1', fluxtable='O/P\_caltable.fluxscale1', reference=['Ampl\_calib'], transfer=['phase\_calib\_field ’, ‘Polarization\_calib\_field'], incremental=False)
3. Analyze the O/P in the CASA logger and see for a given secondary calibrator field name what flux density scale do you obtain. If possible also note down the Signal to noise ratio (SNR) printed for given calibrator field.
4. Use VLA calibrator manual to see if the flux density you obtained for the secondary calibrators look fine. To do this check here:

<http://www.vla.nrao.edu/astro/calib/manual/csource.html>

1. Plot the rescaled amplitudes for R and L polarizations using the following command and check how the amlitude gain factors vary across sources compared to image in section f: plotcal(caltable='O/P\_caltable\_from\_step\_1.fluxscale1',xaxis='time',yaxis='amp',poln='R',figfile='O/P\_fig\_name-fluxscale1-amp-R.png')

Now, if you have all calibration solutions ready we can apply these calibrations and then image!!!

## Applying Calibrations

1. We should have applycal task in the CASA. Using this task we will first apply calibrations to each of the calibrator by merely changing the field name in following command to the given calibrators field name:
applycal(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',field='calib\_field\_name',gaintable=['O/P\_caltable.antpos','O/P\_caltable.fluxscale1','O/P\_caltable.K0','O/P\_caltable.B0'],gainfield=['','field\_name','','','','',''], interp=['','nearest','','','','',''], calwt=[False], parang=False)
2. **A**pply the calibration to the target fields in the mosaic, linearly interpolating the gain solutions from the secondary calibrator. In this case however, we want to apply the amplitude and phase gains derived from the secondary calibrator that is close to the target source on the sky. As we assume that the gains are very similar for these two. If the weather is well behaved it is a reasonable approximation. This will hopefully provide a good calibration with very small inaccuracies. So, the command for it is similar to the one used for calibrator with small changes:
applycal(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms', field='2~8', gaintable=['O/P\_caltable.antpos', 'O/P\_caltable.fluxscale1', 'O/P\_caltable.K0', 'O/P\_caltable.B0'],gainfield=['','phase\_calibrator','','','','',''], interp=['','linear','','','','',''],
calwt=[False],parang=False)
3. ***Now,*** that the visibilities are well calibrated, it’s a great idea to inspect them. Make standard plots again with plotcal.
*#IN CASA*plotms(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',field='0',correlation='',timerange='08:02:00~08:17:00',antenna='',avgtime='60s',xaxis='channel',yaxis='amp',ydatacolumn='corrected',plotfile='fig\_filename-fld0-corrected-amp.png')

plotms(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',field='0',correlation='',timerange='08:02:00~08:17:00',antenna='',avgtime='60s',xaxis='channel',yaxis= ‘phase',ydatacolumn='corrected',plotfile='fig\_filename-fld0-corrected-phase.png')

plotms(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',field='1',correlation='RR,LL',timerange='08:02:00~08:17:00',antenna='',avgtime='60s',xaxis='channel',yaxis='amp',ydatacolumn='corrected',plotfile='fig\_filename-fld1-corrected-amp.png')

plotms(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',field='1',correlation='RR,LL',timerange='08:02:00~08:17:00',antenna='',avgtime='60s',xaxis='channel',yaxis='phase',ydatacolumn='corrected',plotfile='fig\_filename-fld1-corrected-phase.png')
4. Another nice display is the amplitude vs. phase, this should show a nice ball of the visibilities centered around zero phase(with some scatter). To do this:
plotms(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',field='1',correlation='RR,LL',timerange='',antenna='',avgtime='60s',
xaxis='phase',xdatacolumn='corrected',yaxis='amp',ydatacolumn='corrected',plotrange=[-180,180,0,3],coloraxis='corr',plotfile='fig\_name-fld1-corrected-ampvsphase.png')
5. **Now that the calibration has been applied** to the target data, we can split off the science targets, creating a new, calibrated measurement set containing all the target fields.

split(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',outputvis='3c391\_ctm\_mosaic\_10s\_spw0\_output.ms', datacolumn='corrected',field='2~8')

**FINALLY, let’s move to imaging!!**

# **Part -5 - IMAGING Post-Calibration**

The image or sky brightness relation is a Fourier transform of the visibility. Refer lecture

1. CASA as we saw earlier has the **‘clean’** task, which helps in interactively cleaning the image and saving the output files with different headers which can subsequently be viewed. We will reuse this command to interactively clean the visibility files and output the image.
2. The command to do so is: clean(vis='3c391\_ctm\_mosaic\_10s\_spw0.ms',imagename='O/P\_image\_name-initial', field='',spw='', mode='mfs', niter=5000, gain=0.1, threshold='1.0mJy', psfmode='clark', imagermode='mosaic', ftmachine='mosaic', multiscale=[0], interactive=True, imsize=[480,480], cell=['2.5arcsec','2.5arcsec'], stokes='I', weighting='briggs',robust=0.5,usescratch=False)
3. To see this image do :
viewer('O/P\_image\_name.image')
What do you observe now compare it with pre calibration image list changes?