Radio Astronomy

Prof. Abhirup Datta

Department of Astronomy, Astrophysics, and Space Engineering

Indian Institute of Technology Indore

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Introduction to CASA

Hello everyone I am Swarna Chatterjee and today I will introduce you to common astronomy software application or CASA. So I am doing my PhD currently in IIT, Indore under Prof. Abhirup Datta and I am also a fellow colleague of UTA Harsha Avinash Tanti. So during my PhD I have mainly focused in reducing radio astronomical data sets using CASA. So today I will give you a brief introduction to how to use CASA for interferometric data reduction and imaging. Now I will give a brief overview of what the data reduction steps include.

So after any telescopic observation we receive raw data sets from the telescope facility. But this raw data along with the information of any astronomical object that we targeted to observe it also has some unwanted or bad data which we need to identify and then remove or flag from this raw data. So we need to identify them and these bad data so called bad data are called as RFI or radio frequency interference in interferometric observations. So where does these RFIs come from? Well it can come from the satellites in working in this frequency range of observation, several mobile towers like for GMRT observations the geo network, the Airtel network they are RFI for the observe GMRT observation in some bands or several instrumental transmission system these perform as RFI which we need to identify and immediately remove from our data.

Then we proceed towards the calibration where we correct for several other effects that can affect our scientific outcome. Then we receive the initial image of our targeted observation but then again we need to do a calibration which is called as self calibration which I will again discuss later in detail and then finally we receive a image which can be used for performing science. So here this is a link from where you can download the CASA and there it is also described how to install it in your system and the installation is very simple you just need to go to this website download the preferred version of CASA you want to install and then give the path in your system. Here is a tutorial by VLA which you can use to learn CASA and this includes several basic steps which I also will show you. Now these are some of the data archives from where you can easily get any telescopic observation.

This is the VLA archive and if you go to this archive so here you will get several observations that VLA has performed throughout in ALMA archives same you will get for several ALMA observations data and this is the GMRT archive. So you can go to these archives give a input that this observation you need to download and then you can download the observation and then proceed with the next steps. After downloading the data from any of the previously mentioned archive we will receive a FITZ file. So to analyze the data or visualize the data understand what are the ARRI files we must convert the FITZ file into a visibility file or the CASA measurement set. For that we will use the import UV FITZ task in CASA.

So we will open up the we will write CASA in terminal which will open up python interface and then we will write their import UV FITZ and FITZ file name we will give whatever our FITZ file name is that we received from the archive for my case it is given as obs.fitz and then i have given a visibility file name or this fizz as obs.ms. So this is your choice that you can give whatever you wish to give and please write also .ms as extension after that.

Now to visualize the data we will initially perform a list of task. So we will write in the terminal list of and then give this visibility name and we will visualize the observation. Here we have taken observation of able 1914 cluster which was observed with GMRT. So i basically know that our target is A1914 but if you dont know there are ways to find out which is your calibrators and which is your target. How to find that out? So flux calibrator is usually observed in the beginning of any observation or in the end of any observation or both the times.

Here we can see 3C286 was observed as our flux calibrator. It is generally observed for 10 to 15 minutes. Now we can see it was observed from 12 hours 14 minutes to 12 hours 24 minutes that means basically 10 minutes it was observed in the beginning. Again we see that it was observed in the end of the observation. Then something was observed named 1331305.

So this is our phase calibrator. So idea to observe phase calibrator is initially, alternatively with target. So we will observe phase calibrator once then we will proceed with target observation. Again we will observe phase calibrator, again target, again phase calibrator, again target. And we can perform during observation we can perform this loop whatever is needed for the observation scientifically or technically.

So here we can see there has been performed 3 loops of this phase. 1, 2, 3 and 4 sorry 4 loops of this phase calibrator and target observation. And at the end again flux calibrator was observed. So I have marked this 1331 plus 305 which was observed as phase calibrator and the target. Now how to identify which was phase and which was phase calibrator and which was target.In all this loop so phase calibrator will be obviously observed for lesser time. That is here it was observed from 1227 to 1232 basically 5 minutes. While the target will be observed for longer time because we need to do science with that source and there are specific scientific and technical requirements that is required for this observation. So we keep that in mind and then take our observation. So target is obviously observed for more time.
As we can see 1914 was observed from 1235 to 1317. That is much more time than the observation period of our phase calibrator which was just 5 minutes. Here another thing I will mention that is the integration time. So integration time is basically the time period for which the data has been averaged during performing the observation and that is termed as integration time. One more thing you need to note down from this list of that is the field IDs.

So here you can see that 3C286 has been given the field ID 0 and then 1331 plus 305 that is our phase calibrator has been given the field ID of 1 and A1114 which is our target has been given the field ID 2 and these field IDs you need to remember while performing the data reduction. Also from list of you can see the antenna IDs which is not shown here but while you will perform the task list of you will also see the several antenna IDs which will be shown down and you can mark the antenna names from that. Now as I have mentioned how the observation is taken so now I will tell what are the calibrators and why these are needed for any telescopic interferometric observations. For any radio interferometric observations we need to observe a few calibrator sources. The basic calibrator source which must be flux calibrator and phase calibrator.

Flux calibrator is generally an isolated compact source situated outside our field of view of interest and this source is with a known flux density. This is needed for estimating the flux density of our phase calibrator and target further. So after from this flux density calibrator we bootstrap the flux density for our sources. There are 3 standard flux calibrators that are 3C48, 3C147 and 3C286. As we have already seen, for our observation 3C286 was chosen as a flux calibrator.

So depending on which of these 3 sources are above the horizon during our observing session the flux calibrator is chosen. This flux calibrator is also used as band pass calibrator often. Another target calibrator is the phase calibrator. Phase calibrator is needed to account for the various gain variations or ionospheric phase variations that occurs during the observation session. For choice of good phase calibrator is always nearby the target which we are planning to observe and its very good if the phase calibrator is situated in less than 10 degree of our target source.

List of standard phase calibrators can be found in this given website of VLA calibrator list. Now for visualization we will do a few basic plots and the basic plots will be amplitude vs channel, time and UV wave. So here we will perform a plot image task in the term CASA. We will give our measurement set name which is visibility vis equals to obs.ms then we want to see how the plot looks for the flux calibrator.

We know that it had a field ID 0. So we will give field ID 0 here. Correlation we will observe both the correlation RR and LL correlation we have given both. Here we want to see for all antennas so I have keep this antenna space blank but if you want to observe for any specific antenna you can identify the antenna name from the list of and then give the antenna name in this space. Spectral window so for VLA there are 16 spectral windows for wideband data for GMRT there is only one spectral window and as our data is from GMRT so here i have not given any spectral window and I want to see how the plot looks for all the spectral windows.

So this also i have kept blank. The X axis we can change as a time channel or UV wave as i have mentioned here and Y axis i have kept at amplitude. Now after the plots we have to look in the plots for any anomalies, any sudden change in amplitude over a small range and also we need to identify any non working antennas. So how to identify the non working antennas any non working antennas will show very small amplitude compare to the other antennas and so we can visualize and if we identify any non working antennas from that it should be carefully visualized and then we can remove it or flag it from the data. So after visualization we will proceed with the flagging.We need to flag the initial few seconds of each scan before proceeding further. So for that we will use the task flag data. So here i have given the measurement set name again and mode i have kept as quack and quack interval is kept as 10. So this is for 10 seconds and quack mode is given as beginning or beg. If you also want to flag the last 10 seconds then you have to put this beg as end.

So there you need to put quack mode as end. Now why this initial flagging is needed because for each time of observation or the telescope changes from flux calibrator observation to phase calibrator observation or to from phase calibrator to the target observation it needs some initial time to get to set for the observation. So its always a good idea to flag the initial few seconds. Generally 10 seconds is preferable also you can flag the ending 10 seconds. Now after that we will flag any bad channels or time range or from our data after visualization with plot image.

Here i have shown a plot of the amplitude vs channel and we can see a very bright peak of amplitude here in channel 0. So we will identify the channel number and then we will manually flag it from the data. You can also as i mentioned you can also visualize for all the antennas and then if you identify any bad antenna you can flag it. For my case i have gone through this and i did not note any such antenna which was showing lesser amplitude very less amplitude compare to other antennas so i did not find it useful to flag any of the antennas. But this as you can see this channel 0 has a very bright RFIP so obviously we need to flag it.

For that we have used flag data we have kept the mode as manual because i want to take also a backup of whatever i am flagging so i have kept the flag backup true and spectral window or the channel number we have to specify with this SPW parameter. So in SPW there are two parameters that we can give the first parameter is the spectral window number as our data is from GMRT so there is only one spectral window but if your observation is from VLA then there are 16 spectral windows for VLA wideband data and if you want to flag any of the channel from any spectral window you need to give the spectral window number here and then you can give the channel number here. So for GMRT as there is only spectral window with the spectral window id is 0 i have put it as 0 and then channel number is 0 so you need to remember that if your data observation set is spreaded over 124 channels then the channel number the channel index starts from 0. So for 124 channels your last channel index will be 123. Now we are moving towards advanced flagging so in previous slide whatever i have explained was manual mode but this manual mode flagging can be very labor intensive and also very time taking.

So TF-Crop is a advanced level of flagging which works on both uncalibrated data sets which is this right now we have not done any calibration so here also we can perform TF-Crop and also after we perform the calibration then again we can perform TF-Crop on our data sets. TF-Crop carefully analyzes the data and then flags so it is less time taking affair so saves a lot of time which can be taken if we go with manual flagging mode so its always a good idea to use TF-Crop before proceeding with calibrations. So what TF-Crop does is it takes a average over the visibility amplitude over a time period then fits a robust piece polynomial function to model the base of RFI spikes then it calculates the data minus fit which gives the sigma and subtracts any point deviating from n sigma. So n sigma the value of n we can give in TF-Crop. Now i will tell you how to use this TF-Crop mode for this again we will use the flag data task so here again we will give the measurement set name and the visibility that this is ops.

ms mode last time we have kept manual but this time we are shifting the mode to TF-Crop which is the flagging mode. Now we will perform the field id here i have given 0 so when performing TF-Crop to base calibrator we will give field id as 1 and while performing TF-Crop to our target we will give field id as 2. Now i want to perform over all the antennas so this antenna space i have kept blank but if you want to perform in any specific antennas you can give the specific antenna name but its good idea to perform all antennas so it will flag any remaining RFIs from all the antennas. Now data column i have given here as data because we are performing it on uncalibrated data when we will perform TF-Crop on a calibrated data sets we can we have to give the data column as corrected one. So that time the data column should be given as corrected data column.

Now as i mentioned this n sigma so the value of n we are putting here this value of n for frequency cutoff is given as 4 while for time cutoff the value of n has been given as 3. Now this extend flags i have kept false so what extend flags does is if you keep it as true it will flag any data it has flagged for RR polarization it will also flag for LL polarization. So i choose to keep it false so RR and LL polarization will be flagged differently and any extra flagging done for any of the polarization will not be extended to the other polarization. Now action here we will visualize first so i have kept as calculate and you can see how it is flagging and with the display command where display both is gives will show both the RR and LL polarization. Now while we want to perform the flagging then we have to change this action to apply from calculate.

So now we will see what are the results after tf crop so these are two plots of amplitude verses time and amplitude verses channel i have shown the plot for antenna C08. So you can see we cannot see any of very obvious rfis in this plots and the plots look quite good so here i have shown only for antenna C08 because C08 i am going to choose as my reference antenna as well so for calibration performing calibration we need to choose a reference antenna and that antenna will be selected as reference and all the other like delay or any other calibration parameters will be calculated setting that antenna as reference antenna. So i examined that C08 had a good amplitude over time and channel so i have chosen this as reference antenna. You can visualize this plots for all the antennas and choose any of the antennas which you feel the amplitude verses time plot or amplitude verses channel plot are very good compared to other antennas you can choose that as reference antenna. Now i will proceed with the calibration so for calibration you need to do first set the flux density of the flux calibrator using this setg task so here you give the observation file name and then use a standard model using which the flux density will be set for the flux calibrator that is the field id 0.

Here i have preferred to use the standard kpfield 2012 model there are several other models and you can choose any of that model which you use to choose. Now we will proceed with the initial phase calibration so this phase calibration is needed for correction of errors induced from variable ionosphere or any electronics and this phase calibration is very much essential to average over small phase variations happening with time over the band pass. For this we will use the gain cal task in casa so we have to give a cal table name which i have given here obs.obs.g1 and the gain type for this is given as g because we need to perform this calibration in flux calibrator so field id was given as 0 and the reference antenna as i have mentioned was given as c08.

So after visually inspecting i have chosen a channel range of 27 to 36 which had a good and consistent amplitude values over channels and cal mode is kept as p because it is phase calibration and solid i have taken as 60 seconds which is on what time period this solutions will be averaged. Now after performing this gain cal task we will visualize using plotms our results so we will use again plotms but this time vis is given as obs.g1 which was our cal table so we will visualize this and we will visualize for time vs phase graph and to check the phase range in minus 180 to plus 180 degree i have set this plot range minus 180 to plus 180 and i have also given a iteration over antenna. So then we see that this phase vs time plot it is shown here for antenna c09 and we see that phase vs time plots look very good and there are no certain anomaly or phase variation over the time the phase variation over the time is not that much. Now we will calculate the delays so here we will solve for the respective delay in response of each antenna with respective to the reference antenna which is c08.

For this again we will use the gain cal task we have put now cal table as obs.g1 for delay calibration the gain type is changed to k and last time we have kept the gain type as g. Now here solving we are using as infinite because we want to see any delay antenna response over the whole observation time period so whatever your observation time period is generally obviously falls under the time period of infinite. So if you dont need to remember what was your observation time period you can just set this solving to infinite and then perform this delay calibration task. So here i have chosen to combine for all the scan as you already saw that our flux calibrator had two scans so here we are combining for the scan and we are giving the initial cal table that we observed observation.

g1 as a gain table here. Now after performing the gain cal task we will again use plot image for a visualization giving obs.k1 as base file and then x axis as antenna and y axis as delay and here we can see delay of each antennas compare to the reference antennas and we see that the antenna have a delay around 80 ns to 30 ns. Now we will proceed with band pass calibration so band pass calibration is needed for correcting the gain variation that is induced for the wide frequency range of observation and the time period. So this band pass calibration will correct for the gain variation. For this we will use the band pass task we have given the visibility name, cal table we have written as obs.

b1, solving again we have chosen as infinite we are doing for all the scans for of the flux calibrator with field id 0, reference antenna name has been given again i have chosen to combine the scan and gain tables i have used observation.g1 and observation.k1. So using this information from these gain tables it will calculate the band pass and its correct for this gain variation. So after performing band pass calibration again we will visualize using the plot image task and here are the two plots of amplitude vs channel and phase vs channel.

So we see that phase variation over the channel range which also represents the frequency range is quite consistent. So we know that the calibration we have performed was very good. We also see the amplitude decreased slightly with increasing frequency which is expected but we see that the amplitude suddenly drops after this channel of 110. So we will prefer to remove this channel after 110.

Now we will proceed with the final gain calibration. So whatever calibration task we were performing till now was on flux calibrator that means the flux calibrator also served as our band pass calibrator. But now we will perform a gain calibration on the flux calibrator and then that gain solutions we will get we will again apply to our phase calibrator. So for this again we are using the gain care task. We have now named our care table as obs.gn1 just to remember that the initial gain care table was given as obs.

g1. Now we are writing this as gn1. You can give the care table name as you prefer. So now this field id is 0 which is our flux calibrator field id. Solvent again I have chosen as 60 sec. I have given a mean SNR for performing the solutions which is given as 3 and I have given a spectral window range which I already showed you that from 5 to 110 the amplitude variation was quite consistent. So that is the spectral window range I am choosing to calculate the final gain solutions.

So again we have kept as G and calmod we have kept as AP which is amplitude plus phase. And we are giving the information from obs.

k1 and obs.b1. We are not giving the information from obs.g1 because again we are performing that same gain calibration. Now after performing this calibration task we will append whatever solutions we are getting from flux calibrator to that of the phase calibrator. So we will do this gain care task again but here in field id we have given the field id 1 that is the phase calibrator. And append also we have kept as true.

Now we will scale the flux density of phase calibrator. For that we will use the flux scale start. So here I have given this flux scale task I have used and visibility is given. Cal table we are using is obs.

gn1 that we just calculated. Flux table name I have given as obs.fcl1. So here the reference from which the flux density will be calculated is obviously our flux calibrator that has the field id 0. And we have to transfer this flux to the phase calibrator that is why I have put transfer equals to 1. So this 0 and 1 are the field id of flux and phase calibrator. Now whatever calibration solutions we have received from the calibration task we will apply those calibrations to our calibrators and check how it has worked.

For that we will use the apply care task. So here I have given the visibility file my field ids for 0 for flux calibrator for 1 for phase calibrator and then I am applying the solutions. Apply mode I have kept as cal flag street in both the cases because if we perform any flagging while performing the calibration apply mode cal flag street we consider those flagging and then apply to the solutions accordingly. Flag back up again I have kept 2 gain tables which I want to take into consideration while applying I have given which is the flux scaling table and the delay and band pass calibration table and for flux scale for flux calibrator I have given the gain field 0 for phase calibrator gain field I have given as 1 which will take the flux scaling for the phase calibrator from this ops.1 flux scale table and interpolation I have kept as nearest and nearest flag for all the calibration tables. Now after applying the calibration we will see how the our calibration has worked.

It also helps to identify any remaining rfis or any bad data in our data. So after performing the calibration we should expect the data to centrally concentrated so we see in the amplitude corrected vs channel plot there are residual bad data points and the bad data points are standing as outliers and are not concentrated in the center which is should be we get after calibration. So our flux density calibrator should have a flux density around this value of 25 but we see there are some outliers. So we will flag this using again some advanced mode flagging.

Now we will use r flag. So r flag only works on calibrated data. We can also use tfcrop as well and I already mentioned that for tfcrop you can keep the other parameters same and only the data column you need to change as corrected. So you can again use tfcrop and also use r flag on calibrated data. So what r flag does is r flag divides all the frequency and time ranges over several small small bins and then calculates the median rms per bin and then calculates sigma and then flag points deviating from a value of n sigma where again we can give the value of n as we desired and which looks for good and which gives a better result. So here I have given the value of n for time dev scale as 5 and for frick dev scale as 4 and then again I have chosen to keep extend flag as false. So this action as I already mentioned while only to visualize what the flagging will do you can keep it as calculate and when to apply the flagging result you can keep it as applied.

Now we see the results after r flag. So we see the additional outliers that were spanning in these ranges in the calibrated data are now successfully removed. This r flag was applied for flux calibrated and this same procedure should be applied for phase calibrated as well. As we have seen that after calibration and applying r flag and tf crop in the data our data sets has been mostly rfi free. Now after all the flagging is done we can expect that the remaining data is the good data. So its always a good idea to before proceeding further with the target and applying these calibration solutions to our target we clear all these calibration solutions and redo it again with the good data.

For this we will clear the first calibration solution that has been applied to our flux and phase calibrator. For that we will use the casa clear care task and we will just give our measurement set name and after that we will repeat the steps from slide 11 to slide 15. Dont forget to update the new gain table names while repeating the calibration steps. It will help you to not to overwrite the initial calibration tables and the suggested new table names should be initially we have given it as g1, k1 etc.

Now because it is the second time we are performing we can give it as obs.g2, obs.k2 etc. And after the second calibration if you again feel that you need to repeat the calibration you can again clear the calibration and then repeat these steps. Now after we are satisfied with the calibration table in the flux and phase calibration we should proceed with the imaging of the calibrators.

For that we will use the casa t-clean task. With t-clean helps to generate a image which can then be converted to a fixed image. So for performing t-clean we need to give our observation measurement set as an input here i am making an image of the flux calibrator which has the field id 0 so that has been given here. This threshold has been set to 0.01 millijansky and the n-iter is set as 10,000 iterations. So these are interconnected when we perform this task t-clean the cleaning will stop either if the n-iter that is number of iterations while performing the cleaning if there are 10,000 iterations successfully done then the cleaning will stop and generate the image otherwise if the background rms noise reaches 0.

01 millijansky then also the t-clean will stop. So these two values threshold and n-iter are interconnected whichever reaches earlier the t-clean will stop. I have given a image name as flux so it will generate a image name flux.image after the t-clean is over and this cell size i have taken as 1.5 arc second. So the basic idea is to take a cell size that will generate 5 pixels per your beam size or your resolution.So here for 317 megahertz which was our observing frequency we get a resolution around 7.7 arc second. So 1.5 arc second if we take the cell size as 1.

5 arc second that gives us around 5 pixels or 5 of the cell size per beam that is the 7.5 arc second or approximately 7.7 arc second and this is the image size that will give our final image size in terms of the cell size. I have kept here this interactive term false because i dont want to visualize this GUI after each iteration of this cleaning procedure and this weighting i have taken as uniform which reduces the side lobes best and gives the highest resolution for any cleaning process. This same procedure can be applied for the phase calibrator where we just have to input field id 1 for phase calibrator and we can check the image of the calibrator.

So here is the image of the flux calibrator. The same should be done for the phase calibrator. Now after making the flux and phase calibrator image if we see the images are good we will apply the solutions to the target which is the field 2 for that we will keep similar parameters and we have given that gain field from which we are applying the solutions is 1 here and we are applying the solutions from the phase calibrator to our target and so we will apply the solutions to our target and then we will split the data using task split. So i will describe why we needed to split the data but we are splitting using the task split and we are giving the input visibility which was our visibility that we have been using till now which is obs.ms and now after splitting we will get another output visibility file which can be given in the output viz parameter and i have named this as target.ms and then this field id is given as 2 so now it will split the target data from the rest of the dataset. Now after splitting the target data we will proceed with the self calibration of target till now whatever gain solutions were applied to the target were from the calibrators but still there will be some residual errors in amplitude and phase.

So now after this calibration we will split the target data target itself will be acting as a calibrator and we will input the gain solutions from the model itself to correct for the residual amplitude and phase error. This is an iterative process typically 3 to 4 rounds of self calibration we do we can also do more round of self calibrations as needed for final improved image. So what are the reasons for errors that are still remaining in the solutions because target and flux and phase calibrators are observed in different time span and during different time span there are different positions of this target in the sky and also the ionosphere is changing according to position in the sky. Thats why we need to correct for the residual error using target only. Self calibration includes several steps the initial step is make an image of your target for that we have used the tc lintask and after splitting the data now the field id in the target.

ms is 0 for our target because it doesn't have any additional fields so it has been changed initially in obs.ms the field id of target was 2 but now after splitting the data the field id of target will be 0 and you can also visualize it using the list of tasks on the target.ms. So then i have made an initial image of the target and while making the initial image i have kept saved model as model column.

So this model column will be further used for getting the solutions. Now after getting the image and the model column is saved in the information and the information from the model column is saved on the ms we will again perform the gain caratask on the target.ms. I have given the name to caratable as self cal1.g. Splint here i have kept as 8 minute this splint can be reduced to 4 2 and 1 minute at the end and minsnr again i have kept as 3 and gain type i have kept as g and calmod as p.

Now after that we need to apply the solutions to the target again and then this procedure need to be iterated again and again until major improvement of the image quality is achieved. So initially i have used 8 minute as splint and you can gradually lower it to 1 minute and then apply it. And you can see that the image rms also improves significantly and we reach lower rms. So here is the final image of the targeted galaxy cluster abl 1914 that i have received after my data reduction and in similar process you can image other galaxy cluster other galaxies and supernova remnants whatever we are observing in through radio telescopes.