Radio Astronomy

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Lecture 2 - Revision

So, hello everyone. I think this is the last interactive session for us and it's been a pleasure for us to be able to deliver and interact with you guys. So what we will have today, again like yesterday, what we will do, we will revise this. Yesterday I computed kind of half and more than half of the revision and the rest will be revised today. And after that, we will have some discussion and the second part, sir will take, regarding few applications and other concepts. So hello everyone.

I am Harsha Avinash Tanti, your TA for this course. Currently I am a research scholar at Department of Astronomy, Astrophysics and Space Engineering at IIT, Indore. Now I hope everyone can see the screen. As we discussed yesterday about the radio band.

And so there is a radio window due to which we can observe space in different regions. So in optical, we have optical telescope and radio band, we have radio telescopes. And for, if you want to observe other bands, we have to go out of the atmospheric boundary of the earth such that we can observe our universe in those wavelengths. Now, I will skip the slides, which we did in the last session. So we finished off with revising the observation techniques and some important formulas is using, when we are using single dish telescope, single dish telescopes.

Now since till now, means till the week five, I believe, week five, we covered some basic units in astronomy, like flux density, what is brightness temperature, then what is specific intensity, intensities, all this stuff. And addition to that, all the kind of hardware which goes into astronomy. Now when we go to, when we want to do astronomy, the first thing we need to know where the star is located at, right? To do an observation, we need to know some kind of area or area of the sky which we are observing. So for that, we need to have some kind of measurement techniques or some kind of dimensional units to represent a particular region of the sky or particular star in the sky or particular source in the sky. Okay.

So for which we have a coordinate system, just like we have a Cartesian coordinate system XYZ and mathematically we have spherical coordinate system as well as cylindrical coordinate system. And then there is something called Euclidean space. There are different kinds of coordinate systems, but in radio astronomy, we mainly use, means the most used coordinate system is equatorial coordinate system. Wherein the, say we have, this is what a general diagram of equatorial coordinate system is. So we choose a fixed point at the vernal equinox.

Vernal equinox is kind of a means if you create a circle around the sun and kind of intersect it between the equator and the pole. So that intersection is termed as vernal equinox. It occurs twice a year. When the sun crosses the celestial equator, this is the definition of vernal equinox. Now you can kind of think of this in a way like you have longitude and latitude in earth to represent any position of a user.

So in the same way, if you extend that in, extend that concept into the space, so you will have some kind of a long and lat to show where the sources are. But this longitude latitude would, we cannot extend this concept directly to space because it is earth fixed coordinate system. It changes with earth. If earth is rotating, the longitude and latitude will change for any particular source. So a new kind of coordinate system is invented equatorial coordinate system where the declination is your corresponding latitudes and your right ascension is related, is assigned with respect to the vernal equinox times.

So there are some things you should know. There are two terms in equatorial coordinate system, which is RA and DEC, right ascension and declination. RA is kind of, you can say, represents a latitude in this, sorry, longitude in this coordinate system. And it is in hours, minutes and seconds. The unit is in hours, minutes and seconds and declination is a kind of latitude in your coordinate system and represented in degree minutes and seconds.

So these are the units and now this right ascension and declination is fixed for any source, means most of the sources outside our solar system are very far away from our solar system. So that's there. So in week seven, you can find the more elaborated discussion about the right ascension and declination. Now there is something called LST. When you study any other coordinate system.

Now this LST depends upon the, and the full form of it is local side real time. So local side real time is defined as it should be zero hours when the vernal equinox is on the observer's local meridian. Now what is local meridian? Local meridian is like, say you are here and this is south and this is north. And if we join this two point like this, so this is a local meridian. Now this should be zero when we are at zero hours means like this meridian will point towards your vernal equinox point.

This point, say if you are here and if the local meridian is like this, then this is LST zero hours. Now with this, there is something termed as hour angle and this alpha is nothing but right ascension. Now these two terms, why this came into picture is the RA and deck coordinate system is defined such as it doesn't get affected by Earth's rotation. Now the Earth's rotation period, we say to 24 hours, but it's not 24 hours. It's near around four minutes less than the 24 hours because of which there is an error in the 360 degree rotation and which is accounted for in local sidereal time.

So that's why local sidereal time and local time are different because of the Earth's rotation is not completely 24 hours. So local sidereal time takes the exact hours for the Earth's rotation and based on that local sidereal time is calculated and local time is just 24 hours whatever we do, we have in our watches and all. Now this hour angle, what is hour angle? Say if you are watching any source, now this is the Earth and then this is your declination. This will be declination and this kind of curves will be your right ascensions. So just like your latitude and longitude, this will be Delta and this will be Alpha, means right ascension.

If Earth is moving, this coordinate system doesn't move. This is fixed. If the coordinate system is fixed, all the Earth is moving. Since the Earth is moving, if you are an observer somewhere, say here, then you will move and the Earth is moved, then after some time you will reach here. Now here to here you travelled an angle in terms of the greater sphere.

You travelled an angle. So that angle is known as hour angle. Now say this is your Earth, this is your Earth. Now the observer is here and due to the Earth motion you reached here. So this is the amount of angle you covered and which will be known as hour angle.

So there is a simple relation between locus-sidereal time and hour angle, which is your LST is equal to what? RA plus hour angle. So this is the simple relation you should remember because when we do analysis, we tend to plot in terms of LST because in terms of LST, its source is mostly fixed in the equatorial coordinate system. Now there is, I mean, you can, this is, let's move on to the next coordinate system. The next coordinate system in galactic coordinates where the Sun is the kind of the center for the coordinate system origin and the zero degree is towards the galaxy center, means our Milky Way galaxy center. Now from there, the similar lat long type of coordinate system is generated and the both L and B said that longitude and latitude of galactic longitude and latitude are in degree minutes and seconds.

So this is also used for kind of, if we are observing with respect to suns, say if you are doing a study where sun comes into picture, the mostly represent means mostly used positional coordinate or the coordinate system is galactic coordinate system. So now before moving forward, what is the importance of learning this kind of coordinate system? The thing which we did, I am not revising it here, you can view it in the seventh week, is that there is coordinate transformation defined for this based on trigonometric functions. Now this galactic coordinate system or the equatorial coordinate system can be translated to lat long and the most important thing which we require is azimuthal elevation. Say if you are using an antenna, say you have an antenna, elevation is the angle required you need to take, means the angle for antenna you move in the kind of a vertical angle, the vertical way and azimuth is the horizontal rotation. So if you want to point any source at a particular array and deck, you should know about azimuth and elevation.

There are several apps also like Star Trekker, Stellarium and this type of apps which can show you the azimuth, real-time azimuth and elevation of different sources but to calculate this you need to use the cosine formula which is discussed in the seventh week. Now this thing is very important because we need to go back and forth into LST calculation as well as the coordinate transformation calculations and if we miss by a certain degrees of values also because of which we can miss the source which we are looking at because the means more sophisticated interferometers have very arc second resolution. So if your error is between few arc second that means you might miss your source. So this is why we require this coordinate system and the knowledge of coordinate system very well. Now moving towards in the week 7 itself, we have basic interferometer where there is two and if we to realize this we what we will see is we will think about this is say we have a single dish of 100 meter and for simplicity sake I will take 20 we are observing 21 centimeter line.

Now with this is what will be the angular resolution we are looking at. It's roughly 1.22 into your 0.21 by 100. If we ignore this so we will have 0.0021 radians of resolution. Now if we want to detect even finer source like which is in few milli arc second what we have to do we have to increase the dimension of the antenna means the resolution or the angle theta is inversely proportional to the dimension of the antenna. So if you want to do observation at a particular wavelength we need to increase the dimension of the antenna bigger and bigger. And there is a practical limit on the how much big antenna you can make. You can't make a 100 kilometer antenna. So using the array theory we got to know that we can use array theory in antennas we can use whose multiple antennas separated by a distance to emulate for a bigger dish antenna.

Now this put forward the concept of basic interferometer where we have two antennas separated by a baseline B. And that is correlated. Now what happens here if you have two antennas separated by a distance if there is a source up here it will reach the antenna at different time and that time required is given by tau. $\tau = \frac{b \sin\theta}{c}$ This is tau beta tau baseline this is baseline and sine theta over c which is speed of light. Now because of this and the principle of Young's double slit experiment basically you will see that this causes a kind of sinusoidal wave if there is a kind of a coherent means a single source out there.

So you will see when you correlate these two you will find a sinusoidal signal. Or the which you can term it like this that if you have a single source in the sky it will create a kind of a sinusoidal pattern or you can sample the sky in this direction say sample the sky in kind of a sinusoidal pattern. So instead of having a single or you can say instead of having a single beam you have like a multiple beams here so you can sample the sky like this. But this thing also has a limit it with its field of view. The field of view of a basic interferometer is defined by the diameter of individual antenna.

So what you will have you will have one bigger field of view and in which due to the interferometry you will have a smaller resolution beams. So like this so you can see where I am going at with this so using two antennas we can sample the sky horizontally so if we have another antenna over here so the number of baseline increased to three so with three baseline we can sample it in other way. Now the thing to note here is the baseline so the thing you should keep in mind when you are doing interferometric principle redundant baseline will cause same pattern. So there should be minimum redundant baseline or there should be no redundant baseline in some cases. Redundant baseline will have you will be you won't be able to figure out which phase or which signal variation is from which baseline because both will generate same kind of pattern and if they are in the same location or the same direction kind of thing say you have a baseline here and here you have another antenna which is also B.

Now you won't be able to figure out if you correlate these things these two signals you won't be able to figure out which is from means what information it is adding. So in the same line you can't have redundant baseline so if you have an antenna here you can have a baseline here but although the baseline will same but the baseline vector is different which will have a different UV coverage in the UV plane. So now I termed a thing called UV coverage. Now UV coverage is what is due to your rotation of the earth. Now if you have an antenna structure over the earth like say you have two three antenna like this now earth is rotating what will happen and you will sample the sky the sample a sky will be sampled like this and the means these two for these two baseline will be sample like this for this two it will be sample means these two if it samples like this and these two will sample like this and there will be a different UV coverage like you will sample the sky in a different way due to the earth's rotation.

Now with this then you have something called sampling function and means you grid this UV coverage and then do some point spread function and those are means image processing means creating an image essentially out of an interferometer which is also known as rotation for earth's rotation for synthesis imaging. So this is what synthesis imaging means you have a set of baseline and you due to the rotation of the earth you take advantage means kind of you exploit that and take different samples in sky and make a image. Now comes with interferometer comes a different problem that we will have a multiple sensors and multiple sorry multiple systems that multiple system will have their own system temperature. So for which the sensitivity of the interferometer will change. Now if you have multiple sets of antenna the interferometer sensitivity equation is given by this.

So this is in a sense it is very similar to your similar to your single dish equation. So this is the equation very similar to the single dish one. Now this here the extra term you will see here is the n here the n is nothing but number of baselines in the in your interferometer facility. Now this n n minus one is nothing but your arithmetic mean. So if you have n number of baseline so what will be the total of that n n minus one by two I believe this is the means the sum of one to n looks like.

$$\sigma(F_\nu) = \frac{\sqrt{2}k}{\eta_c \eta_A A_{geom}} \frac{T_{sys}}{\sqrt{(1/2)N(N-1)(\Delta t/t_{int})\ t_{int}\Delta\nu}} = \frac{2k}{\eta_c \eta_A A_{geom}} \frac{T_{sys}}{\sqrt{N(N-1)\Delta t \Delta\nu}}$$

So by that it came into picture. Now if you see the sensitivity it decreased by factor of kind of n to n minus one. If you observe if you see again the yeah this one so here the sensitivity depends upon effective area and only the observed time multiplied with the bandwidth. Now if you move towards interferometer you see that the your sensitivity is increased by a huge margin if you have n number of antennas in your interferometer. Now provided that the system temperature for each antenna is maintained at the same temperature here there shouldn't be any fluctuations if there is the system temperature for each antenna is different that should be accounted for or and that essentially is calculated as T one square plus root over T one T two square means like square sum square root of the sum square of the temperatures because this way is kind of approximated that approximate system temperature and there is two more terms over here which is n a and n c means eta a eta c. So these two are efficiency of aperture of aperture efficiency and correlated efficiency.

Now as I said we if we have n number of antennas we need to mix those signals or correlate those signals with each other so for which the correlated efficiency comes into picture how efficient is your correlated and that depends upon your sampling speed of the ADC and the sampling speed of the ADC and how sensitive your instrument is actually. So these things and the losses are considered like that but the simple thing by which they account for all these losses or calibrate the system is by looking first at a calibrated source means like a source which for which you have proper data sheet how much the flux is how much the how much its phase is so there is two types of calibrate flux calibrator as well as phase calibrator using which you can calibrate your antenna. If you just like you remember if you remember the calculations we did for single dish is here the V means voltage calibration kind of thing in where you have V or V you can calculate the system temperature by viewing the calibrated source. Now same thing you can do for your interferometer and is being done when you are doing any major observation using means national facilities like GMRT. So in context to this I think this was in a Winton's assignment and so let's do this again in this session and so we have we want to detect an unresolved source at 22.2 gigahertz where we have a sensitivity limit of 0.3 Janske and we did not detect the source. Now if we use an array of three antennas all the systems will be at 50 Kelvin and has aperture of 30.4 meter square observing a single polarization with bandwidth of 50 megahertz and correlation efficiency is to be assumed 0.8. Now said that if we fail to detect the source we would like at least to half the upper limit on the flux density half the upper limit on the flux density. So upper limit on the flux density is half and the R five times the RMS noise. So upper limit is half and RMS is five times that means the total means total means gap should be around 10. Okay the factor of 10. Now the factor of 10 comes into picture then that means you need to be able to detect the sensitivity level of 0.3 Janske per synthesized beam. And if you plug in the values into the equation you will arrive at 119 seconds and it's for about two minutes of observation or observation. Now with the same thing if we do it for single dish we will arrive at 0.05 Janske. Now you can see the difference in the detection limit say for two minutes you calculated it for 0.03 and for single dish you have 0.05. So your sensitivity has increased in interferometer. This is because although you are using smaller antenna but what means you have increased the number of antenna thereby increasing the total area. Now if you have the comparable area say for example you have an element interferometer where having some geometric area so for which you will have equation like 1 over n, n minus 1. Sigma nu f nu is proportional to this.

Now if you have and this is a geo. Now if you have the single dish of n times the geometric area say this is for interferometer I will term it as i and single dish f nu and this is s will be proportional to 1 by n times your a geometric. What I said is you have an interferometer of a geometric area of means n element interferometer n element interferometer of a geometric area and on the other hand you have the single dish of n times the geometric area. Now if you do the ratio of this so sigma f i to sigma f nu s what you will get you will get root over n, n minus 1, n over n minus 1. So this what does this represent? This represent that the sensitivity of the interferometer is almost equal to the sensitivity of a single dish interferometer having the n times of the area of a single dish of an interferometer. So if you have a single dish telescope you need to have n times the area whereas you can have a smaller dish and a small means n times smaller dish and you have you can place it around some area to create a n element interferometer achieving the same amount of sensitivity level.

Now these are the main key points you should know about when you are doing some kind of means radio means if you are dealing with radio instrumentation and this stuff. Now after this something comes imaging. So in imaging what you have you do you utilize the rotation of the earth to create a UV coverage mean to see how the n number of elements and the n number of baseline in covers your sky and based on that at you create an image which is also in week 8 or 9. In week 8 and 9 so showed something called dirty image from where how we can remove the point spread function how we can denoise it there are different algorithms as in I think week 9 week 8 and week 9 and week 9 casa lectures week 8 and 9 casa lectures you can those some there are some software tools casa, AIBS, APES by which you can kind of analyze is interferometer data. So this thing actually sums up the entire instrumentation part of the instrumentation or instrument related summary of the radio astronomy and there are different techniques by which you can do imaging for which you can go through the lectures week 8 onwards. So with this thank you.