

## **Radio Astronomy**

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### **Co-ordinate System**

Hello and welcome to this week 7 for lecture 1 in radio astronomy. We will start a discussion this week on something called coordinate system. Now what is a coordinate system and why do we need it? Of course the entire approach of astronomy is to detect celestial objects on the sky and so we need to know how to locate those objects. How to locate those objects, the stars, the galaxies, when they are supposed to be up, when we should point at the telescope towards which part of the sky and whether it is observable from our given location on the Earth. As we know depending on whether you are in the northern hemisphere or southern hemisphere certain parts of the sky are not visible to us. So that whole discussion we will start today with emphasis on something called coordinate system.

It is very important to define a coordinate system as we start the discussion on where to point the telescope when to observe a particular source etc. So often if you see this kind of a bloody image it is a time lapsed image where you have kept at the telescope site and you have seen the sky which goes around because of the movement of the Earth. We will come back and explain this figure in a bit but this is quite a well known feature. It happens because of a large time lapse which captures the movement of the stars in the sky.

Similar thing is also noticed in case of like this analema where if you are in a particular position on the surface of the Earth and you keep staring, keep looking at the sun or take the sun's image every day at the same time across the entire year you will see that the sun will make a figure of 8 but a little bit skewed kind of projection on the sky. And again this is because of the movement of the Earth with respect to the sun. Depending on where you are on the surface of the Earth you can see various time lapse images showing variety of patterns. It basically means that you are at different parts of the globe. These things are not exactly in the same location, they are in different parts and they are movement capturing a time lapse movement of the stars across the sky.

The primary reason for this is the movement of the Earth, the rotation, the revolution, the tilt with respect to the right-lipped plane. And so this is the particular picture of the

Earth which is moving around the sun and with its own tilt and which causes seasons but also which causes this variety of movement of different stars, galaxies on the sky. So continuing on the same line if we can from the perspective of the Earth, if the observer is on the Earth, so with respect to the Earth you can see the solar declination changing across the entire year. So it makes some kind of a curve with respect to its position from a fixed point on the Earth which is partially because of also because of the Earth's rotation about its own axis and around the sun, the revolution. So this is with respect to the Earth.

So if an observer is on the Earth it is much easier to assume that there is a celestial sphere and on the celestial sphere every star has a coordinate and that kind of moves with respect to the Earth. And so that coordinate system or different coordinate system based on the celestial sphere is how we can track a star or a galaxy or a cosmic source on the sky. So we will come to the discussion in the later slides. Just to explain this particular image, if you have a telescope, an optical telescope and you point towards the north celestial pole if you are in the northern hemisphere and so if your axis is around parallel to the polar axis then you for time lapse image will kind of give you this kind of image which is exactly what background one shows. Okay so location is very important.

Measurement of the position accuracy of individual sources are also important. This is a list of different measurements done over the years and you can see this goes down in terms of this AS is arc seconds, so seconds of an arc, then MAS constitutes of milliarcsecond and microarcsecond. So if you see as we go from 1400 AD to 2000 AD this entire thing has come down from thousands of arcseconds which is kind of few degrees down to a few microarcseconds. Okay that is a huge amount of precision which has increased over the years, over centuries right that is quite commendable. These are few catalogues which are very famous nowadays and you can see the different accuracy in positions which are available with us.

So to increase the accuracy exact location of the stars, the galaxies, the cosmic sources, we need to understand their coordinates accurately. We need to understand, we need to measure, we need to determine. So a coordinate system, necessity of one evolves naturally right. So as we motivated in the last few slides that we kind of designed something called a celestial sphere. Celestial sphere is nothing but it is kind of a crater sphere on centering the earth, where the center is the earth itself, the center of the earth, center of the celestial sphere as well.

And there are a couple of other things which has to be defined. First one is if you relocate an observer near point O, then if you're looking towards the sky, the location exactly 90 degree top, at the top of us 90 degree from the horizon is the zenith, that is

one definition. If you're looking towards the center, you define the narrative point, the horizon is 90 degree from the zenith. Okay and so you can point towards different sources as a function of this elevation angle or azimuth angle from the pole point position of the location of the observer. For a definition, there is something called north celestial pole, which is the northern pole of the celestial sphere and the south celestial pole in the same respect.

The equator is near towards the zero degree celestial latitude and which positions itself with the movement of the sun, the celestial sphere. And so you can define the northern celestial pole, southern celestial pole and any line which is joining this northern pole with the southern pole passing through the zenith is the meridian of the location where the observer is. So few things, the location of the observer, if you know that, then you can draw a tangent. This is the horizon for the observer, anything below that the observer cannot see at a given time. Thanks to the movement of the earth, the sky will keep on rotating around the observer.

The vertically up top position pointing towards the sky is called zenith and below is nadir and the position of the now the sources across the sky can be measured in terms of the elevation and azimuth angle with respect to of course the north and the south pole. So now if you define the celestial sphere which is kind of a bigger sphere drawn on top of the earth keeping the center of the earth as center of the celestial sphere. Now if you draw the celestial equator it contains the sun's path around and the northern pole and the southern pole by itself. It's called the north celestial pole and the south celestial pole. Any line which is connecting the two poles, the north and the south poles, the north and the south poles are connected to the solar system.

So the solar system is connected to the solar system. Any line which is connecting the north pole and the south pole and passing through the zenith is called the meridian, local meridian. Okay so that's pretty much what we need to know. So the celestial sphere, just to recap, an imaginary sphere that rotated about an axis passing through the north and the south poles of the earth and intersecting the celestial sphere at the north and south celestial poles. The imaginary image in the stars in the sky to be attached to the surface of this sphere.

The ecliptic, the path of the sun with respect to the distant constellations as observed from earth, the ecliptic is the line where the plane of the earth's orbit cuts the celestial sphere. Vernal equinox, twice during the year the sun crosses the celestial equator, once moving northward along the ecliptic and later on moving to the south. In the first case the point of intersection is called the vernal equinox and the southern crossing occurs at the autumnal equinox. So that's how we define in the last slide. So in the vernal equinox

the sun intersects with this celestial equator and starts moving towards the north around the ecliptic and later on moving towards the south after crossing this at the autumnal equinox.

The another thing which is important is the solar time or synodic time. The solar time is defined as an average interval of 24 hours between the meridian crossings of the sun. It is the average time elapsed during which an object comes back to the same position with respect to the sun. There are few standard reference frames for position in astronomy. The place of observation, if that is the origin of the coordinates, then it is called topocentric frame.

If center of earth is at the origin of the coordinates, then it's called geocentric frame. Center of the sun is at the origin, it's called heliocentric frame. Center of mass is called barycentric frame. Center of mass is called barycentric frame. If the local vertical is chosen as direction, it's called horizontal system.

Celestial poles are chosen as pointing north and south, it's called equatorial system. And normal to the ecliptic system, it's called ecliptic system. And a pole by convention is called, one of them is called galactic system. So we will touch upon ecliptic system, not ecliptic, we will touch upon equatorial system, horizontal system, we will not discuss ecliptic, and we also touch upon galactic system for this particular lecture. So how to look at an object? Say if you have a sphere, a standard sphere, you just need what? You know the radius of the sphere.

So you need the azimuth angle and elevation angles. Supposedly you draw a spherical polar coordinate system, you know that at a radius of  $r$  there is a sphere. So let me redraw. So if I need to point of  $P$  on the sphere, so say it is going across. So the projection down here, this will cut a distance of  $\theta$ , angle of  $\theta$ , and an angle of  $\phi$  with respect to the two axes.

So  $x$ ,  $y$ , and  $z$  axis. So if I know my distance  $r$  is already known because it is a sphere, if you know  $\theta$  and  $\phi$ , I can locate my object on the sky for a horizontal system. Okay, that is easy. What you have to remember is solar day is 24 hours, arc spin period is a little bit less than 24 hours, and we have to define something called sidereal time. Typically we use things like light ascension and declination, but we will come one by one as we go through it. So the different coordinate system, equatorial we already mentioned, this we will be covering, ecliptic we will not cover, galactic we will cover, and also the horizon.

So for horizon coordinate system, there is an altitude  $h$ , which is defined as the angle

measured from the horizon to the object along the great circle that passes through an object, that object and the point on the celestial sphere directly above the observer known as zenith. Azimuth is  $a$ , so you can define this way, or you can also define this as the previous slide we have done. This is  $\theta$  and typically what we say is  $\phi$ . So same thing which we drawn earlier, where you have  $x$ ,  $y$ , and  $z$ , you have a point on the sphere drawn at a radius of  $r$ , so you have a projection on the  $x$  and  $y$  plane, it makes an angle  $\theta$  with the  $z$  axis and  $\phi$  with the  $x$  axis, and so on and so forth. So if you know the altitude and azimuth, you know the position of that particular source.

This is called the horizon coordinate system. Easy to know the position of a star at a place from the given point of the telescope. But one drawback is that it varies from one position where the observer is to the next position. So it's not, it's very local, it's very relative, and so it is good for, to know from the position of telescope itself. But if you want to cross check with another fellow observer, this is not the universal coordinate system.

So if you define something more which is, can be used by everybody from different parts of the earth. So we end up talking about equatorial system, very widely used. It is defined in terms of right ascension or  $\alpha$  and declination or  $\delta$ . It's almost synonymous, basically synonymous with what we say is like the longitudes are referring to the right ascension. So it's like the longitude of our terrestrial sphere.

And this is like, the declination is like the latitude of our terrestrial sphere. This also varies from minus 90 to plus 90. And this also goes across for 24 hours or 360 degree is travelled in 24 hours. So we typically express right ascension in terms of hours, minutes and seconds. And we typically express declination in terms of degree, arc minutes and arc seconds.

Okay, so that's the difference between the two. Typically, you see this is referred to as degree minutes and arc seconds like that. And of course, plus or minus depending on which side of the equator that particular source is located. So how do we go about doing this? So let's first define the hour angle and declination and from hour angle, we will come to the RA also. So from the declination is basically, it's just the distance.

Suppose there is a source of, so there is a cosmic source at the location  $x$  on the celestial sphere. Now the  $\delta$  is basically the angular distance between, sorry and then so if we draw the meridian passing through  $x$  intersecting at the north celestial pole and the south celestial pole, you draw imaginary line, which passing through that location  $x$  of that cosmic source. So the, so declination is the angular separation between the intersection of  $x$  on that meridian and the intercept of the meridian with the celestial equator. That

distance is known as the, is known as the declination. What about the hour angle? The hour angle is the angular separation between this meridian, the meridian which is passing through  $x$  and the meridian which is passing through the zenith of the observer at a given position.

So that's the celestial meridian and this location, the angular separation between these two is called the hour angle. Okay, also defined in terms of hours, minutes and seconds like the RA. Now supposedly, so this is hour angle and declination. So declination is universal, that is fine because it depends on the meridian which is passing through the source. But hour angle again becomes relative to the location of the particular observer because it passes, it is measure of the angular separation between the two longitudes or celestial meridian and the meridian passing through this source.

The celestial meridian is depending on the zenith of the observer. So let us try to remove that also. For that, we need to choose a reference point. What do we choose? We choose the vernal equinox as the fixed point. So the point where the vernal equinox happens on the celestial equator, that point is chosen as the reference point.

So if that is the case, then yeah, so it is analogous, so right ascension is analogous to longitude and is measured eastward along the celestial equator from the vernal equinox point of this kind of a distorted gamma you can say to its intersection with the objects hour circle. So right ascension becomes zero on this and then it starts going, counting eastwards in hours. And so it comes back and makes the entire revolution and it goes back to 24 hours just before meeting the same point. Okay, so clear.

So what did we do? Just a recap of that again. What we did is we defined few points. We defined first the declination which started from locating the source  $X$  on the celestial sphere and you draw an imaginary meridian passing from the north celestial point pole to south celestial pole passing through  $X$ . Very good. So the angular separation between that point where  $X$  lies and the intersection of this meridian with the equator, that angular separation of both is known as the declination. And the angular separation between this meridian which is passing through  $X$  and the meridian which is the local meridian which is passing through the zenith of the observer, the angular separation between those two meridians is known as the hour angle.

So when the, for example, when if the source is passing through the zenith then its hour angle will be equals to zero. Right. So the other thing is, so right. So basically now we have defined the declination which is not dependent on the position of the observer and we have defined the hour angle. But hour angle is still with respect to the position of the observer.

So to remove that observer specific position we define a reference point. The reference point is the vernal equinox point where from where the sun starts moving along the ecliptic to the, towards north, that position where it intercepts the celestial equator, that position is treated. So when the meridian is passing through that vernal equinox point it is known as the zero hour line. So as it moves eastwards the Ra goes from zero to one, two, three, four. Like this it covers the entire sphere and comes back to 24 hours.

Okay. So that is how we define the Ra and the declination and that becomes more like universally acceptable coordinate system. So we define Ra and Dec as equatorial coordinate system or alpha and delta. Now the advantage is that since the equatorial coordinate system is based on celestial equator and vernal equinox, changes in the latitude, longitude of the observer do not affect the values of right-hand essential and declination. They are similarly unaffected by the annual motion of the earth around the sun.

Okay. So that is, we have successfully have defined our equatorial coordinate system which does not depend on the position of the observer. So we now define another most important thing which is the local side real time. Now let us stick to the previous thing. So what we defined in the previous slide is that we defined the fixed point of the vernal equinox when the sun is going northward on the ecliptic. That point is fixed and the meridian which is passing through that particular point is defined under zero Ra.

Okay. So we also define local side real time to be zero hours when the vernal equinox is on the observer's local meridian. Okay. So when the observer's local meridian matches, contains the, so supposedly we look into this meridian which is passing through the vernal equinox. So if this becomes the observer's local meridian passing through the zenith, then there the local side real time is counted to be equal to zero. So if you do all the math, the relationship which we can come up with is our angle is Lst minus Ra or the right ascension.

So a couple of important things is when any source is passing through the local meridian, then our angle is equal to zero. Our angle is zero at local meridian crossing. This location is also very importantly called the transit.

We will come to that. That is our angle equal to zero. That basically implies that Lst is equal to the Ra of the source. This is number one, case number one. Case number two is the hour angle of the vernal equinox. So at vernal equinox Ra is defined to be zero.

So then Lst is equal to hour angle at the vernal equinox point. Okay, so two things to

remember. First one is very powerful. I will tell you why. And the second one is also important to remember the difference between these two. I will not go into details but you can definitely transform from the one we learned so far.

The two things, horizon to hour frame and transformation from the hour to the equatorial frame. You can do that. Both of them. So hour frame is the intermediate one which has the hour angle and declination.

And then hour angle of declination too. So this is the horizon which is defined by the theta phi or the elevation and azimuth also called the altitude. Sorry, it is known as defined as  $h$  by the altitude and azimuth. This also is there and from there to the hour angle and delta and this one is going from hour angle and delta to  $R_a$  delta or  $\alpha$  delta no matter what.

However you define that. Okay, so you can go through this. These transformations are best remembered as it is. It is a little less to be explained. So we skip to the next slide. So, very well. So basically now what we discussed in that sphere from the observer point of view, we don't see a sphere.

We just see a hemisphere, the sky above us. Supposedly you have your observer and you point your telescope as a nice thing taken from the Calgary website. There is the reference in the next slide to this. So if you point your telescope in the north-south direction, so you essentially choose a geographic north-south location and you draw the imaginary line connecting this.

This is your local meridian. This is known as your local meridian. This is the line. And that line crosses through the zenith of the local position. So you have a celestial body which is kind of has its own motion. Supposedly, so it is moving from the east to the west.

So it is moving, the celestial body is moving in this direction. The intersection of the celestial body, this motion on the local meridian, this location is called transit. This is the place where our angle is equal to zero which implies that at that particular location the  $R_A$  is given by the local side real time or vice versa. Okay, so supposedly we are in the northern hemisphere.

Say I just take my location near Indore. It is 22 point something. I just define this as 22 degree north. That's the zenith. So you can see this is a different thing from Canada. So you can you can have a little bit more listening.

So you can see these lines which are passing through and meeting the east-west. These are the constant declination lines. Right, so the source also is passing through a constant declination line. So the source rises in the east and setting towards the west, passes through this blue line. If you have any other location you can just point towards the north or the south and you will see these constant lines of declination and these individual great circles moving across in different. So apart from this line there are other lines which are also going from north and south but not cutting through the zenith and those will also be seen here.

This is a small, yeah, this is the web from where we collected the previous two pictures also. If your observer is looking towards the hemisphere you can see the sky moving across. This is not with respect to that position we were talking about. So I am an Indore, I will take roughly 22 degree north as the zenith point and do some further calculation. So because I am in the 22 degree north, the zenith declination is also equal to 20 degree.

So the declination of the source which is passing through the zenith is equal to delta equal to 22 degree north. That source will exactly rise from the east and goes to the west and pass through the zenith. However there are other sources which can rise a little bit south like this blue line and also go and cut the zenith and meet somewhere here and further. So because I am in 22 degree north there will be the north celestial pole which will be visible to me at an exact elevation of 22 degree from the horizon.

These are the lines which are representing the horizon. Okay so if I look towards the north then I would see the north celestial pole. Okay what else? Any source which passes through the meridian at the meridian crossing those lines are called transits. Okay that is the maximum elevation a source can have when moving through the sky. All right what else we can do? Yeah so depending on so supposedly if we are in the latitude of 22 degree north my south celestial pole will be below the horizon always by about 22 degree.

So if you are at this location you will not be able to see the south celestial pole. So just by this very efficient diagram we can do a huge number of calculations and learn a lot of things. So what have we learned? We have learned about zenith, we have learned about transit, this is the maximum elevation point of a source meaning cosmic source. Okay what else we can learn? We have learned that if your latitude if the latitude of the position matches with the declination of a source then that source transits through the zenith of the observer. Okay another powerful definition.

So with that we move ahead we will discuss further these concepts in more examples. Another coordinate system we wanted to define was the galactic coordinate system very

very widely used initially because a lot of the sources were from the galactic origin so the source localizations were almost in the galactic plane so that's where we started from. So we just briefly discussed this. So it is a projected coordinate system where the sphere the equator is in the galactic plane and that is defined as the galactic plane and the longitude increases counterclockwise from the galactic center. Okay the angles the direction of the north and the south galactic poles are there.

Galaxy in a galactic plane looks like like it's almost in near the equator it's located. So that's the predicted map. Yeah so that's the galactic coordinate system which is mostly based on the galactic in our own galaxy and there are few transformations from the equatorial to galactic plane. First let us understand the few details of the galactic plane. So galactic longitude raises from 0 to 360.

Latitude is goes from plus 90 degree to the negative 90 degree and south pole. Galactic center is located at the  $l$  equal to 0 degree and galactic mid plane is at  $b$  equal to 0 degree. Sun is the origin. Okay so we can you can see how we transform the local the horizon system to  $h$  and  $\delta$  which is already we have we have seen the horizon system to  $h$  and  $\delta$  and galactic and equatorial system. So if you have the galactic system of  $l$  and  $p$  how do we interchange that with  $\alpha$  and  $\delta$  by this.

Let's take up one example to end this discussion. A pair of astronomers learns from of an interesting radio source at a location in the sky given by  $ra$  equal to 12 hour 30 minutes and zero seconds and declination equal to zero. The astronomers decide to check it out and so set out to observe it with their own telescope which is located at a longitude of 75 degree west and latitude of 35 degree north. They first check their computer and see that the current  $lst$  at telescope is three hours. So what are the following quantities the  $ra$  and  $dec$  of the astronomers zenith. What is the current hour angle of the radio source? Is the radio source above or below the horizon this time? What will be the azimuth and altitude of the desired sky location when it rises and what is the azimuth and altitude of the desired sky location as it transits? So quite a few.

So  $ra$  of the zenith at a given time is equal to the  $lst$  corresponding to that moment so because our angle is as our angle is equal to zero at the transit. So declination of an observer is observer zenith is the same as the observer's latitude so the corresponding zenith corresponds to  $\delta$  equal to 35 degree and our  $ra$  is this. That's easy. The hour angle is easily calculated by subtracting the  $ra$  from the  $lst$  of the target source so if you know that  $lst$  of the target source then you can calculate the hour angle to be equal to this.

At a given time. Altitude you can put the values of zenith declination of zenith is known and the declination of the sky position is also known so altitude is 55 degree. So

we come to the end of this particular lecture and we will continue discussing the coordinate systems some more examples of it in the next class. One lecture after the next class. As you know that we have this material is available in multiple places we have particularly used the book of Roy and clerk and also some notes from Saraspolon as well as the two hyper hyperlinks we have given in the slides itself.

So thank you very much for joining us for this lecture we will see you in the next lecture as well. Thanks a lot. Bye.