Elements of Solar Energy Conversion
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Lecture - 13

Hello and welcome back to the series of lectures on Elements of Solar Energy Conversion. So, we have covered till now about 12 lectures. So, we are about a third through the whole course and this is the lecture number 13 ok.

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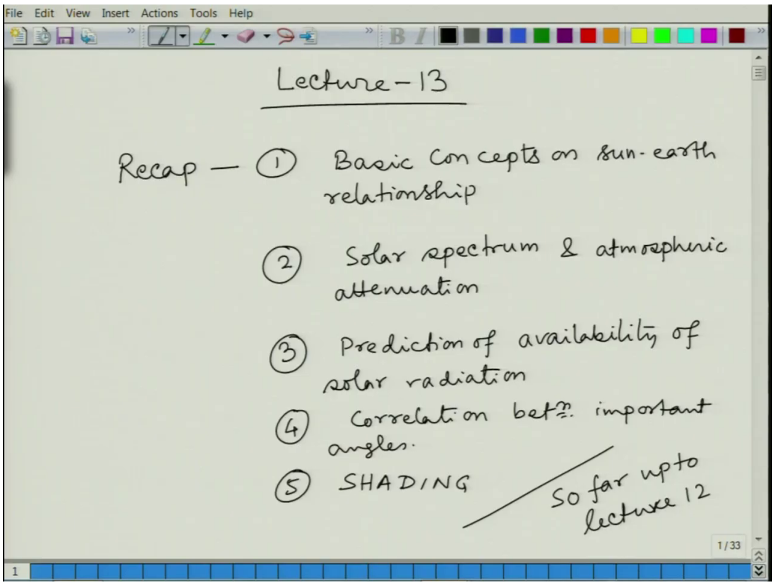

So, what we covered so far the major topics that we covered. The basic concepts on sun earth relationship ok. Then we covered the solar spectrum and atmospheric attenuation ok. 3rd thing we covered the prediction of availability of solar radiation ok. Then the major topic that we saw next to this was the correlation between important angles ok.

And 5th thing that we finished in the last lecture was the shading; both the shading in terms of the some object which is which can possibly block a location or shading in terms of the windows and parallel rows of solar collectors ok. So, so far we have covered this much. So, far up to lecture 12 ok, this is what we did.

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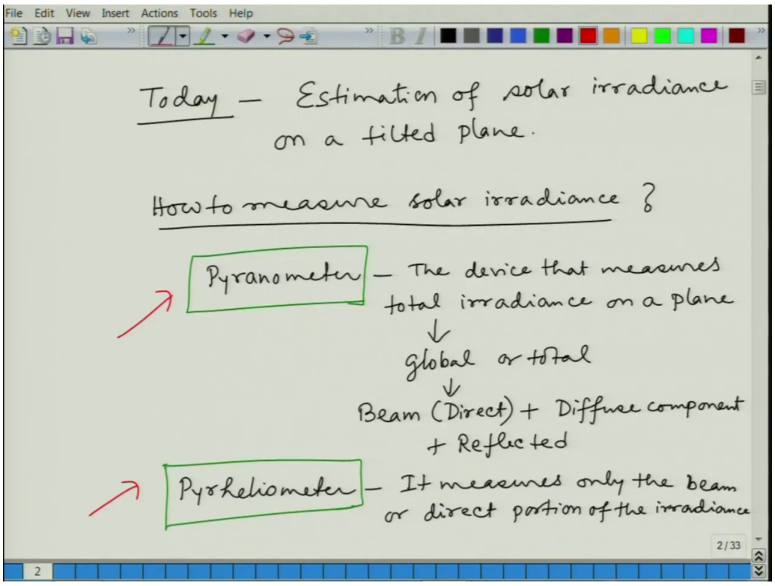

So, today what we are going to discuss is the estimation of solar irradiance on a tilted plane ok. So, this is a very vital topic which tells you how much solar energy will be available to your collector and often these solar collectors are placed in a tilted position, tilted to the horizontal plane ok.

So, in such a situation what would be the total availability of the solar irradiance, that is a critical parameter and so, far what we did? We have looked at all the possible details that goes into this kind of analysis or this kind of estimation ok. So, we are in a position to look at this topic estimation of solar irradiance on a tilted plane ok.

But before we proceed we need to find how to measure because we can estimate and we have to validate whether our estimation is correct or not and we need to measure the exact value of this irradiance. How to measure? Ok. So, there are two major equipment that do this particular thing ok, measure the solar irradiance.

First one is called pyrano meter. I guess or I hope that you heard this name before this class pyranometer means the device that measures total irradiance on a plane. Total irradiance what do you mean? We often term it global as well global or total both are same. So, it means that it has all these components.

Beam component which is nothing but the direct part of the solar radiation also the diffuse component as well as the reflected part ok. We will see how each of them will contribute to this total irradiance in a while. So, pyranometer so, please note that whatever measurement or whatever value a pyranometer gives, it is the value of the global or total irradiance ok, which includes all of the beam diffuse as well as reflected irradiance ok.

The next or the other instrument that is related to such measurement is called pyrheliometer, and what does it do? It measures only the beam or direct portion of the irradiance ok. So, pyrheliometer. Please remember that whatever value it gives, it only gives the direct or beam part of the total irradiance ok, it does not give you the total.

So, this is a critical difference between these two which I implore you to remember and whenever you see reading from a pyranometer, it is total and whenever you see a reading from the pyrheliometer it is the direct part only ok. So, how these devices work? What is the working principle? That is out of the scope of the syllabus you can look that up from other sources.

And the books that are suggested in the introductory lecture, there also you will find in all these books you will find how these devices work and if you are interested, you can go and check that out ok. Coming back to the discussion that we started is the estimation of irradiance solar irradiance on a tilted plane.

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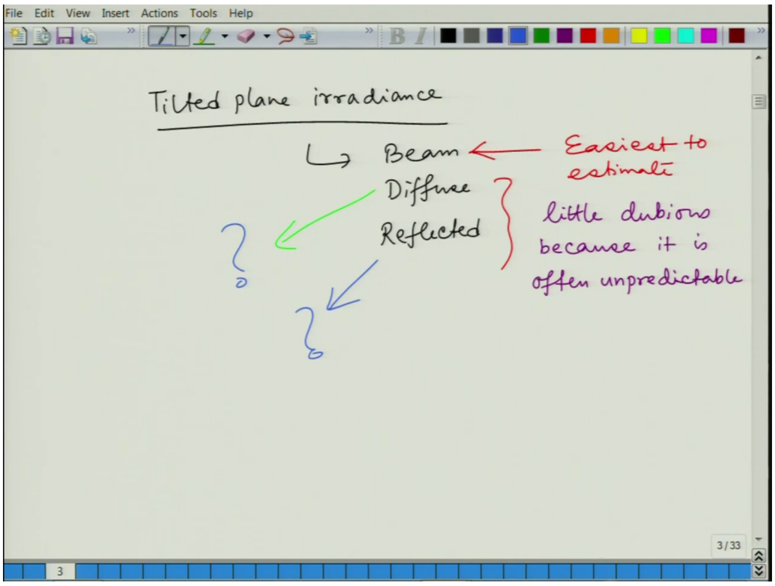

So, tilted plane irradiance, we have already seen that it will be beam, diffuse and reflected there will be three portion portions of the total irradiance. And this one is the easiest to estimate because we have some tools to find out the exact direction of the beam radiation, that we have seen in earlier lectures that how to find this important angles, whenever you are given a particular location, a particular time or day then you can find what would be the exact angle of the beam radiation ok.

And from that how much will be available to the tilted plane is easy to find out from the angle of incidence right. So, this is the easiest part and these two are little hazy ok. So, little dubious because it is often unpredictable ok. That is why it is difficult to estimate and why it is unpredictable?

Suppose, this diffuse part ok, whenever we talk about diffuse part, it depends on many things like the atmospheric condition, the cloud cover and the time of the day as well; that means, air mass. Air mass will be different at in the morning, noon and afternoon. So, all these factors they contribute to the diffuse component ok.

And it is very difficult to estimate clearly how much that would be. And reflected part if we see reflected part also has this complexity because when you estimate the reflected component for a particular solar collector, then after that during the operation it may happen that there are some new constructions, new trees are coming up around.

So, the shading profile as well as how much radiation will be reflected through other bodies objects to the collector that is also little unpredictable. So, these two are little dubious to calculate, but anyway we will assume that we can somehow measure them and continue with our estimation procedure.

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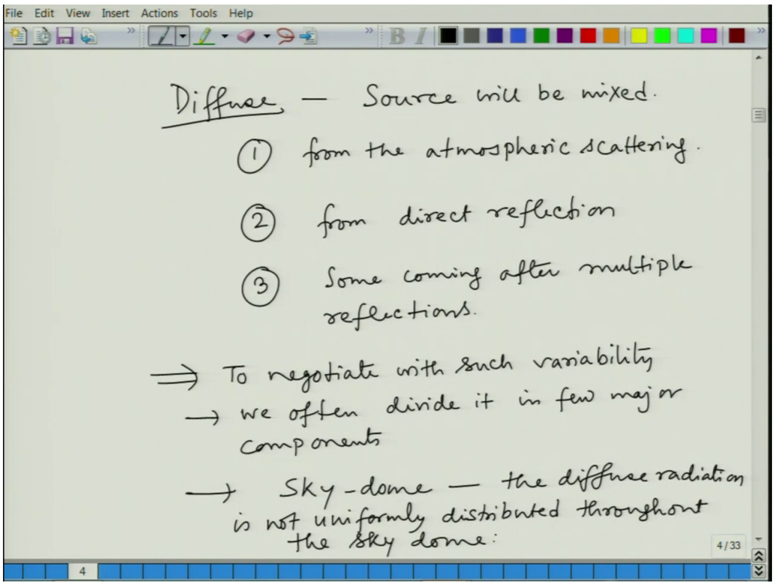

So, first let me talk about the diffuse radiation. So, for diffuse radiation, the source will be mixed, it would not be a single source ok. So, what would be the sources? 1; from the atmospheric scattering, then from direct reflection from some other body ok and some coming from or coming after multiple reflections.

So, it is not mandatory that it comes directly after one reflection ok. So, when it comes to multiple reflections then it's become difficult to single out and measure it the amount of radiation. So, to negotiate with such variability, we often divide it in few major components ok. How we do it that we will see in a minute. So, the assumption is or what we see is the sky dome. The diffuse radiation is not uniformly distributed throughout the sky dome ok. So, if it is not uniformly distributed how can we divide it?

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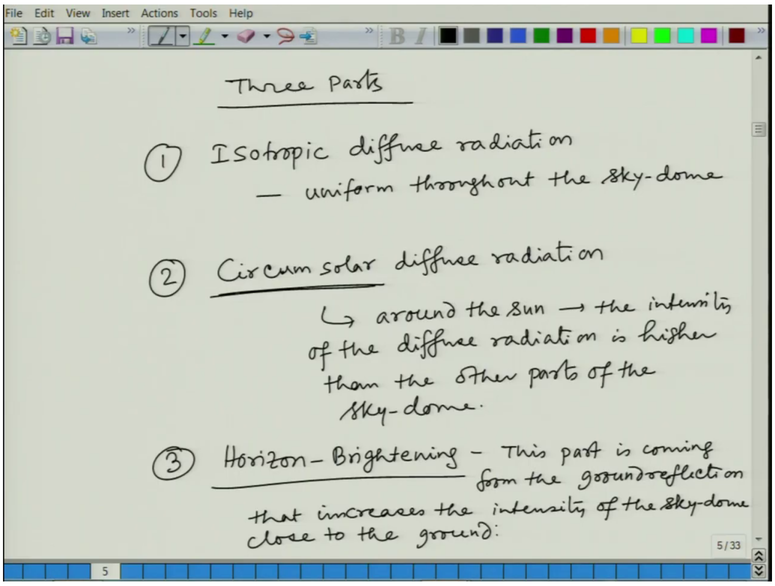

So, we divide it in three parts ok. 1st one is we call isotropic diffuse radiation what is isotropic? You mean isotropic means, it is same in all direction that is what the term isotropic mean. So, this is the part which we assume that uniform throughout the sky dome ok.

The next part we assume is a circum solar diffuse radiation. What is circum solar stand for? It is around the sun; the intensity of the diffuse radiation is higher than the other parts of the sky dome is not it? Have you have not you seen that wherever whatever location the sun is the intensity of the diffuse radiation.

Even if you do not if you shade it the direct radiation if you shade it, then that amount of diffuse radiation you will get is much more compared to from the other directions ok. Because the scattering that is the direct radiation is going through is maximum due in the circum solar direction and even then the amount will be maximum because it comes along with the direct radiation ok.

The 3rd component we take is called horizon brightening ok. So, how come this horizon brightening is how does this brightening happen? This happens because lot of reflection that are coming near the objects on the ground ok because all the objects are on the ground and that will give you a little more intensity near the horizon ok. So, this part is coming from the ground reflection that increases the intensity of the sky dome close to the ground ok. So, these are the three major parts we talk about.

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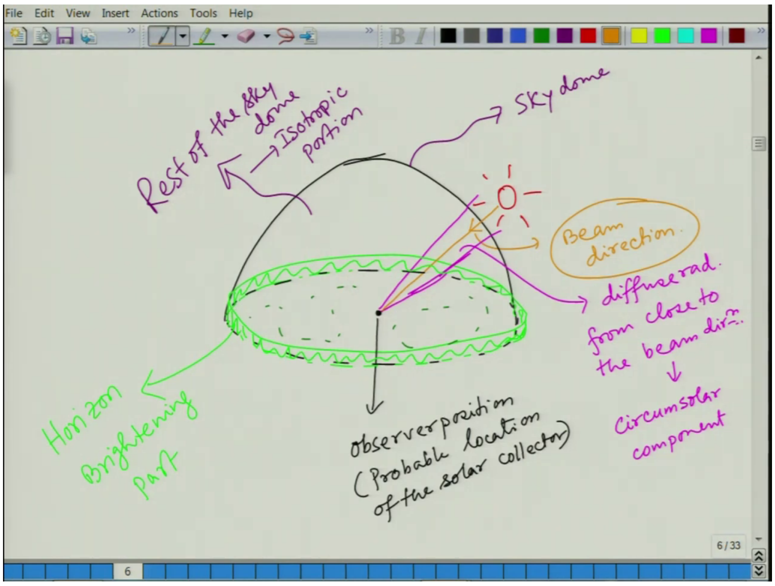

So, if we try to draw this. So, let us say here is our location or the position of the solar collector, where the intensity we are interested about ok. So, what does it see? It sees a sky dome which looks like this right.

So, this is the observer position or we can also say the probable location of the solar collector and this is the sky dome as if it is a big hemispherical bowl that is placed on top of that location where it is the center of that hemisphere ok. So, this is the sky dome. Now suppose we have sun somewhere here, ok.

So, the beam direction will be this right. So, this is the beam direction. Now whatever is coming close to this beam direction let us say here. So, whatever is coming close to this beam direction, this part the diffuse radiation from close to the beam direction, we call it circumsolar component. Circum means, around and solar means related to sun. So, around the solar beam that is what the circum solar mean ok.

And we have another part which is called horizon brightening. So, we what is the horizon? Horizon is this particular line right this is the horizon and whatever he whatever are here different objects on the ground everything will reflect diffusely and brighten a portion near the horizon ok. So, there will be a portion near the horizon which will be little extra bright right and that is what we called horizon brightening part ok.

So, these two are major components of extra diffuse radiation the rest of it the rest of it rest of the sky we have a uniform a radiation available diffuse radiation and that is what we called isotropic portion and it does not depend on the direction. So, this is these are the three major components of the diffuse radiation and we also have shown that the another major component of the total radiation will be the beam radiation.

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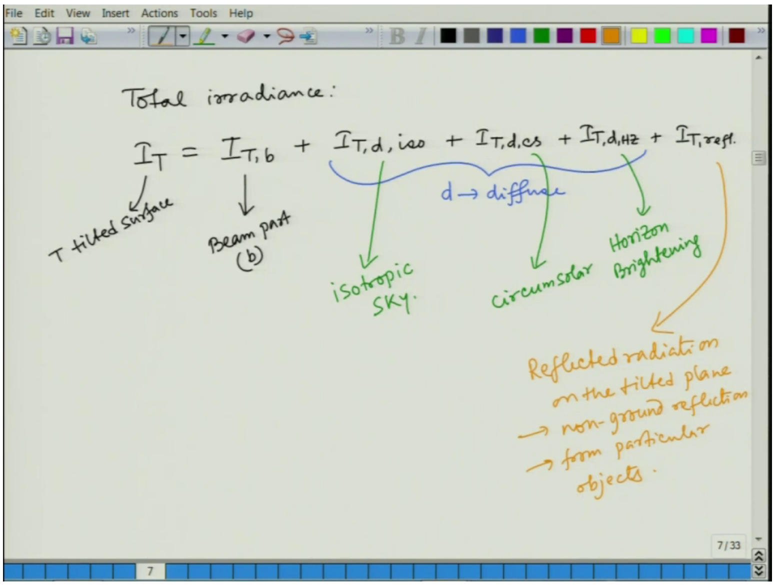

Now, if we write the total irradiance, then let me first write the expression then I will explain each of these terms what do they mean ok. So, this is I T will be, I T subscript b plus I T subscript small d and subscripted with iso plus I T small d and then c s subscripted which stands for circumsolar plus I T small d and H Z which is horizon brightening part plus the reflected part.

It may be direct or it may be diffuse; we dont know if there is a specular reflector around a big mirror or something, then there will be direct augmentation of the beam radiation through reflection as well as it can have the diffuse part if you have a non-specular reflector ok. So, let me first explain each of these terms. This T stands for tilted. So, what we are after is the total irradiance on a tilted surface and what it comprises of? First one is beam part and it is designated with this symbol b b stands for beam.

So, that is why it is designated. Now three of these if you see each of these has a subscript small d. So, that stands for diffuse small d stands for diffuse radiation and we have three components of it. What are the three components? This one is for the isotropic sky what it means we have seen just couple of minutes ago this one stands for circumsolar and this one stands for horizon brightening right.

So, that gives you three components of the diffuse radiation and the last one that we see here is the reflected radiation on the tilted plane. So, this reflection is coming other than the background ground reflection.

So, ground reflections are somehow taken in the horizon brightening and the isotropic component of the diffuse radiation, but this the last term the reflected term is coming from the non ground reflections or from particular objects ok. And that is how we cover it. And now what we can see, we can go into the details of each of these components.

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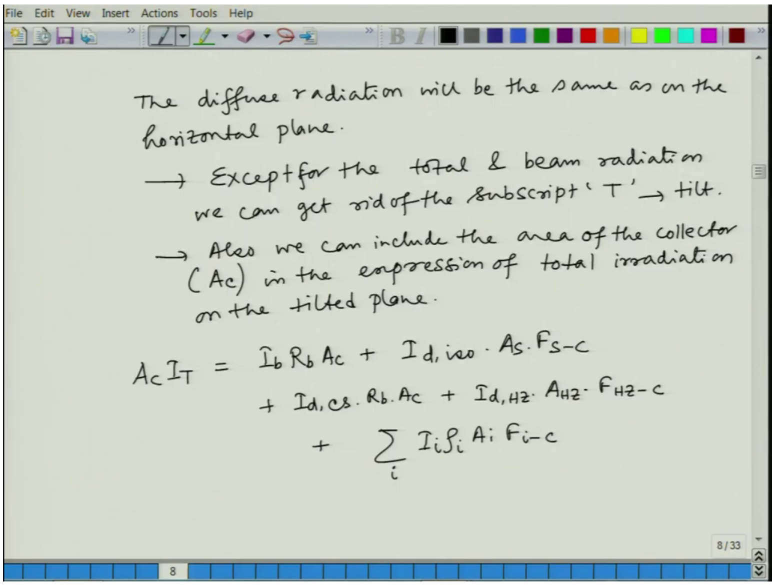

So, one thing we notice here the diffuse radiation will be the same as on the horizontal plane right. Because horizontal plane I mean the diffuse radiation does not have a definite direction right. So, that is why it does not depend on the angle of inclination or the tilt of the plane ok.

So, that is why they will be same. So, what we can do? Except for the total and beam radiation, we can get rid of the subscript T. Subscript T stands for tilt right. So, if that is the same then we can get rid of that part. So, what we can write? And also we can include the area of the collector which we call A c in the expression of total irradiation on the tilted plane right.

So, what we can write? A c I T will be I b R b into A c; I will explain what this R b stands for plus I d, iso multiplied by A s F s c I will come in each of these terms. So, please have patience plus I d, c s R b into A c plus I d, HZ multiplied by A HZ, F HZ to c plus summation of different reflected terms A i F i c summation over all the possible reflectors ok. So, this is somewhat overwhelming and jumping few steps. So, let me explain each of these terms.

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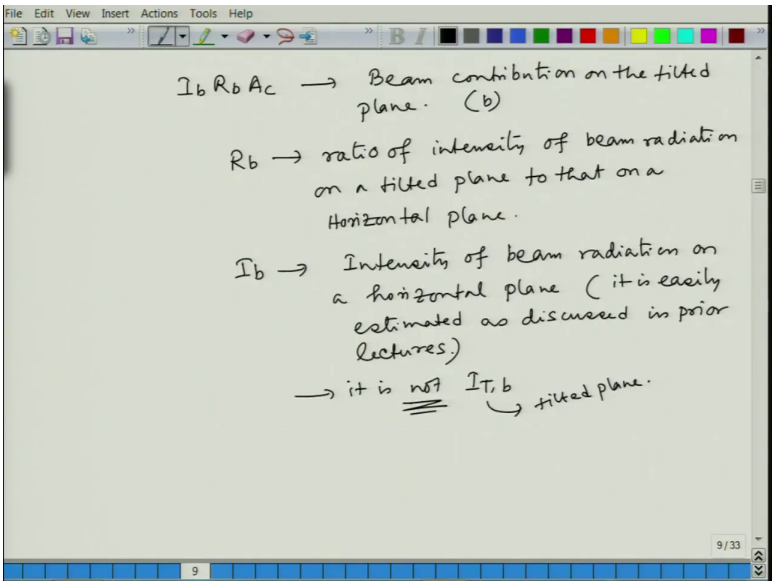

So, first thing is the first term which is I b R b A c. So, this is the beam contribution on the tilted plane ok and that is designated with this subscript b right. Now what is R b? This is a new symbol coming abruptly. So, let me explain. So, this is the ratio of intensity of beam radiation on a tilted plane to that on a horizontal plane.

Why do we need to connect it to the horizontal plane? Because in earlier lectures we have seen that all the prediction models that predicts the availability of total solar radiation they give you some values on the horizontal plane ok. So, whenever you want to predict it on a tilted plane, you need a conversion factor ok. So, that is why this R b is important and how that is calculated, what it means will come in a while.

So, that gives you the conversion from horizontal plane value to the tilted plane value ok. And this I b here is also not the tilted plane value because. So, I b is the intensity of beam radiation on a horizontal plane and that is what is easily estimated. It is easily estimated as discussed in prior lectures and it is different it is not I T, b which was used earlier. So, this T is absent here, this stands for tilted plane ok. So, it is not I T, b please remember this ok.

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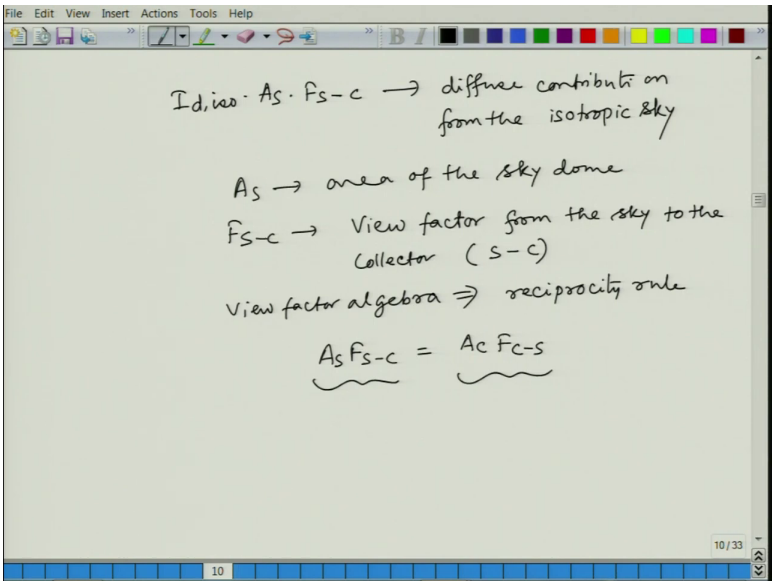

So, that is the first term then let us take the next term which is I d, iso multiplied by A s multiplied by F s c what does it mean? So, this term actually is the diffuse contribution from the isotropic sky ok; iso you can see it is there that tells you that its isotropic sky, small d stands for the diffuse radiation, what are the other things?

So, A s is the area of the sky dome. So, it depends on where you let your imagination go, where you go, what is the size of the sky dome you are taking the radius that you are taking and there you have to take the intensity of the sky ok. So, and the A s will be area at that location wherever you are setting the boundary of your sky dome and its the choice is with the engineer or you. And what is F s c?

Can you guess by this time? You have seen this in your radiation heat transfer course right or class. So, there this is the view factor. View factor between or view factor from the sky to the collector this what it means s stands for sky and this dash; that means, to the collector.

So, if some object is there which is looking from the sky dome how much portion of that will be visible to the collector that is what the view factor is it is a geometric factor right and if you are confused with this view factor please go back to your radiation heat transfer class and look at this or a text book where view factor is discussed. So, view factor algebra also gives us it gives us the reciprocity rule.

What does it mean? It means that this A s multiplied by F s c will be equal to A c multiplied by F c s ok. If you look from the sky to the collector that is this and if you look from the collector to the sky that is this and this product of the view factor and the area will be same irrespective of from where you are looking at ok. So, this relation will be applicable.

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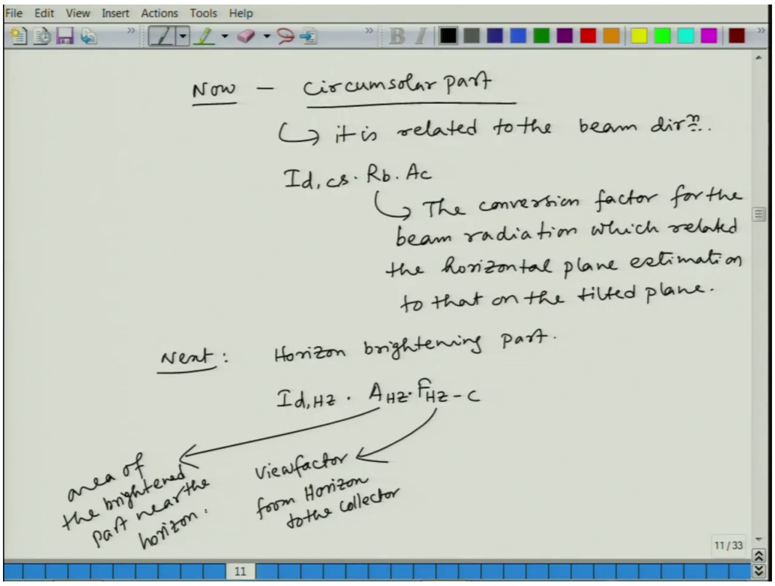

Now, the next part which is circumsolar part ok. So, this circumsolar part you have seen so, far that it relates to the direction of beam ok. So, it is related to the beam direction ok and that is why we write it this way; I d, cs that is circumsolar and then R b, A c. So, we do not need a view factor there, but we do need the conversion factor for the beam radiation which relates the horizontal plane estimation to that on the tilted plane.

This is diffuse radiation of course, but it has a directional notion as well that is why we are including this R b factor to this particular term ok. Next the horizon brightening part ok. Again just like the isotropic sky or isotropic part of the diffuse radiation, we will use the view factor correlation because again it does not have a direction specific value ok that is why we see that we have this I d horizon multiplied by A horizon.

So, you have to again fix how far you will allow the horizon to go and depending on that you will have the area of the horizon brightening area and the intensity there and we will have this view factor as well ok. So, this is view factor from horizon to the collector sorry that is the this is the view factor and here A z is the area of the brightened part near the horizon that is how we designate it.

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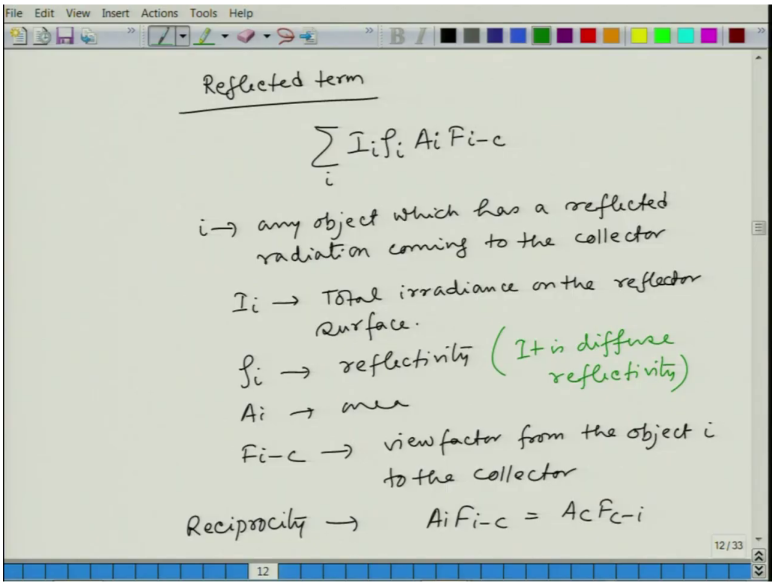

And the last term is the reflected term which is a summation term ok. So, this is I i rho i A i F i dash c and summation is over i. So, for each. So, i is any object which has a reflected radiation coming to the collector ok. So, it is getting reflected from that object i and that coming to the collector.

Now, this I i is now the intensity or the total intensity on that reflected or reflector surface ok. Total irradiance on the reflector surface and rho i is the reflectivity of that surface ok. A i is the area and F i c is again the view factor ok, view factor from the object i to the collector.

Again, we will have the reciprocity whenever we require to use it. Reciprocity means; A i multiplied by F i c will be equal to A c multiplied by F c i ok. So, this you have seen earlier; and here we need to remember that this reflectivity ok, it is diffuse reflectivity ok.

So, whatever we are not considering specular, we can consider then that will be a separate term, but this is the specular reflectivity I mean non specular reflectivity or diffuse reflectivity whether beam or diffuse radiation is coming on the reflector surface, what is going out of that is always the diffuse radiation that is the assumption we are taking.

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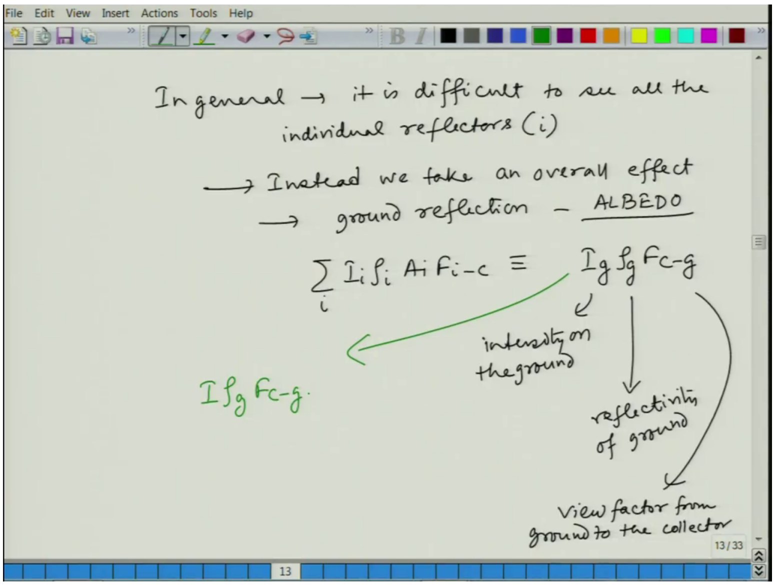

So, in general it is difficult and often not necessary as well to see all the individual reflectors; that means, all these different objects i that we do not count or we do not need ok. So, what we do? Instead we take an overall effect which we call ground reflection or often that is also called ALBEDO. This term you will see here and there, but basically it means the ground reflection. So, the whole term this whole summation i I i rho i A i F i c we equivalently write it in terms of this I into.

So, rather I g rho g F c g ok what it means? This is intensity on the ground. So, as if we have a single body. The overall effect is captured in a single body the intensity of that is I g and this is rho g is reflectivity t v t of ground and this F c g is the view factor from ground to the collector ok and often this term is written as I rho g F c g.

Because that particular g on the ground that is the horizontal plane right ground is assumed to be the horizontal plane even if you have some undulations. So, the effective horizontal plane that is the ground level and the same symbol that we use i without any subscript; that means, the intensity on the horizontal plane. So, this we can write.

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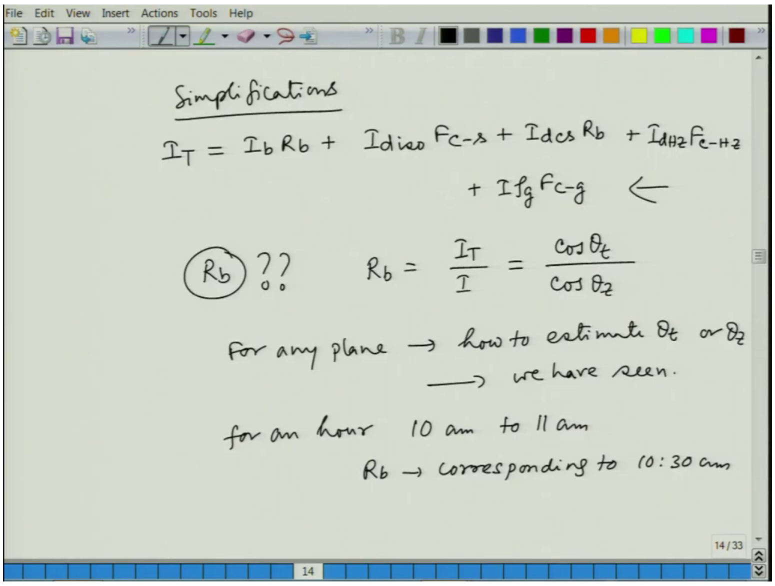

Now, if we now put all the simplifications what we can write that this I T will be I b R b plus I d iso F c to s plus I d cs multiplied by R b plus I d horizon multiplied by F c to horizon plus I rho g F c to g. So, from the last relation that we wrote from there we have divided the whole thing by the area of the collector A c and have used the reciprocity relation whenever it is applicable ok, that is how we obtained this particular relation ok. So, far we have not talked about the R b which is very important and what is this R b?

R b is nothing but the factor that relates the intensity on the tilted plane with that of the horizontal plane ok. So, this is nothing but the ratio between the two incidence angles one is the cos of that incidence angle on the tilted plane and for the horizontal plane, the incidence angle is the zenith angle right. So, cos of zenith angle ok. So, this is simple and for any plane we have seen earlier how to estimate theta t or theta z. So, this we have seen right.

So, well and good, but the problem is that the theta t and theta z they are changing in every minute right it is a continuous variable. So, what we do? We take for an hour suppose for an hour.

So, 10 am to 11 am what we do? We take the R b corresponding to 10.30 or the midpoint of that hour. So, R b corresponding to 10.30 am that is how we estimate R b because it is not possible to do in every minute and take the overall effect. So, what we do? We take the midpoint of that.

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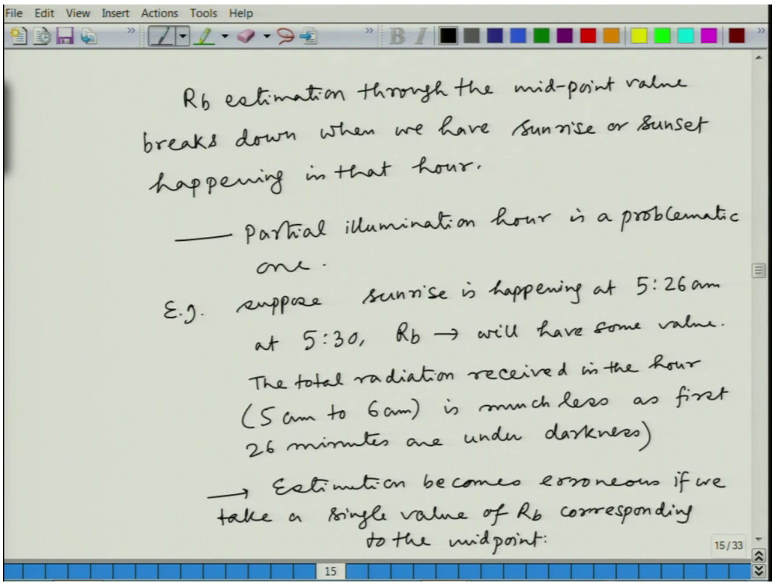

But that particular assumption breaks down when we have the our R b estimation through the midpoint value breaks down when we have sunrise or sunset happening in that hour or rather the partial illumination hour is a problematic one, is not it? So, what to do with that? So, what do you mean by that? So, for example, so, suppose sunrise is happening at 5:26 am ok.

Now, at 5:30 estimated R b will have some value right and the total intensity or the total radiation received in the hour between 5 am to 6 am is much less right as first 26 minutes are under darkness right because sun has not risen till the first 26 minutes. So, the estimation becomes erroneous if we take a single value of R b corresponding to the midpoint ok.

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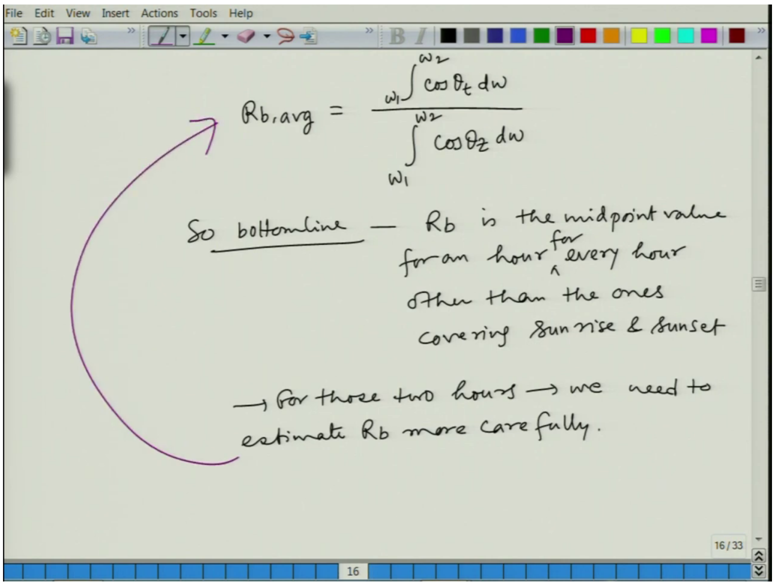

So, what we need to do then? We take an average value of R b corresponding to the whole period ok. So, we integrate the tilted plane incidence angle cosine of that throughout the available period of solar radiation and we do the same thing for the zenith angle and take the average, then it is not a single midpoint value, but it is the average of the whole illuminated hour that is how we do this ok.

But, so, the bottom line is R b is the midpoint value for an hour every or rather for every hour other than the ones covering sunrise and sunset for those two hours we need to estimate R b more carefully by using this kind of method ok.

So, here I stop for this class and next in the next class we will see we will use all these information and we will estimate exactly and we will also see what are the different assumptions we can make. We do not have to take all the components all the time, it depends on the accuracy level that we demand ok.

Thank you very much for your attention.