Solar Photovoltaics: Principles, Technologies and Materials
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Lecture - 06
Solar Radiation Measurements

So, welcome to this lecture number-06 of Solar Photovoltaics course Principles Technologies and Materials. So, we will just do a quick recap of lecture number 5.

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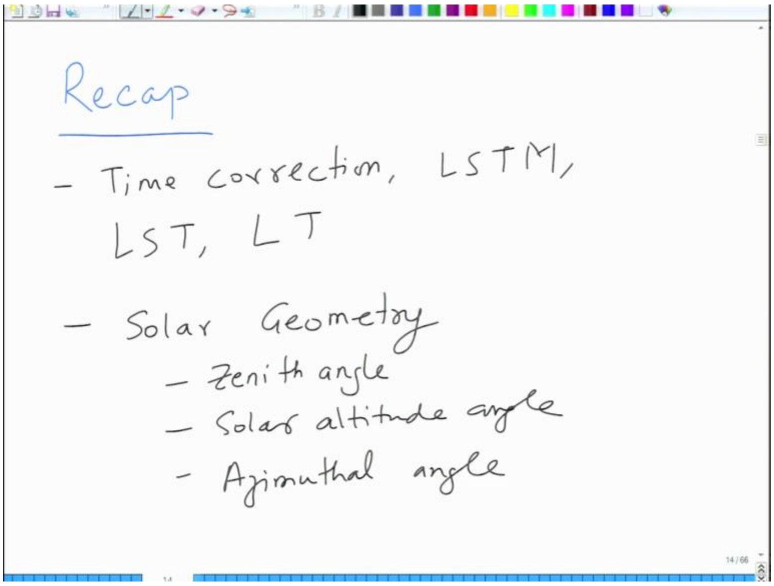

In the previous lecture, we looked at essential methods to correct for time. So, we looked at time correction, concept of LSTM local solar time, local time; so, basically how to correct for actual solar noon and the one which is predicted by your watches. So, these are nothing, but geometrical corrections based on the location of longitude and latitude, because the whole country is by clock is in one time zone, whereas the actual time at a given location may be different from what is given in your watch and that is because of geometrical corrections.

For example, the longitude of Kanpur is different from longitude in Calcutta. So, obviously, Sun would actually rise earlier in Calcutta than Kanpur. So, for Calcutta and Kanpur, the 12 O'clock in clocks will be at the same time, but the noon will happen at the different time so you need to correct for these discrepancies.

And we also got into solar geometry. So, we looked at things like zenith angle, we looked at solar altitude angle, we looked at various azimuthal angles and so on and so forth.

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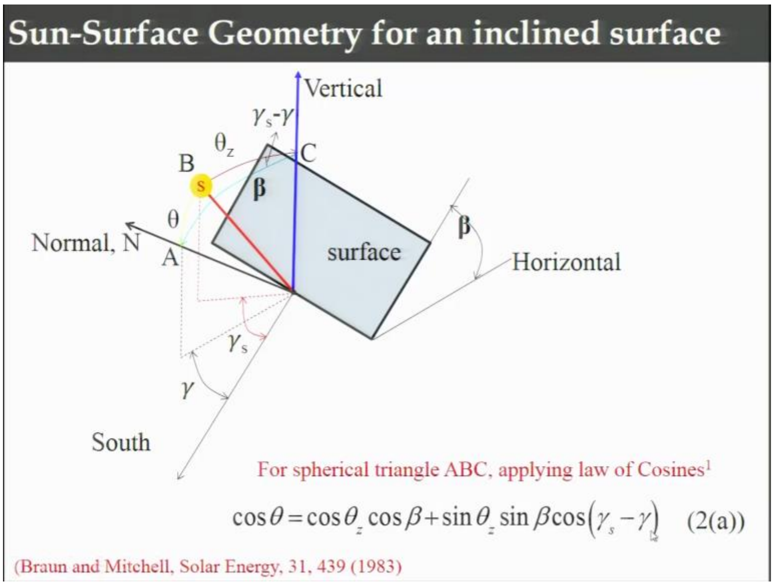

So, when we finished, we were just looking at the geometrical relationships for a inclined body, so let us now switch over to the PPT. So, we were looking at this kind of geometry, where a surface that you want to use is inclined to the horizontal. And this makes an angle beta with respect to the horizontal. And the arrow pointing in this direction is the south arrow and so south in this direction, and north obviously would be opposite of that. And this is the vertical to the horizontal and this is the Sun.

So, sun ray is coming at certain angle to the surface. So, sun ray comes at certain angle to the horizontal, but since the surface makes beta angle with respect to horizontal you need to make that correction in the angle for sun ray on the horizontal surface, so that beta have to be subtracted from the total overall angle. So this is the angle between the vertical and the Sun which is the zenith angle, then we have normal to the surface, so there is a difference between the vertical and the normal to the surface.

Vertical is vertical to the horizontal whereas normal, N is the normal to the surface. So, which means the angle between normal and vertical is going to be beta, because the angle between the surface and horizontal is beta. So, these two angles are going to be beta. And then you can also define some other angles the angle between sun ray and the normal is theta. Angle between the projection of sun ray on the horizontal and its angle with the south is called as gamma; s, solar azimuthal angle the angle of surfaces normal projects its projection on the horizontal and its angle with the south is called as gamma.

So, based on variety of these angles you can define this sole triangle ABC. And by the equivalence of in the geometry you can see that angle between BC and AB will be gamma s minus gamma. So, if we do now, we will not get into details of trigonometry, but if we apply the law of cosine, we will get cos theta relation as cos theta is equal to cos theta z cos beta plus sin theta z sin beta into cos gamma s minus cos minus gamma.

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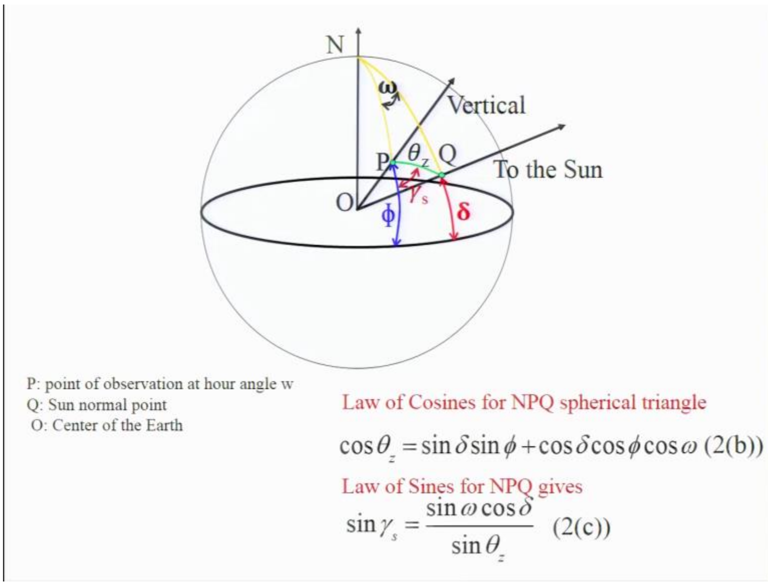

Now, we can represent the whole thing in a different way, in this kind with respect to Earth being is a sphere, and Sun being somewhere around it; so, which is sort of a legitimate design. And again, using the equal law of the cosine, we can determine cos theta z which will be equal to sin theta sin phi plus cos delta cos phi cos omega.

So, we can see that in the previous one we had relation for cos theta now it is a relation for cos theta z it is a zenith angle. And law of sin s will again give you relation, so the idea is to get two expressions where you require minimum number of angles to make predictions. So, law of sins will give you sin omega gamma s which is the solar azimuthal angle in terms of omega delta and theta z.

We see some of these angles are easy to work out. For examples, zenith angle, it can be found out easily. And delta is the declination angle and omega is the hour angle. So, these three angles are easy to decipher, whereas solar angle azimuthal angle is not decipher. So, you would like to replace the quantities which are not given easily by the quantities which are available to us, so that is why these three expressions come into being.

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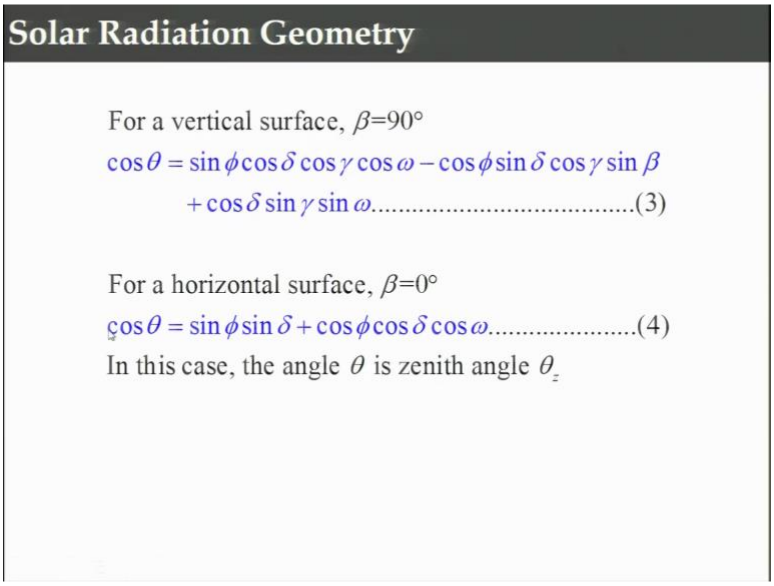

Now, we just simplify these expressions; so, vertical surface with beta is equal to 90 degree. This simplifies to cos theta to sin phi sin delta cos gamma cos omega cos phi cos sin delta cos gamma sin beta and another term including cos delta sin gamma and sin omega. So, we can see here phi is the position dependent term; delta is the declination angle which is day dependent term. Gamma is the angle of surface normal with respect to north south, so that we may have to define; omega is the hour angle.

So, these three angles phi, delta and omega are easily known, whereas gamma we would know because of orientation of surface. Similarly, for a horizontal surface, this even simplifies further, because then beta becomes equal to 0 degree; so, all the cos sin beta terms become sort of 0; so, as a result now this cos theta is only sin phi sin delta plus cos phi cos delta cos omega. So, here everything is easily determinable, phi is the position dependent term, delta is the declination angle, phi is again position dependent, delta is declination angle and omega is the hour angle.

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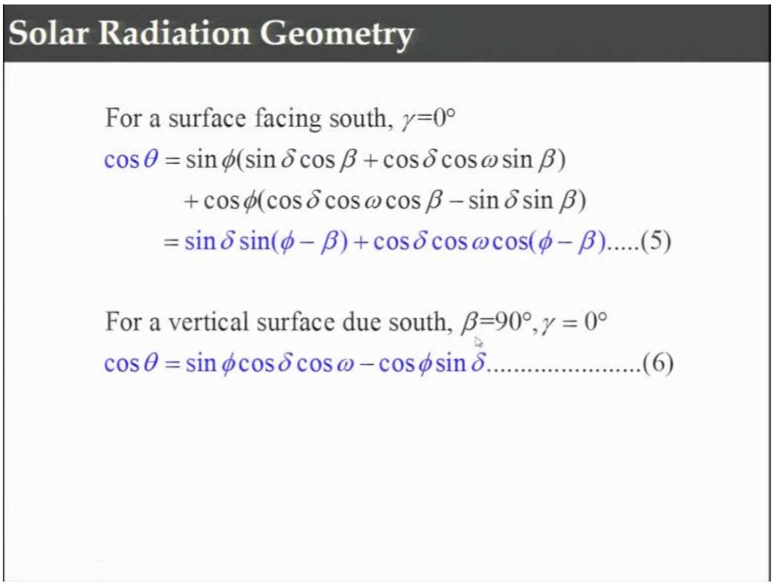

So, this is how you can do for various things. We can simplify over for a surface which faces south. For a surface which faces south, the projection of normal coincide with the south line. So, as a result gamma becomes equal to 0. Again, this equation gets simplified to cos theta is equal to sin delta sin phi minus beta plus cos delta cos omega cos phi minus beta. And beta is the angle of inclination, phi is position dependent term, de delta is day dependent term and omega is time dependent term.

We can also further simplify for a vertical surface due south. So, in this case beta is 90, gamma is 0. So, this again gets simplified to cos theta term; so, basically the ideas to determine cos theta. What was cos theta? Theta is the angle between the sunbeam and the so, if we go back to previous picture, theta is the angle between the sunbeam and the normal to the surface. So, basically this is what we are interested in determining.

So, if we have inclined surface which does not phase south then it gets complicated, but if you make simplifications like surface facing south or surface being horizontal, surface being vertical these becomes little bit simpler. So, these are approximations one can make.

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Solar Radiation Geometry

We can also express the angle of incidence θ in terms of zenith angle θ_z, slope β, surface azimuthal angle γ, and solar azimuthal angle γ_s as following:

$$\cos\theta = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(\gamma_s - \gamma) \quad \text{.................(7)}$$

Solar azimuthal angle γ_s is obtained as following:

$$\cos\gamma_s = \left(\cos\theta_z \sin\phi - \sin\delta\right) / \sin\theta_z \sin\phi \quad \text{........................(8)}$$

However, we can also determine for a surface which is at certain angle. So, in that case we need to know delta gamma.

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Sunrise, Sunset, Day Length

For a horizontal surface, we can find out the hour angle ω_s corresponding to sunrise or sunset by substituting θ_z=90° in eqn (4) i.e.

$$\cos\omega_s = -\tan\phi \tan\delta \quad OR$$

$$\omega_s = \cos^{-1}\left(-\tan\phi \tan\delta\right) \quad \text{..(9)}$$

= (+*ve* for sunrise and -ve for sunset)

Maximum Day Length

$$S_{max} = \frac{2}{15}\cos^{-1}\left(-\tan\phi \tan\delta\right) \quad \text{......................................(10)}$$

So, we can also define few more things sunrise, sunset and day length. So, for a horizontal surface, one can find out what is the hour angle corresponding to sunrise, sunset. And for this we determine theta z to be equal to 90 degree in the previous equation. So, cos omega s is equal to minus tan phi tan delta or omega s can be written as cos inverse minus of tan phi tan delta. And this value is positive for sunrise and negative for sunset.

So, since omega s is positive for sunrise negative for sunset, day length can be found by omega s minus of minus omega s. So, basically this becomes 2 omega s. So, if we look at the whole equation, day length, S max is equal to 2 divided by 15. So, 15 is nothing but we know 360 degrees in 24 hours. This 15 is it in hours basically. So, if we look at the whole thing 15 into S max is equal to 2 into cos inverse minus tan phi tan delta; 2 into cos inverse minus tan phi tan delta is omega s.

So, this is 2 of omega s equal to 15 into S max, 15 is coming because of we want to calculated in hours. If we did not want to calculate it in hours we can eliminate 15. So, maximum day length is 2 divided by 15. So, 2 omega s divided by 15 and we substitute omega s from the previous equation. So, all of this is valid for northern hemisphere. If we need to go for southern hemisphere, we need to make appropriate corrections in the equation which is simple.

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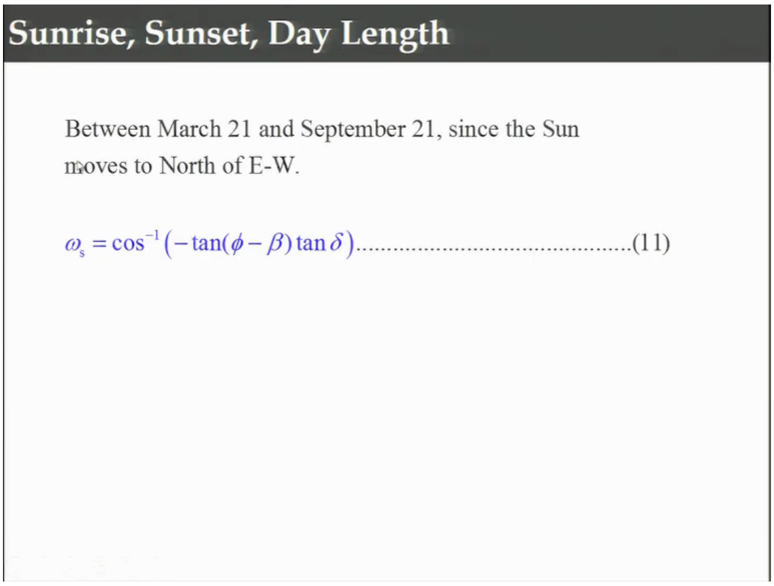

So, this is for an inclined surface, this is for a horizontal surface. But for an inclined surface between March 21 and September 21, we can see as the Sun moves. So, sun goes from East to West, but in winter its more southish, in the summer its more northish. Sun is mostly top in the summer. So, it moves to the north of east-west as a result between 21st March and September 21 and the equation gets modified as it is for inclined surface omega s is equal to cos inverse minus of tan phi minus beta into tan delta. So, we need to consider the beta thing into account for this period.

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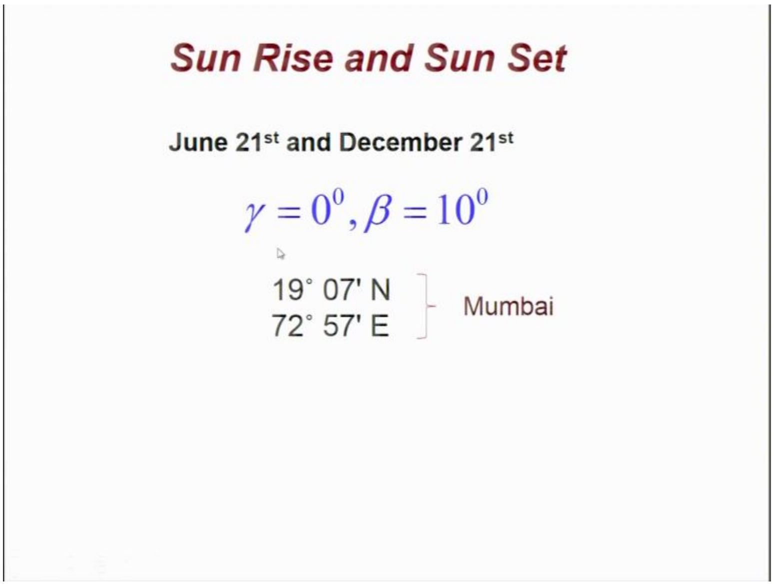

So, for example, let us see for certain position of sun rise and sun set. So, we can say for June 21st and December 21st, let us say gamma is equal to 0, which means surfaces facing due south, and beta is equal to 10 degree. And let us consider Mumbai whose location is 19-degree 7 minutes North, and 72 degree 57 minutes East. So, phi is given as 19 07.

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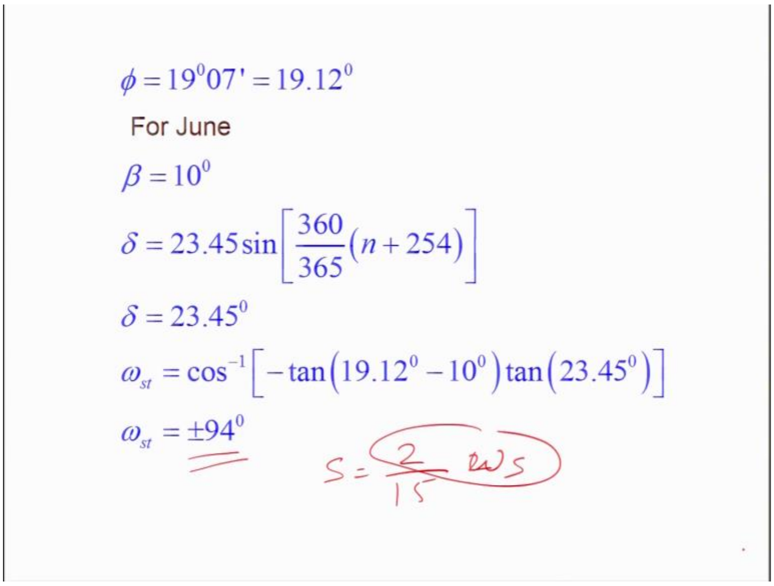

So, phi is 19 07 which is 19.12 degree. For June, beta is equal to 10 degree. You can find out delta, delta is 23.45 sin of 360 by 365 into n plus 254.

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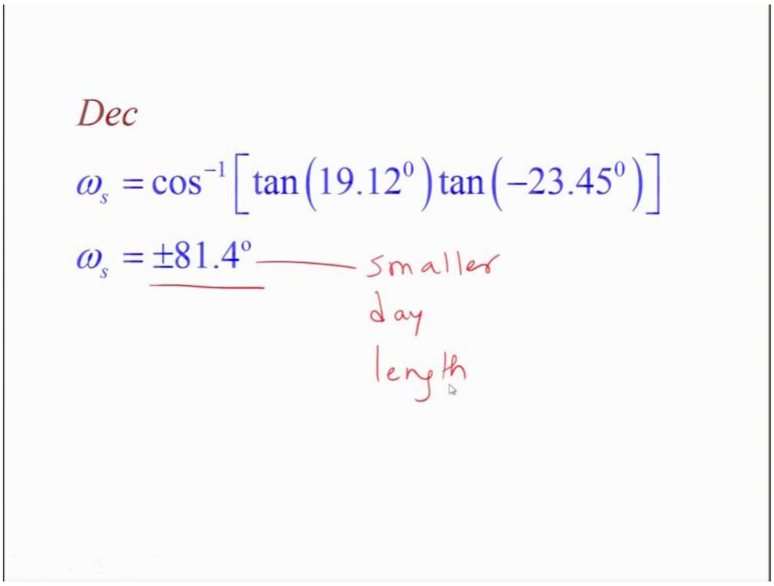

So, this will be your delta value. Then omega can be calculated as cos inverse minus of tan for inclined surface phi minus beta. So, this is phi, this is beta tan of 23.45. And so, as a result omega is minus plus minus 94 degree for sun rise and sun set. So, this can be converted to day length.

And for December you can make the similar calculation. For December it would be cos inverse tan 19.12 degree; [FL] in that you can reduce and eliminate the beta. So, beta goes off and tan of minus 23.45. So, this comes to be plus minus 81.4. So, you can now look at the wide day length, obviously, can see that 2 omegas will be larger in case of June than in case of December. So, you can see that your day length will be higher.

So, if we write here, s will be equal to 2 divided by 15 omega s. So, we can see that this will be larger in this case. Whereas, if you go to next one this is a smaller, as a result smaller day length is obtained for December. So, these are simple calculations we can do for where ever you are.

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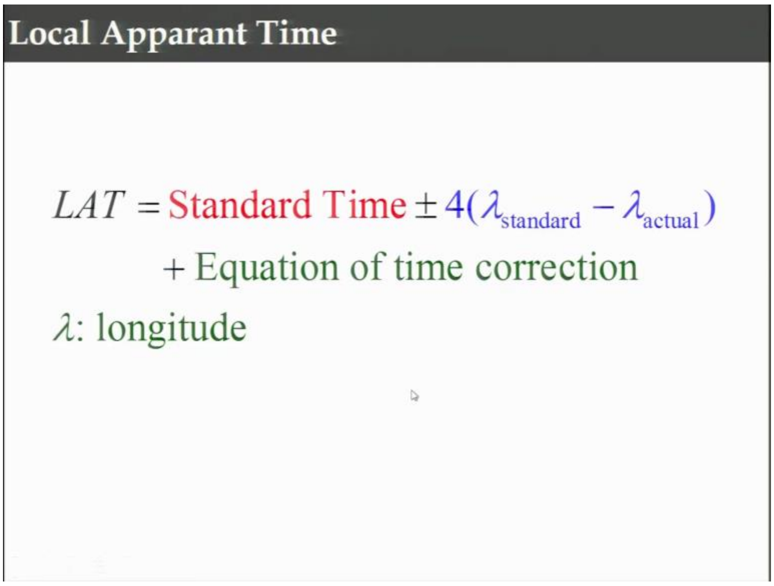

$$LAT = Standard\ Time \pm\ 4(\lambda_{standard} - \lambda_{actual}) + Equation\ of\ time\ correction$$
$$\lambda : Longitude$$

Now, let us look at another parameter which is called as local apparent time which is basically standard time plus minus 4 into lambda standard minus lambda actual. And lambda is nothing but the longitude plus equation of time correction that we looked at earlier. So, local apparent time is equal to standard time plus minus 4 into lambda standard minus lambda actual plus equation of time correction.

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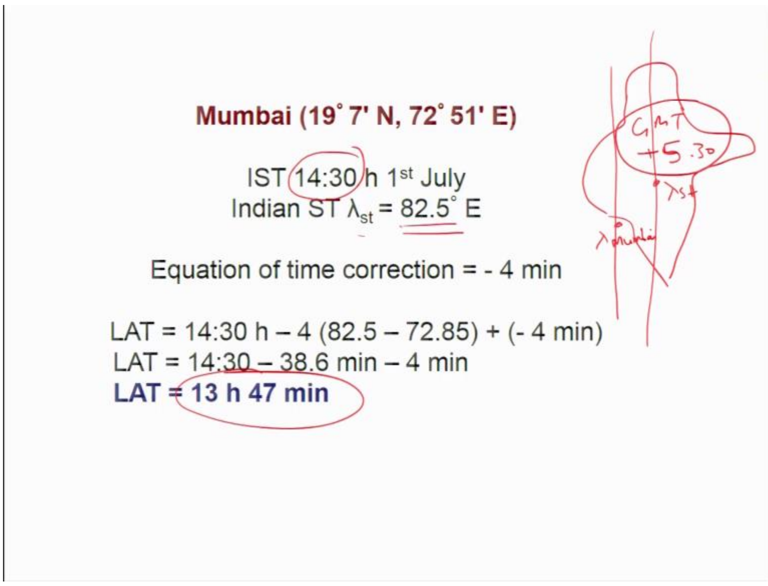

And so if you now look at Mumbai again, Mumbai is longitude latitudes are given. Let us say, IST 14 hours 30 minutes on first of July and Indian standard lambda is 82.5-degree East. So, if you look at equation of time correction, it is minus 4 minutes. So, a standard time is given according to this, because this is your India let us say not very good map, but right. So, Mumbai is somewhere here. Latitude of longitude, the geometrical parameters of Mumbai are different with respect to GMT plus 5.30.

Now, this GMT for 5.30 will correspond to certain lambda value, because longitude of 5.30 would be some from the middle of India which is about Nagpur. So, this would be your standard lambda. Whereas, Mumbai is here this is lambda Mumbai. So, there is a difference here. So, equation of time correction, if you go to previous equation in the previous lecture, it will be turn out to be minus 4 minutes. As a result, local apparent time will be 14.30 hours minus 4 into 82.5 standard lambda minus the actual lambda which is 72.85 plus minus of 4 minutes.

And if you work this out, it comes out to be 13 hours 47 minutes. So, your clock shows the time of 14.30 hours, but actual time in Mumbai is 13.47 hours. Similarly, if you do the same calculation for a Arunachal Pradesh the actual time will come ahead. So, if you look at 14.30 hour’s time, it will become 15.30 for example, in case of Arunachal Pradesh. So, this is how time corrections have to be made for calculate in the actual time.

So, what we have discussed so far is related to the time corrections and geometries and how to calculate angle of solar radiation with respect to a surface that is what we have done. And we have looked at a time correction which will help us in calculating the radiation at appropriate time. So, these are the two things you need the direction and the time.

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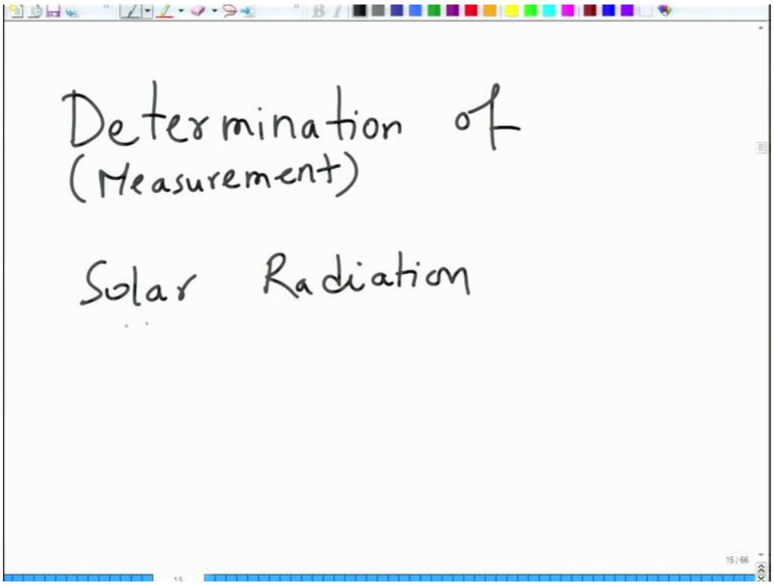

Now, let us look at measurement of solar radiation. So, solar radiation can be defined in various fashion. And lot of these most of these methods of determining solar radiation at a given location or a given day given time are mostly empirical in nature. So, we will not look at all the models due to scarcity of time, we will only look at a few of them.

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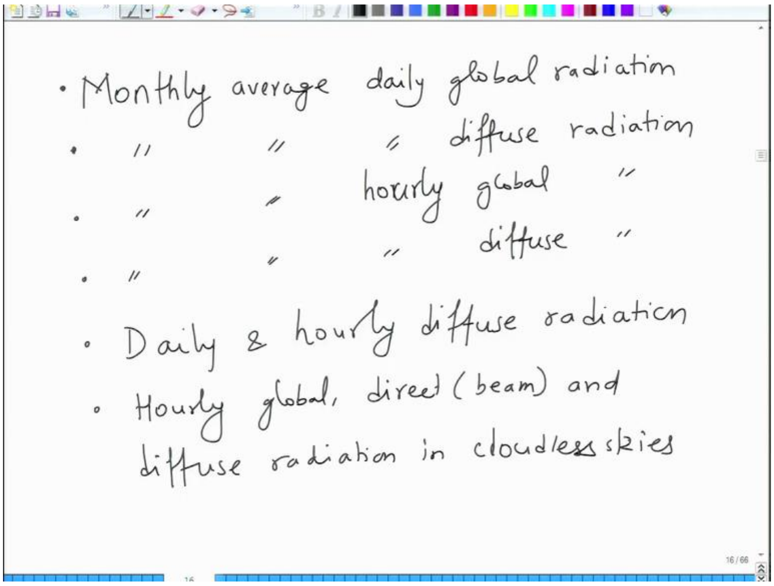

So, the way you define solar radiation measurement there are methods of there are ways in which different people have done. So, for example, first method to decide solar radiation is monthly average daily global radiation. Now, here the trick is you have to measure direct radiation, you have to measure diffuse radiation, and then it can be averaged over a month, it can be average over a day so on and so forth.

There are various models for various definitions such as monthly average daily global radiation, monthly average daily diffuse radiation and monthly average hourly global radiation, then we have monthly average hourly diffuse radiation. And then we have daily and hourly diffuse radiation, and then we have hourly global direct which is also called as beam radiation and diffuse radiation in cloudless skies.

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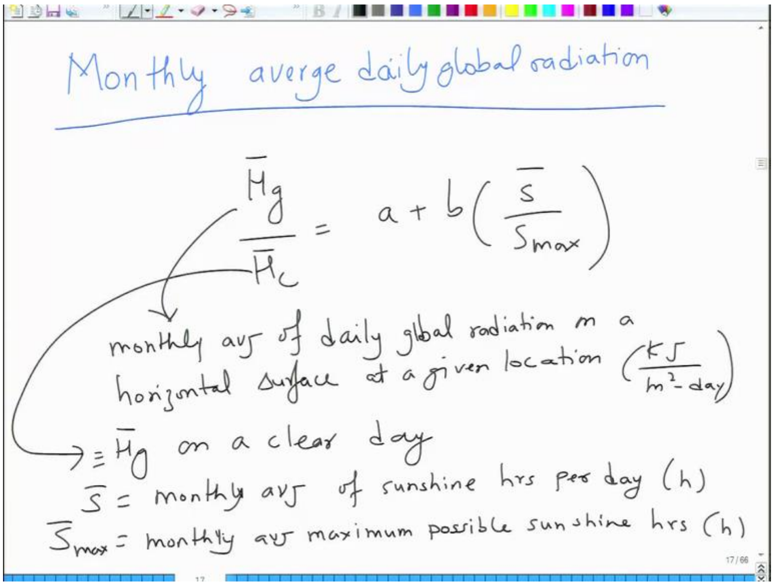

Monthly average daily global radiation

$$\overline{H}_g/\overline{H}_c = a + b(\overline{S}\ /S_{max})$$

So, let us first look at monthly average daily global radiation. So, in this case, the first attempt was made by Angstrom. He said H g bar is divided by H c bar which is a plus b into s bar divided by s max. Now, what are these quantities? Now, H g bar is basically monthly average of monthly average of daily global radiation on a horizontal surface at a given location. And this is in kilo joule per meter square per day. Similarly, H c bar is monthly average of daily global radiation on a horizontal surface at the same location on a clear day.

So, essentially H g bar is equal to H g bar on a clear day. This is on a general day; this is on a clear day again the same thing. s bar is defined as monthly average of sunshine hours per day at the location. So, this is in hours. And then we have s max, you can guess what it would be, it would be monthly average of maximum possible sunshine hours at a given location that is there on the horizontal surface [FL].

So, monthly average maximum possible sunshine hours at the same location on a horizontal surface; and then a and b are the constants which are empirical constants used for data fitting. So, this is mostly empirical. This H g was H c was not very easy to calculate H c bar which is maximum average of daily global radiation on a horizontal surface on a clear day, it is not very easy to mention.

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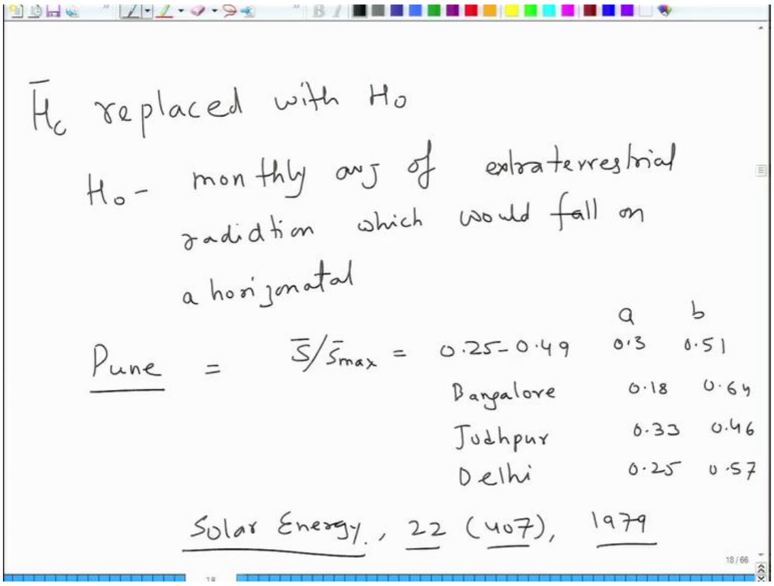

So, H c bar was replaced with another quantity H naught. And what is H naught? Monthly average of extraterrestrial radiation which would fall on a horizontal surface. So, many of these quantities are changed because previous quantities were not easy to obtain as a result changes are made. So, essentially you can do the calculations and work out various values.

For example, for Pune in India, the value of S bar to S max was about 0.25 to 0.49 with a value being 0.3 and b value being 0.51. You can do for various other locations example, place like Bangalore, for which values of a and b would be 0.18 and 0.64 respectively.

If you look at a place like Jodhpur, Jodhpur will give you a value of 0.33 and 0.46. And if you look at something like Delhi, Delhi would be 0.25 and 0.57. So, these data you can obtain in literature. So, there is a paper in solar energy 22, 407, 1979. So, this is the volume number; this is the page number; this is the year number, and this is the name of the journal. Now, so this is what we defined here was, this was the monthly average daily global radiation.

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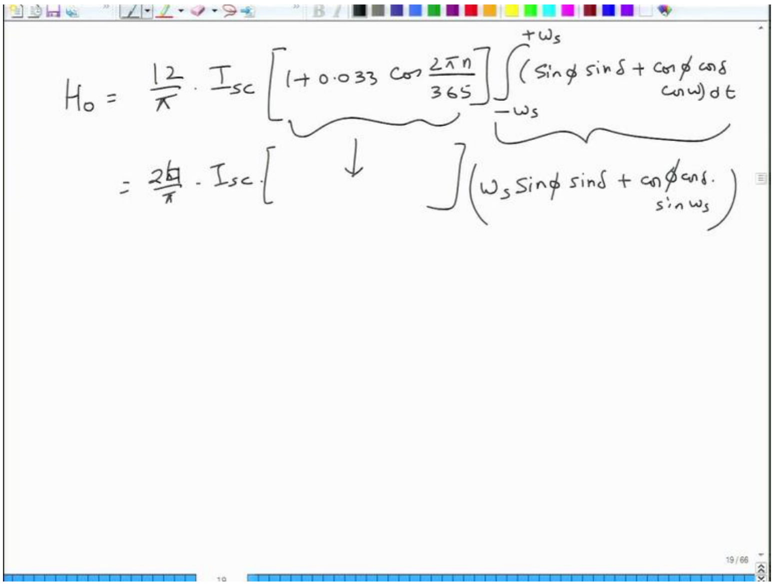

So, how do you work out? Now, H naught is the monthly average of extra-terrestrial radiation that would fall on a horizontal surface. H naught is given by equation; 12 divided by pi into I s c which is the solar constant into 1 plus 0.033 cos of 2 pi n divided by 365, and then you integrate it over whole day.

So, this is essentially cos theta term integrated. So, sin phi sin delta plus cos phi cos delta into cos omega over d over whole time; so, the cos phi term integrated over the whole day and that is what you will obtain for a given location. And this would turn out to be omega s sin phi sin delta plus cos phi cos delta into sin of omega s, this is what this term will turn out to be.

And, if you do this it will become 24 by pi into I s c into the term that you have here and this term 24. And this can be simplified by I mean for a given month and it was found by scientist that you can find average day for a month.

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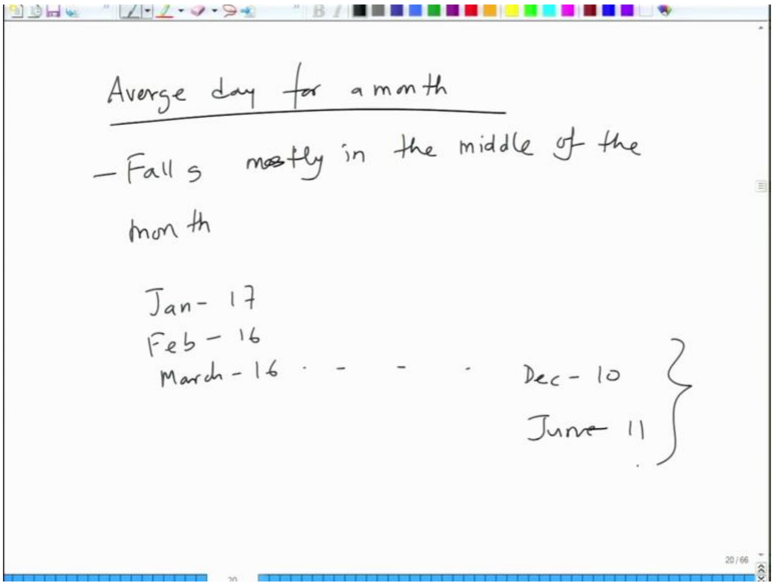

So, if you want to find out the monthly average you can just choose that particular day. So, for example, say average day for a month and this average day falls mostly in the middle of the month, it is not exactly middle, it changes. So, for example, for January it is 17; for February it 16; for March it is of course, this has come after empirical data fitting. So, it is not just you take 15th of January 15th of Feb. Calculations and measurements are made for the whole month and then average out the values and see which day corresponds to the average of it. So, this is what various values would be like.

Whereas for December, it becomes 10; and for June, it is 11th. December show a bit of deviation because June and December are months where you have longest day and longest night. As a result, they have bit of deviations in these two months, but other months show fairly the average days fairly in the vicinity of 15th of every month.

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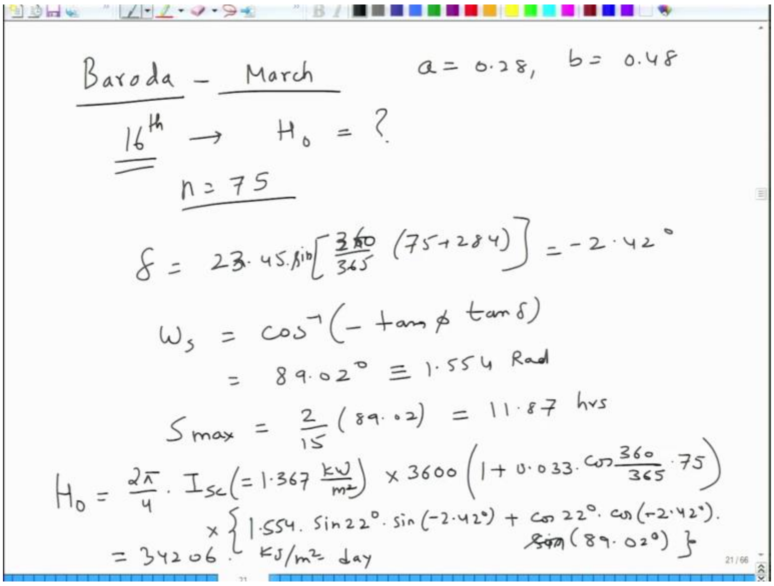

So, if you want to calculate the monthly average radiation let us say in Baroda. For Baroda in March, a is 0.28, and b is 0.48. The average day is 16th. H naught for 16th needs to be calculated and this works out to be equal to 75th day of the year.

So, delta is 23.45 into sin of 2 pi divided by 365 you can say 360 divided by 365 into 75 plus 284, this will give you angle of minus 2.42 degree. Omega s, since it is before 21st of March this is cos inverse minus of tan phi tan delta. And this will be nearly 89.02 degree which is equivalent to 1.554 radiance.

So, we can find out S max which is 2 by 15 into omega s. So, this is 2 by 15 into 89.02. And this turns out to be 11.87 hours all right. H naught can be found by 24 by pi into I sc which is equal to 1.367 kilo watt per meter square into 3600, 3600 is a correction you can see, is for hour into seconds, and then you have 1.033 cos of 360 by 365 into 75 which is n value, and this is multiplied by omega s that is 1.554 into sin of 22. So, if you look at the equation, sin phi which is the latitude for Baroda into sin of minus 2.42 which is delta plus cos of phi which is cos 22 into cos of delta which is minus 2.42 degree into sin of omega s, which is eighty nine point two degree. And if you do the calculation this will turn out to be 34206 kilos joules per meter square per day.

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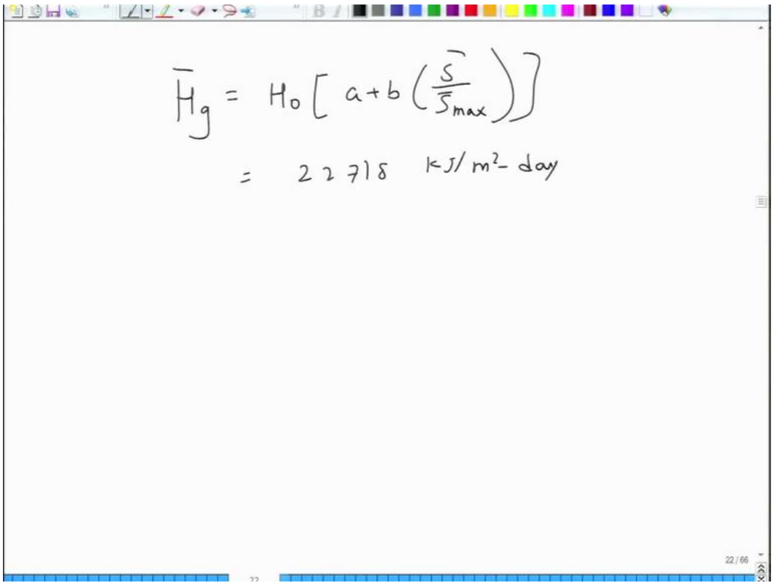

So, if you now make the calculation of H g bar which is the average daily global radiation which is H naught into a plus b S bar divided by S max bar this will be 22718 kilo joules per meter square. The daily global radiation for a given location in Baroda in the month of March is 22718 kilo joule per meter square per day.

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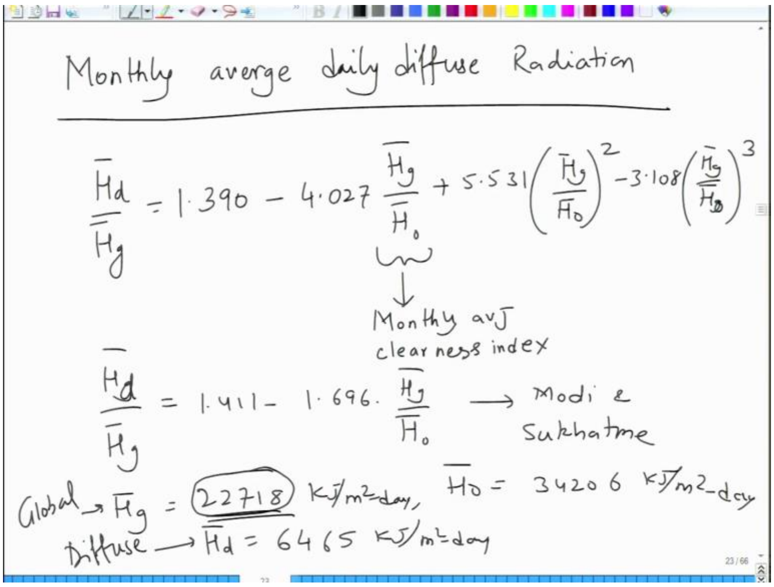

$$Monthly\ average\ daily\ diffuse\ Radiation$$
$$\overline{H}_d/\overline{H}_g = 1.390 - 4.027(\overline{H}_g/\overline{H}_o)^2 - 3.108(\overline{H}_g/\overline{H}_o)^3$$

$$\overline{H}_d/\overline{H}_g = 1.411 - 1.696(\overline{H}_g/\overline{H}_o)$$
$$\overline{H}_g = Global\ Radiation = 22718KJ/m^2 - day$$
$$\overline{H}_d = Diffuse\ Radiation = 6465KJ/m^2 - day$$

So, you can also calculate the monthly average diffuse daily diffuse radiation. So, this is again H d bar divided by H again empirical equation, H d bar is equal to 1.390 minus 4.027 H g bar divided by H naught bar plus 5.531 H g bar divided by H naught bar square minus 3.108 H g bar divided by H naught bar to the power cube. So, this is the daily diffuse radiation, and this is the daily global radiation; monthly average daily diffused radiation, monthly average daily. So, it is again a fitted equation. And this parameter H g bar divided by H naught is called as monthly average clearness index.

So, higher the H g bar is, more this ratio is going to be which means that day is clearer. When the day is clearer, your global radiation is going to be higher in number. And when this parameter is higher, as a result your diffuse radiation also tends to be smaller in amount. This equation has been modified for India. For India you can use a little bit modified equation H d bar divided by H g bar. This is the 1.411 minus 1.696 into H g bar divided by H naught bar. This is done by Modi and Sukhatme.

So, based on the values that you obtain for H g bar and H naught bar for a given day, you can calculate what the diffuse radiation is going to be. So, what we mean from the previous equation, you can just make the calculations. So, if your H g bar is 22.718 kilo joule per meter square per day, and your H naught bar was 3220, 34206 kilos joules per meter square per day. You can calculate what your H d bar is going to be H d bar is going to be 6465 kilo joules per metre square per day.

So, obviously, if you increase the value of H g bar, your H d bar will come down and right. So, direct radiation is nothing but H g bar minus H d bar. So, this is total radiation global. So, this is global; this is diffuse. So, your direct or beam radiation is global minus diffuse. So, 22718 minus 6475 will be the direct radiation.

So, idea is if we have higher amount of beam radiation, this number will go up as compared to diffuse radiation on a clear day. So, similarly there are models for monthly average hourly global radiation, monthly average hourly diffuse radiations, and I will not get into details of those.

So, we cannot cover all of these in this course.

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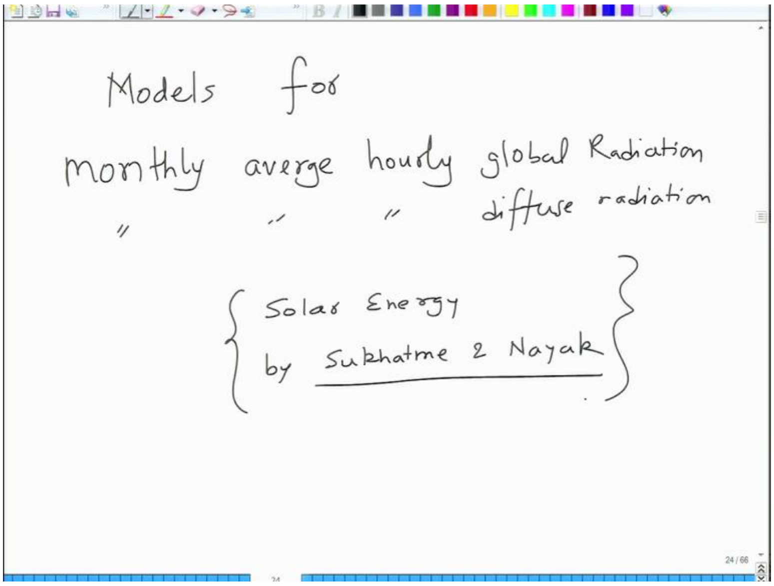

I think it is solar energy or solar thermal storage something like the name of the title is, but anyway you can find it out it is a book by Sukhatme and Naik. The first or second chapter of that book first few chapters of that book discuss these models for a daily average and daily diffuse radiation for given locations in India. So, it is a very nice calculation.

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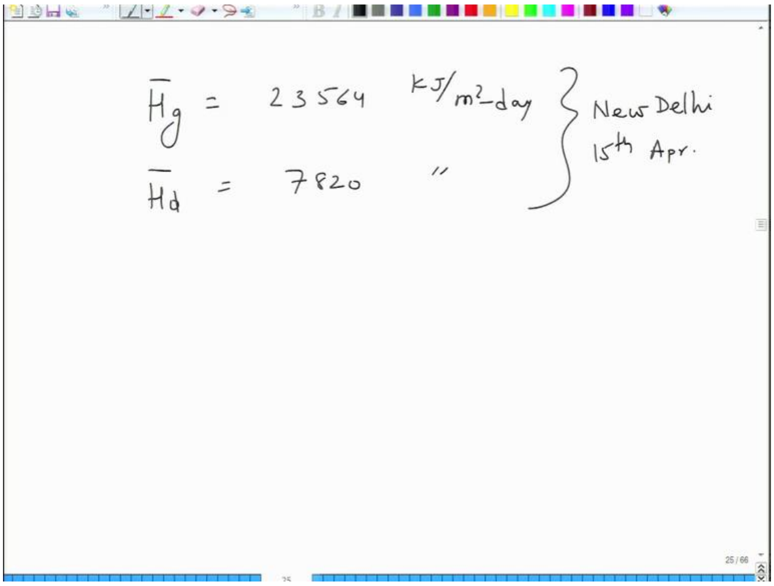

So, let us just give you the values for example, the values if you do on hourly basis, the H g bar turns out to be 23564 kilo joule per meter square per day. And H naught H d bar will be 7820 kilo joules per meter square per day. This is for example, for New Delhi on the April 15th, 15th April for a horizontal surface.

So, again there are empirical equations in which you need to provide the data and you need to calculate what the declination angle is going to be, what the value of hour angle omega s is going to be, what is the day length, similarly you need to calculate what is the extraterrestrial. So, equations are fairly similar, it is just that they have different empirical fitting constants. So, as a result they give you slightly different values. So, you can go to this book by Sukhatme and Naik, and read more about these models which provide these values.

So, if you know that your radiation is coming at certain angle. So, you know what is the global radiation, you know what is the diffuse radiation from this you can find out the direct radiation. Now, you know direct radiation comes directly. So, for a horizontal surface, it is fine, but for an inclined surface you will have to take cos theta of whatever the angle that the normal and the vertical that they make with each other. So, if it is cos if it is cos beta, you will have to modify that with cos beta so that much amount of drop in the direct radiation will happen for an inclined surface. But the diffuse radiation will remain same, diffuse radiation does not have angular dependence as a result diffuse radiation will remains fairly the same.

So, what will happen is that your global radiation for an inclined surface will change as compared to that for a horizontal surface. Of course, these values are time dependent as well because different times will give you different values. So, there will be times at which inclined surface will give you higher radiation, so that is why surfaces are kept inclined because they tend to take out the average value for the day.

Horizontal surface will get maximum radiation only when the Sun is at zenith. So, that is why you will see every solar panel is inclined to the surface at certain angle to average over the whole day in terms of receiving maximum solar radiation or average value of solar radiation which is nothing but AM1.5 G. So, there are models in the same book for tilted surfaces also and so on and so forth that you can read in the books.

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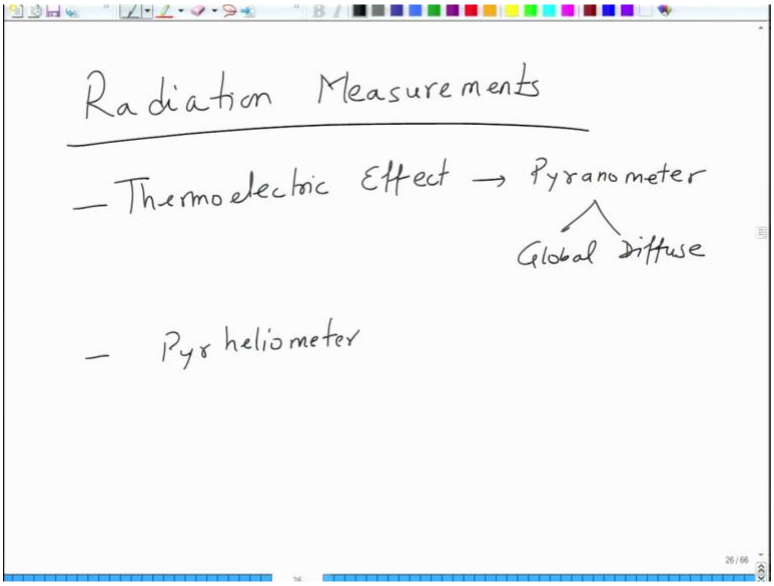

So, how you do the radiation measurement? Radiation measurement is done by basically based on thermoelectric effect. And for this we use equipment called as Pyranometer. And this can measure both global and diffused radiation. And the second one is called as Pyrheliometer. These are the two equipments which are used for measurement of radiation.

So, this was brief discussion on solar radiation, solar geometry, and solar radiation measurement. So, this is essential to know how the solar radiation is measured for a given surface at a given location.

In the next class, in the next lecture onwards, we will move on to the fundamentals of semiconductors which are essential to understand the p-n junction characteristics which nothing but a solar cell architecture. Since p-n junction is made of p and n type semiconductor, we need to know how the carriers move after the radiation absorbed within a solar cell. So, we will discuss that in the next class.

Thank you.