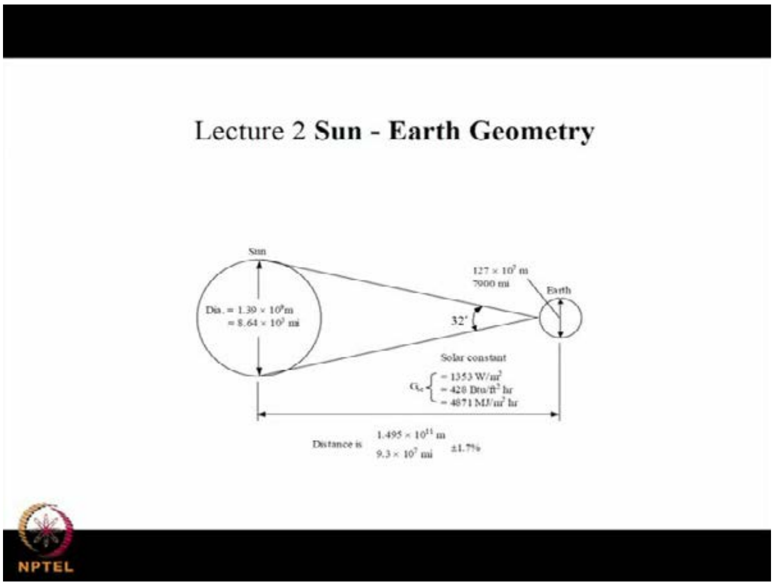
Solar Energy Technology

Prof. V.V. Satyamurty
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

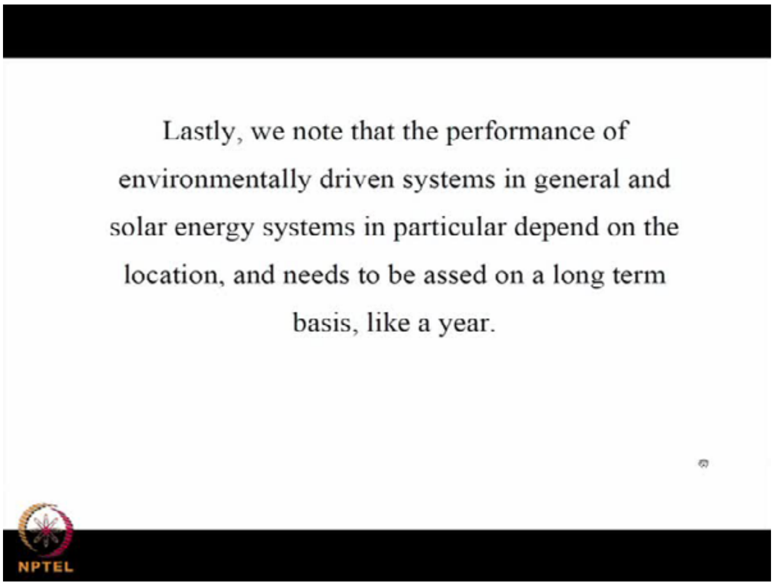
Lecture - 2
Sun-Earth Geometry

(Refer Slide Time: 00:32)



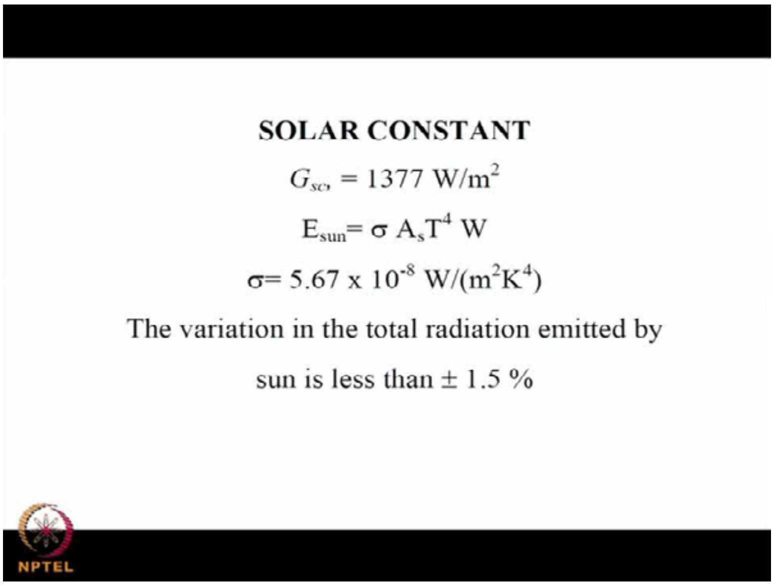
We shall equip ourselves with the necessary information for designing the solar energy devices, and then integrating with the system components, and finally estimate the performance of the systems. First we shall start with the Sun-Earth Geometry, sun is of diameter 1.39 times 10 to the power 9 meters, and it is at a distance of 4 point 1.495 into 10 to the power 11 meters from earth, which varies by a plus minus 1.7 percent depending upon the season. And the sun obtains small angle, 32 minutes or 0.54 degrees with the earth, and here I have indicated, can you see this, solar constant G sc it is a small print, which we will see little later, 1353 watts per meter square right. So, there are various estimates from ranging from 1353 to 1367.

(Refer Slide Time: 01:28)



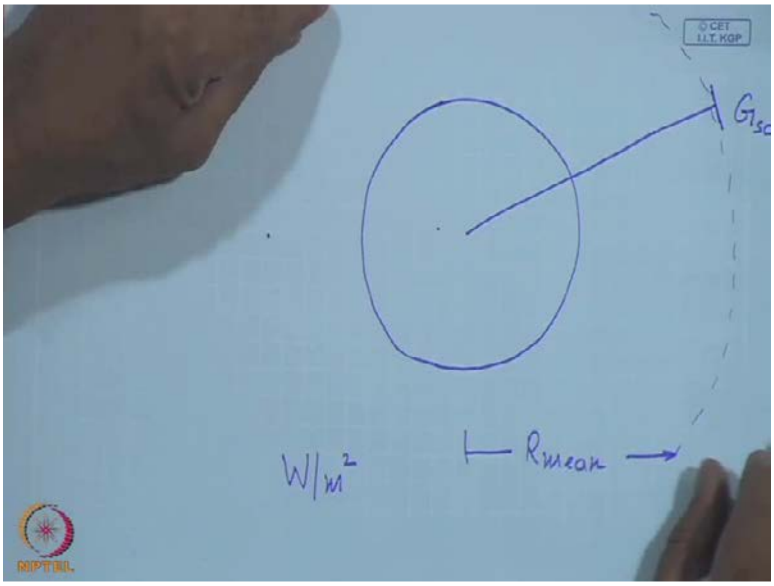
As more and more satellite data becomes available.

(Refer Slide Time: 01:36)



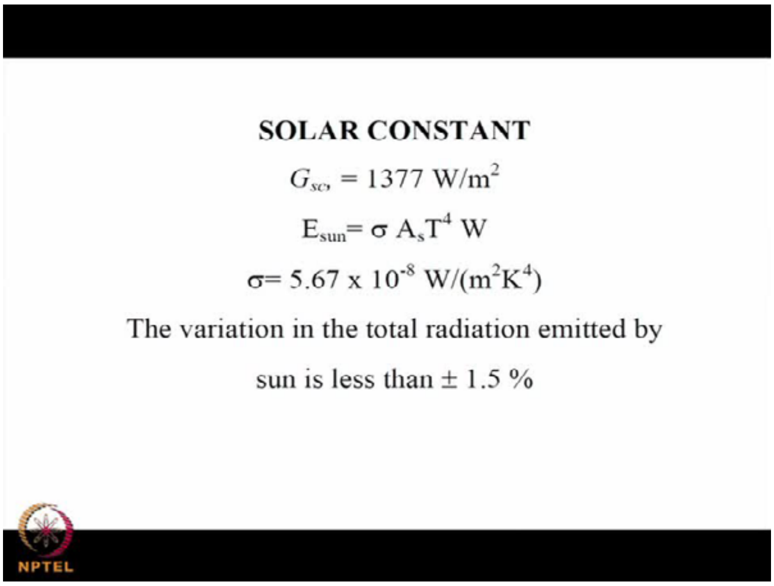
The solar constant got revised up to 1377 Watts per meter square. Now, we shall have a definition of the solar constant.

(Refer Slide Time: 01:51)



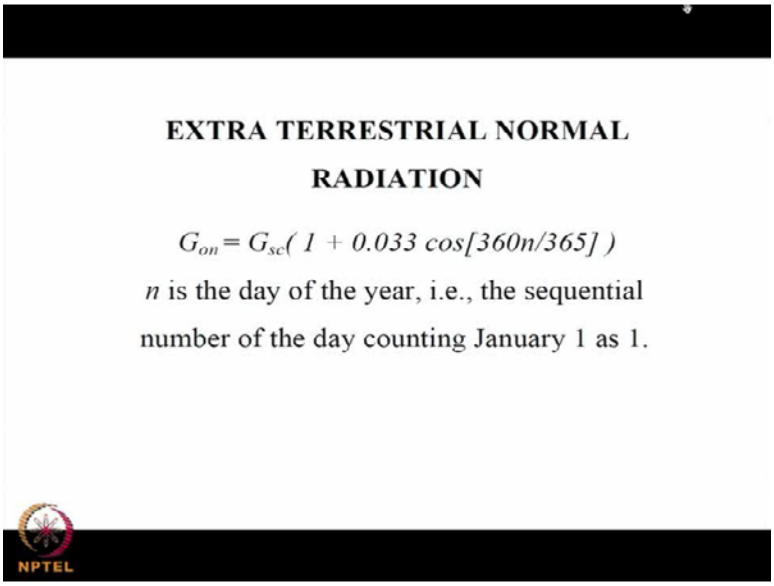
If this is the sun surrounded by a sphere, which is at mean distance between the earth and the sun, and you take any ray and you place a surface normal to the sun's ray. The amount of radiation received by the surface of unit area, located at one sun to earth mean distance is the solar constant, which is G sc that is, in watts per meter square. So, if we multiply by the total surface area at that radius, will be the total limited solar radiation by the sun.

(Refer Slide Time: 02:45)



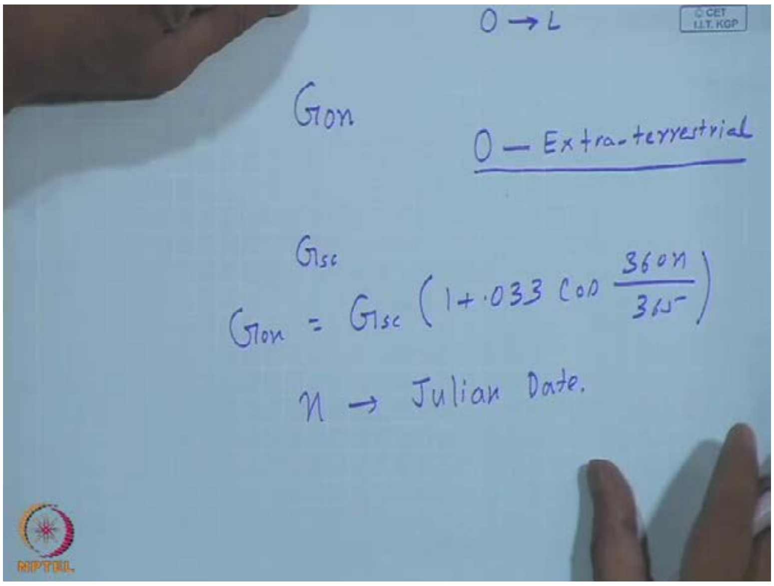
And that, is given by Stefan-Boltzmann constant sigma, times A s, the surface area of the sun multiplied by T to the power 4, where T is an effective temperature of the sun. The variation in the total radiation emitted by sun is less than plus minus 1.5 percent, these are because of, the local disturbances like sun phase, etcetera.

(Refer Slide Time: 03:16)



But, that is often neglected considering many of the uncertainties that, we have in measurement techniques themselves because the no instrument is 100 percent.

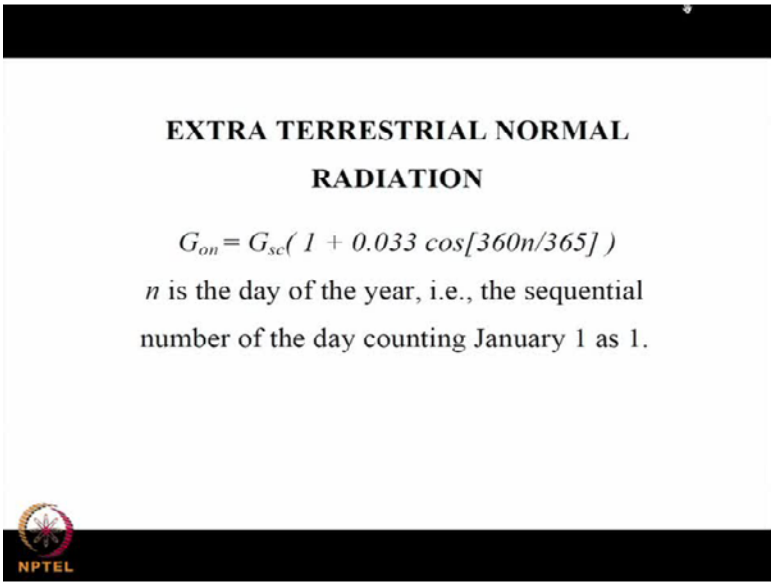
(Refer Slide Time: 03:26)



Then, slightly we define and call it, G on in generally, o stands for extra terrestial I think, I should, suffix o is for extraterrestrial. This needs to be understood in the context, in which it is used, not like the extraterrestrial beings, but this is the amount of radiation, that would be received, if the atmosphere is having 100 percent transpassivity. In other words, if there is no absorption, there is no scattering in the atmosphere, you will receive a certain amount of radiation at any location on the earth, which you can calculate, which we call the extraterrestrial radiation.

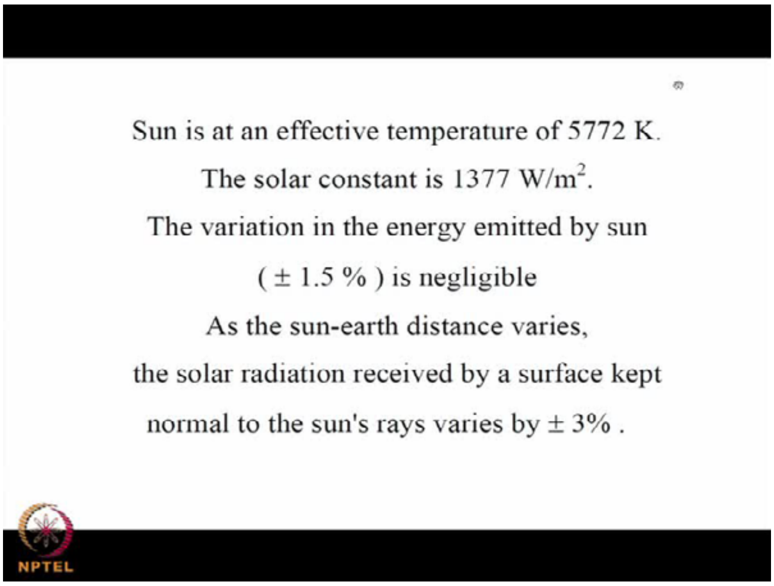
So, G o or G sc sorry is the solar constant, if the surface has been at the mean radius between the sun and the earth distance. If you take, on any given day, that will vary like the solar constant, times 1 plus, it is about point 1.7 percent plus minus 0.033 cos, 360 n by 365. This n is the so called day of the year, also called Julian date, which is simply January 1 is counted as 1 and December 31st will be 365.

(Refer Slide Time: 05:16)



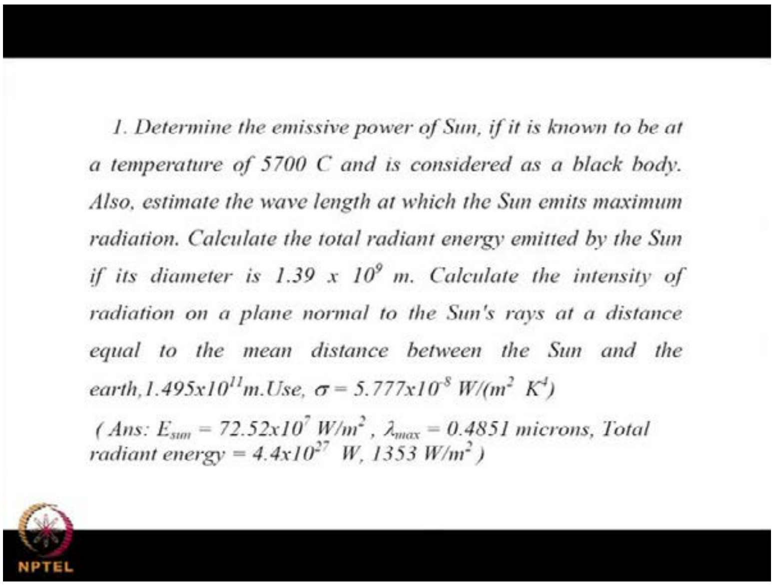
So, now, on an instantaneous basis, we know the extraterrestrial radiation, which is the intensity at any given instance of time. This is the amount of radiation that, will be received, if there is a surface at 1 sun to earth actual distance on that day, n.

(Refer Slide Time: 05:34)



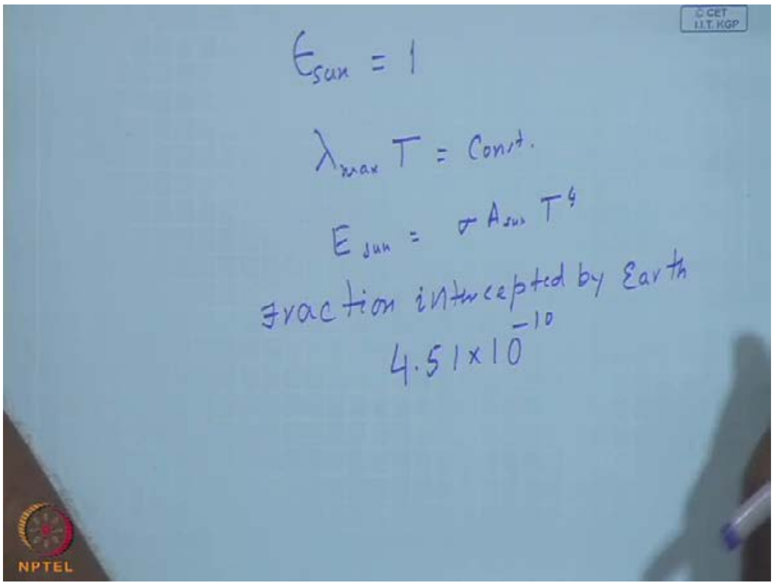
And sun is effective temperature of 5772, the solar constant, which we already said as 1377 and as the sun-earth distance varies, the solar radiation received by a surface kept normal to the sun's rays will vary by plus minus 3 percent. That is 1 plus 0.033 cos 360 n by 365, cosine function will be vary between minus 1 to plus 1, so that is about 3 percent.

(Refer Slide Time: 06:10)



So, we have a small problem, which we already indicated, you can determine the emissive power of the sun, if it is known to be at a temperature of 5700 c and is considered as a black body.

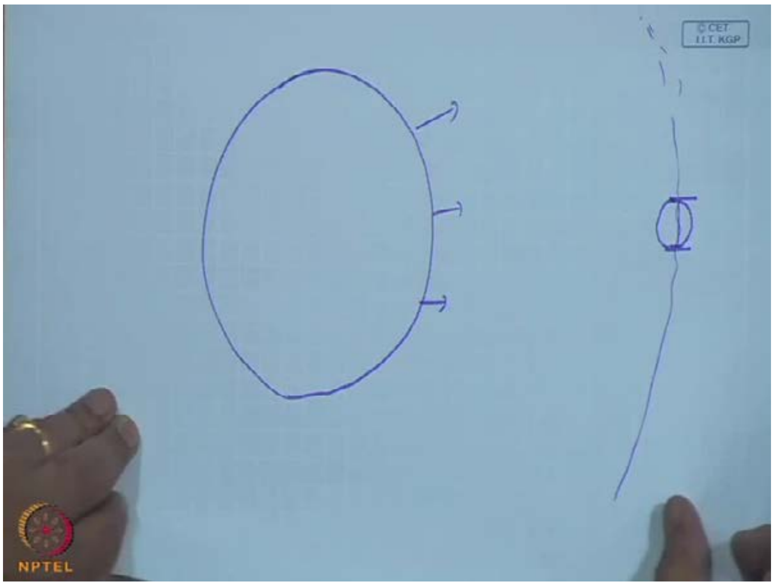
(Refer Slide Time: 06:24)



So that, emissivity of the sun, you can consider it as 1, those are few who are familiar with heat transfer, there will be no problem. Also estimate the wave length, at which the sun emits maximum radiation, that can be done with Wien's displacement law. Lambda max T is a constant and then, calculate the total radiant energy emitted by the sun, if it's diameter is 1.39 into 10 the power 9. That is, E sun, which we have written sigma A sun T to the power 4, and use that 5700 c for the temperature of the sun.

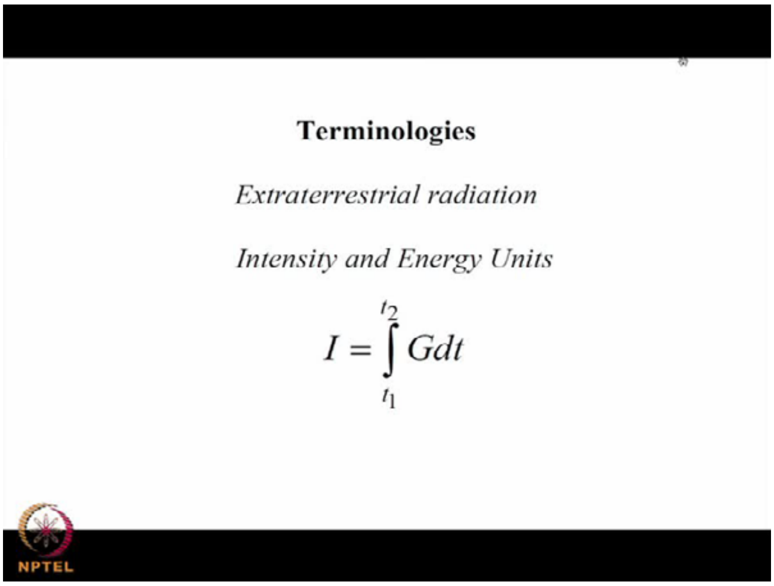
Calculate the intensity of radiation on a plane normal to the sun's rays at a distance equal to the mean distance, between the sun and the earth. That is, 1.495 into 10 to the power minus 11 that will nothing but the solar constant. So, the answers if you plug in all the formula we have already given, E sun is 72.52 into 10 to the power 7 watts per meter square. And one more information, the fraction of the energy intercepted by the earth, can you guess how large or how small, only 4.51 into 10 to the power minus 10 is intercepted by the sun, that becomes clear to you.

(Refer Slide Time: 08:27)



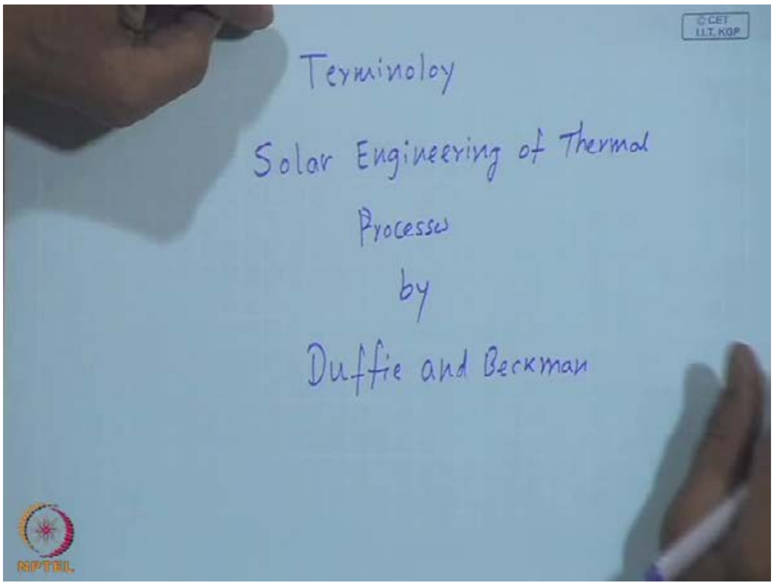
This is the sun's diameter and if this is, somewhere in IIT, possible the earth is at the gol bazaar or so distance, and this is the whole sphere that, will collect the same amount of energy emitted by the sun. And this is the projected area of the earth, which is a small fraction of the total area of the sun, which will turn out to be that 4.51 into 10 to the power minus 11 fraction. You can calculate, what is the total emitted sun is already known, that should be proportion to the projected area to the total area of the sun.

(Refer Slide Time: 09:19)



Now, this is an important thing, and which you have to patiently follow and then, try to remember.

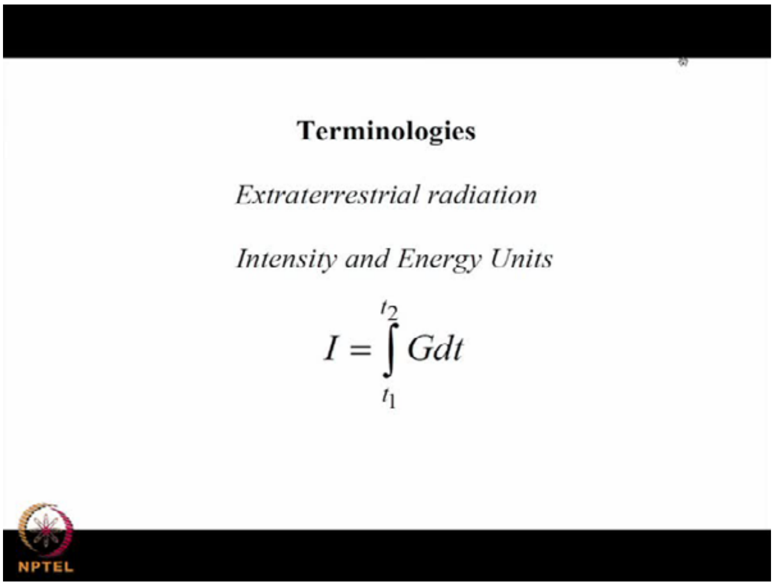
(Refer Slide Time: 09:29)



And that is we will come to terminology and I shall be following strictly used in text book of, this is obviously quiet an authentic book that is available, which deals with the devices as well as systems. And what I tried to do in this course is, apart from fundamental I shall try to highlight the differences, that will be there in the tropical climates, comparative to the colder climates and lower latitudes compare to higher latitudes.

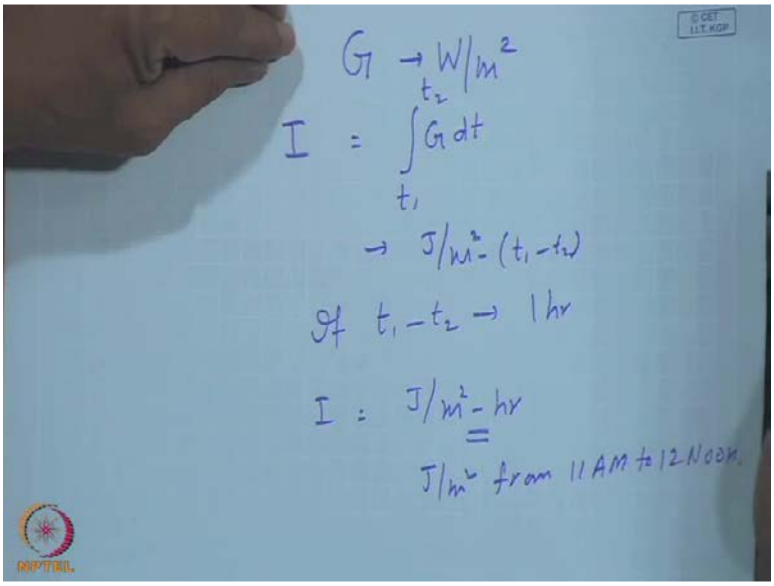
If we have latitudes less than 23 degrees, which is the maximum declination, you have a certain problems right mathematically, you have certain problems. And then orientation wise, you will have a certain problems and most of the algorithms that are in general, written from 23 to 66 degrees will not of latitude, they do not work at lower latitudes and at higher latitudes.

(Refer Slide Time: 11:09)



First thing is extraterrestrial radiation, intensity and energy units.

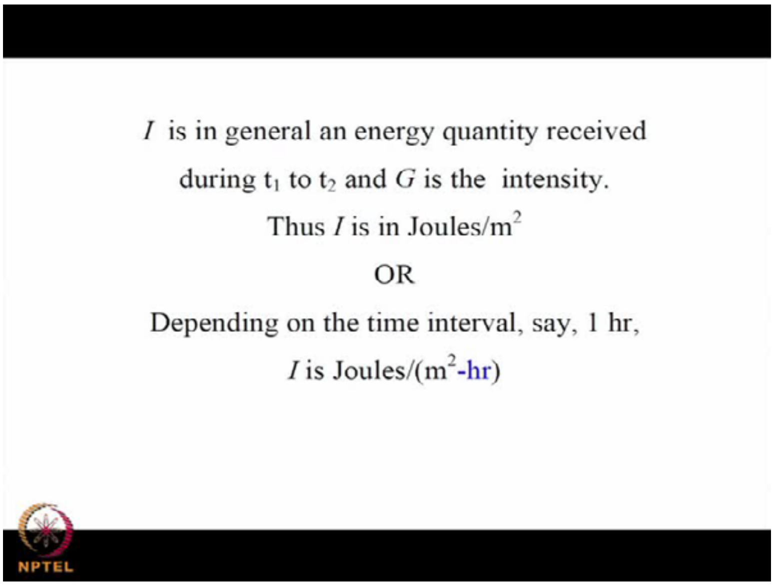
(Refer Slide Time: 11:17)



Now, whether it is terrestrial or if intensity is indicated by G, and which is in watts per meter square, I will be integral G d t or the time period t 1 to t 2. So, this units will be so many joules per meter square, hyphen within t 1 to t 2 that means, it has so many joules of energy is connected collected in the time interval between t 1 and t 2. If t 1 minus t 2 is 1 hour typically available value in the data then, I will be joules per meter square hyphen hour. Please note that, I am emphasizing, it is not joules per meter square hour but it is joules per meter square in 1 hour.

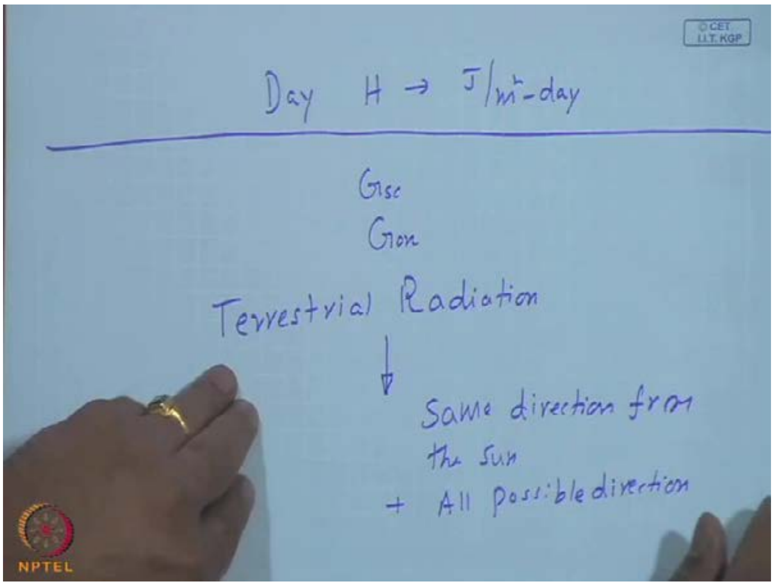
That means, if I multiply by the number of hours in a day or number of hours in a year i will not get the total solar radiation. This is for say, for example, so many joules per meter square from 11 AM to 12 Noon it to be whereas, if it is intensity, if it is uniform, I can multiply with the time and get the total. Otherwise, we have to sum up for every hour or half an hour depending upon the accuracy, that is needed.

(Refer Slide Time: 13:04)



So, that has been already written, depending upon that is exactly, why I highlighted that hour in color, it is so many joules per meter square hyphen hour.

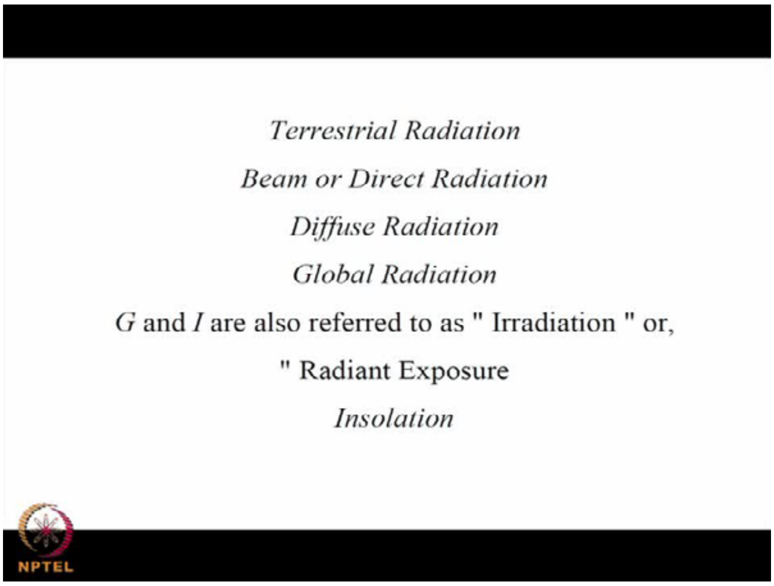
(Refer Slide Time: 13:20)



So, if I have for a entire day generally, indicated by H so many joules per meter square day so depending upon the chosen period of time, I will put that hyphen. With a clear understanding, I cannot multiply by the number of days or hours or to get a total but I have to sum up for different days. Now, we have considered the extraterrestrial radiation by first defining the solar constant and then, or a normal surface, which takes into account the distance variation between the sun and the earth.

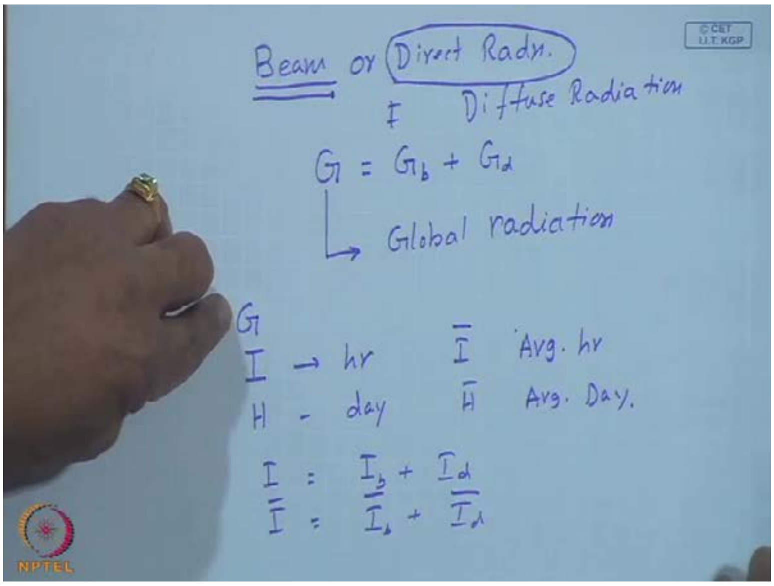
Now, we try to come down to earth and call it terrestrial radiation, in the process of transmission through atmosphere, the solar energy part of it is absorbed c o 2, water molecules, there will be forward scattering, there will be reflection, there will be in-scattering and out-scattering. So, terrestrial radiation will come in the same direction from the sun, if there is a radial line, it will come as a radial line, plus all possible directions, this is the scattered part of it.

(Refer Slide Time: 15:11)



So, G and I are also referred to as other terminologies, as irradiation and radiant exposure and insulation is very specific term that is used, only for solar radiation that is, following though, we shall not use this terminology.

(Refer Slide Time: 15:31)

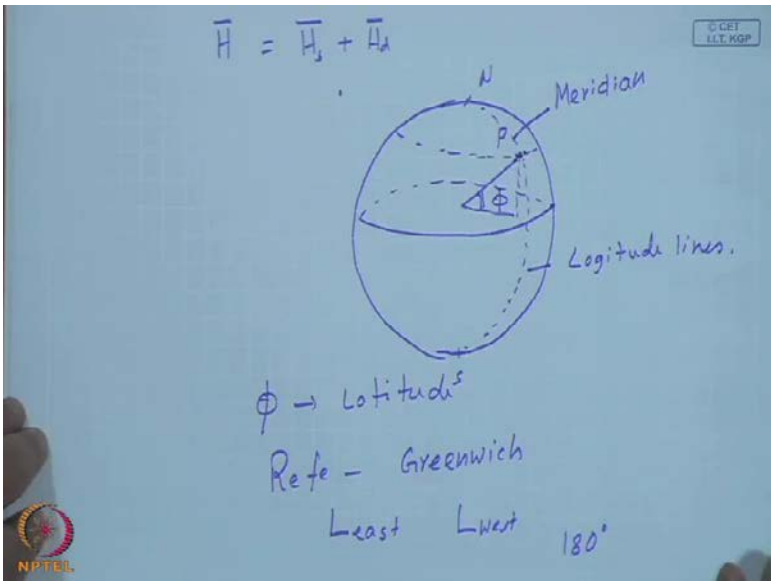


So, this terrestrial radiation consist of, what we call beam or direct radiation, which essentially means, this reaches the surface of the earth without the change in the direction. And it is indicated by, for a early times scale I will write, if G is the total radiation received on the earth, it will consist of G b then, you have got a diffuse radiation, which we shall indicated by G d.

Unfortunately, the first terminology, earlier terminology had been beam radiation and the subscript b is stuck with this G and later on, they started calling it direct radiation and but d, I cannot use it because it is already used by diffuse radiation. So, G total is also called the global radiation, this was also earlier called total radiation but then, people started having confusion total for the day, total for the month, total for the year. So, the terminology is, there is direct radiation, there is diffuse radiation, the sum of which makes the global radiation, as measured on the earth's surface.

Now, if G is the intensity then, I can choose different time scales like I for an hour, like H for a day and I bar for an average hour, which I will define little later, and H bar average day. So, each I will consist of I b plus I d and similarly, I bar also will consist of I b bar plus I d bar, I shall not elaborate on G. Because, this instantaneous or intensity measurement are essential to check the total measured over a period of time and nobody can give you data, even if per second, every second is given, it is integrated out of that second. Consequently, in that sense, there is exactly that intensity can you can go down to a shortest period of a second.

(Refer Slide Time: 18:28)

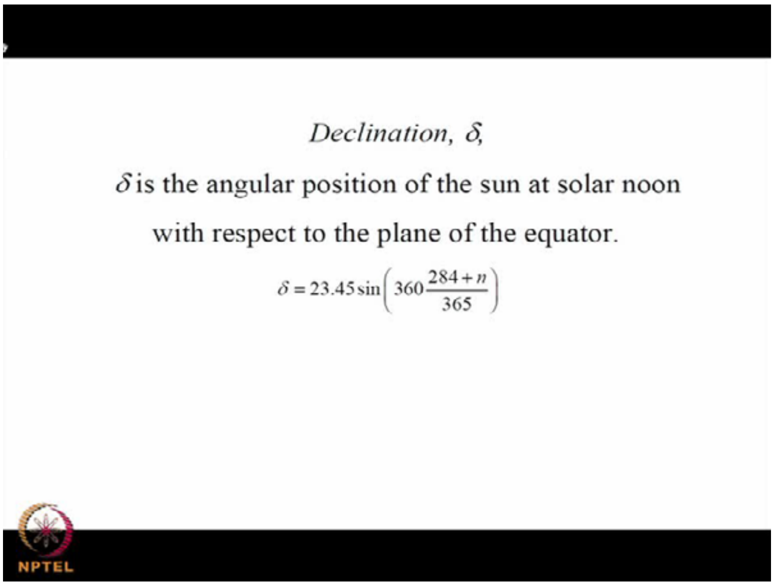


So, you have this and H bar H b bar plus H d bar now, before we go to that, we should know little bit of different angles. If we have earth and there is equatorial plane, and if I consider any point P and the angle between the line joining the point and of course, projected on to the equatorial plane, is the latitude phi. So, all the points on this circle, all the locations will have the same latitude, at the same time, 2 coordinates are necessary to fix the point.

If this is the north pole and this is the south pole, I can draw a meridian passing through that point and that fixes the point P. So, these are called the longitude lines and reference is through Greenwich, and it is latitude east and latitude west, it is given changes as 180 degrees. There is no sign convention associated with the longitude, they do not call it plus 180 or minus 180, you have to understand 80 degrees west, 80 degrees east.

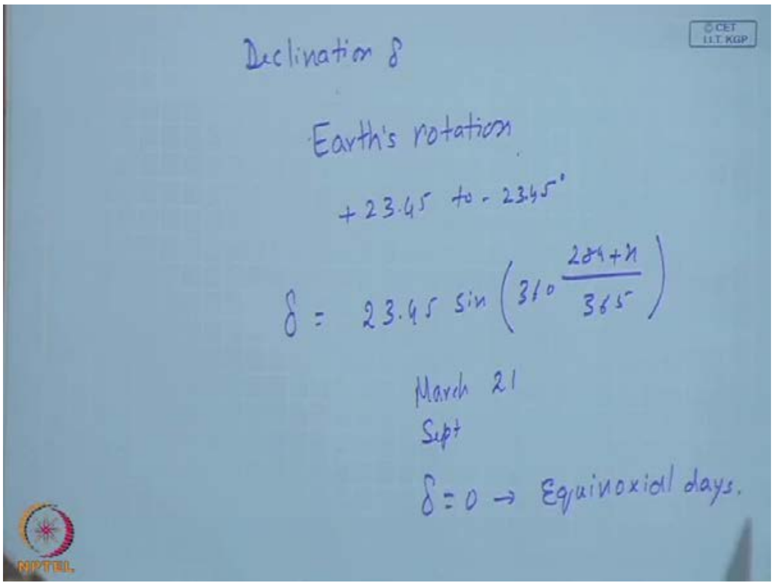
For example, India is 82.5 degrees east, based upon which we have our time, it passes through Allahabad so that is about five and half hours from meanwich Greenwich mean time. So, east of our local or standard time like Calcutta, if you think of solar time, it will be ahead of the clock time.

(Refer Slide Time: 21:03)



And then there is a declination.

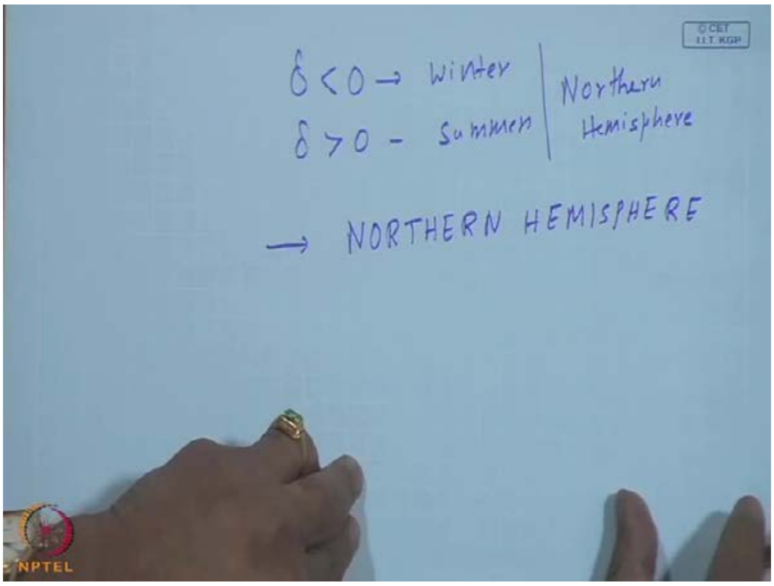
(Refer Slide Time: 21:07)



The best thing is delta, is the angular position of the sun at solar noon, with respect to the plane of the equator, you can just give on the Google earth's rotation that, solve the search word. You have excellent videos and excellent figures then, I can reproduce in this and you have an understanding. This is basically the plane of rotation and the equatorial plane or not the same, the axis over which, the sun is rotating will be tilted towards the north-south axis that, will be varying.

Because, the earth is going through in an elliptic path from plus 23.45 to minus 23.45 degrees and each day, you can calculate according to the this equation, delta is 23.45 sin 360 times, 284 plus n by 365. You can verify for March 21 st and September, if you put the appropriate n, you will get delta equal to 0, these are called the equinoxial days. Similarly, in June and December 21 st you have the summer solstice and the winter solstice where, you have maximum plus 23.45 in June and minus 23.45, the minimum in December.

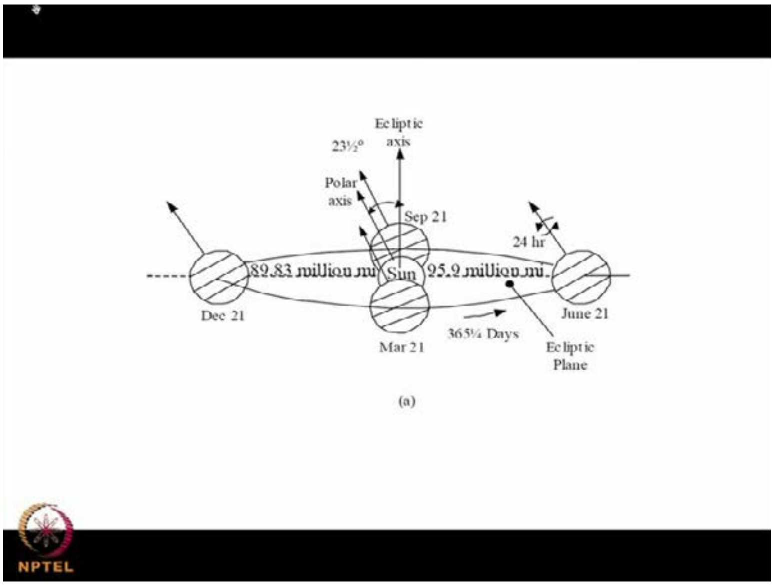
(Refer Slide Time: 23:06)



Broadly speaking, delta less than 0 may be called in winter, may be called winter and delta greater than 0 as summer. This is somewhat for my own convenience because most of the discussion can be done in terms of, positive declination and negative declination though, in between there is autumn, spring, rainy season, so many other seasons. So, we will just call it just winter and summer, mind you this is for the northern hemisphere that is, towards the south north of the equatorial plane.

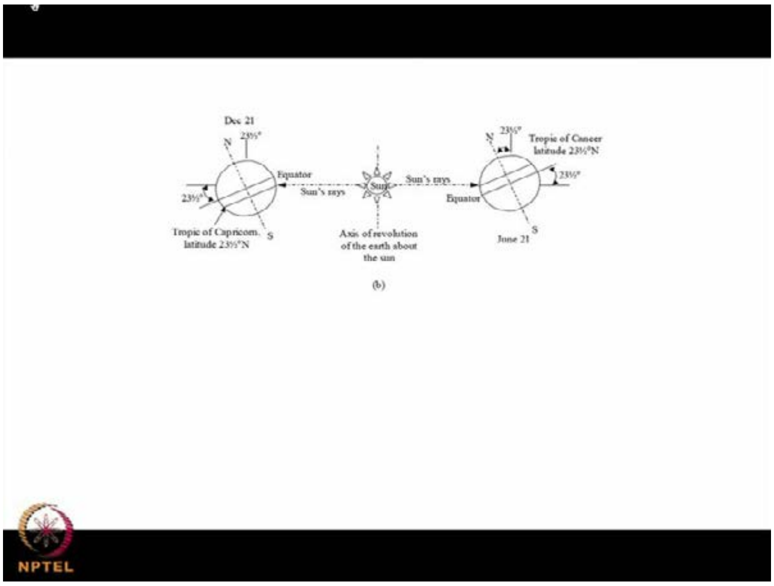
So, we shall also devote throughout this course, unless otherwise, specified for northern hemisphere only. The signs will be different, but one can easily rewrite the appropriate relations for the southern hemisphere also.

(Refer Slide Time: 24:18)



So, this is the one that indicates, how earth goes around the sun and tilt out the angle I mean, this is the best I could draw with hand or whatever border provided.

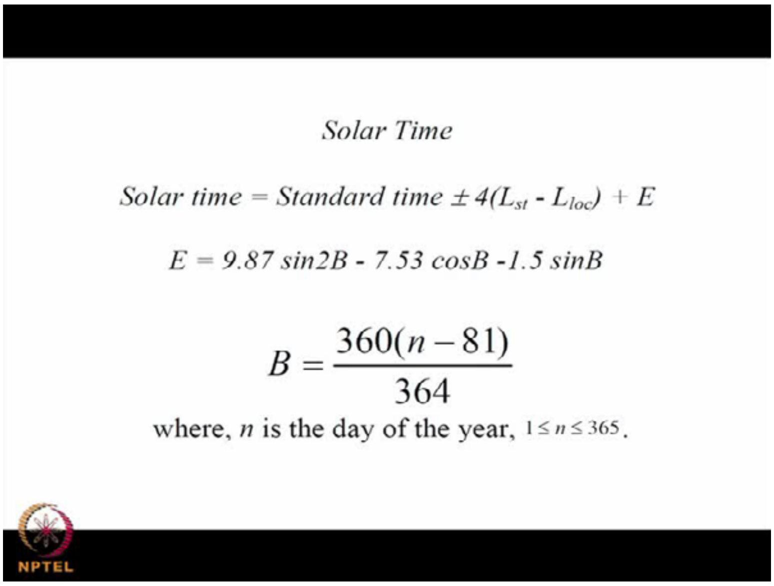
(Refer Slide Time: 24:36)



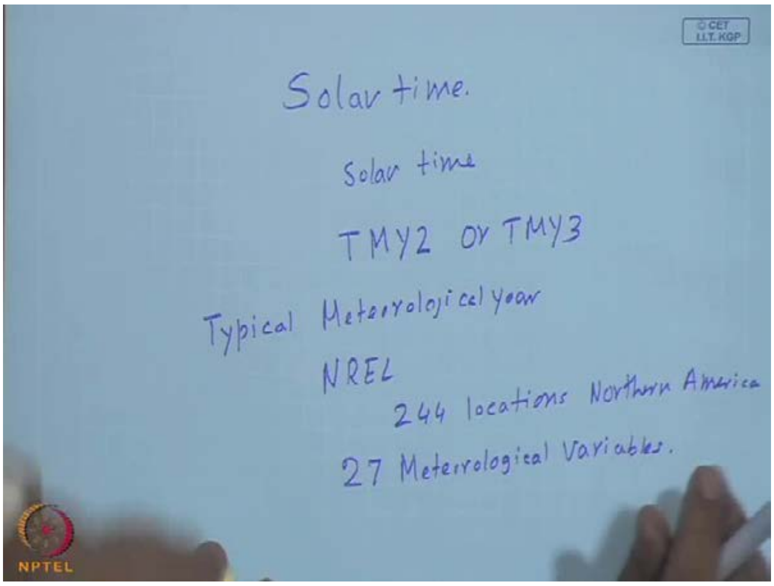
And you have a lot better pictures and including the actual 3D videos clips, we can find out, how it changes with the season. And I think, long time back this information came as a bit of surprise that, sun is nearer to earth in winter or December comparative, what it is in June atleast in northern hemisphere. We have a higher radiation in summer not so much because of, the nearness of the winter but because of the favorable angles.

And in winter, the angles are pretty flat consequently, the path distance may be little different from the physical distance plus atmospheric features, which make the intensity less.

(Refer Slide Time: 25:25)



(Refer Slide Time: 25:31)

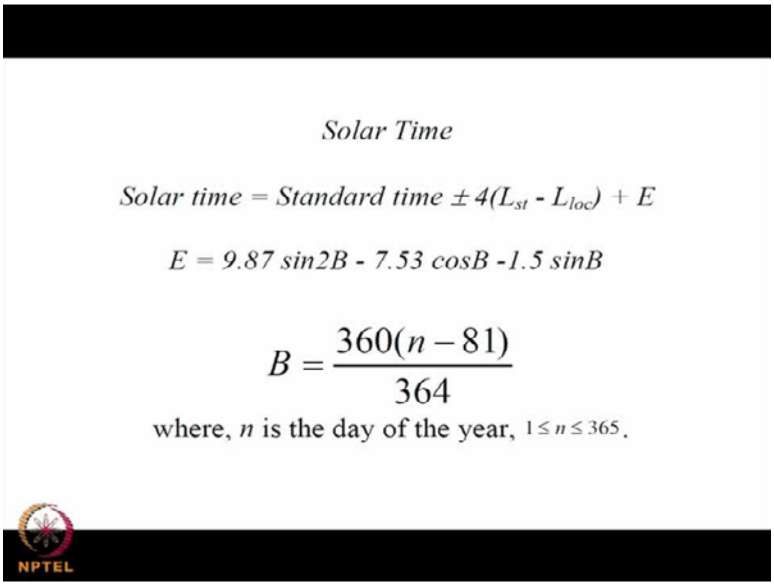


Now, this is one thing we have to be considering, that is solar time and unless otherwise stated, we mean solar time throughout this course and most of the data is given in solar time. For example, one of the sources is TMY2 or TMY3, this is a typical meteorological year compiled by NREL, that is the national renewable energy laboratory in the US. You can just type in TMY2 or TMY3, this is a downloadable file, this has got 244 locations of a Northern America and Canada, I think if I say Northern America, Canada is included right.

So, you have about 244 locations and this is 27 meteorological variables, I cannot list all of them by just my memory, you have to see that. For example, each location or each instant or each hour, solar radiation normal component, diffuse component, direct component plus wind speed, wind direction, precipitation, etcetera and even vegetation and it’s classification, there are about null drivel temperature, medieval temperature, 27 meteorological variable are listed on a hourly time scale.

Now, why it is called a typical meteorological year, I will reserve it for later day, when we really use that.

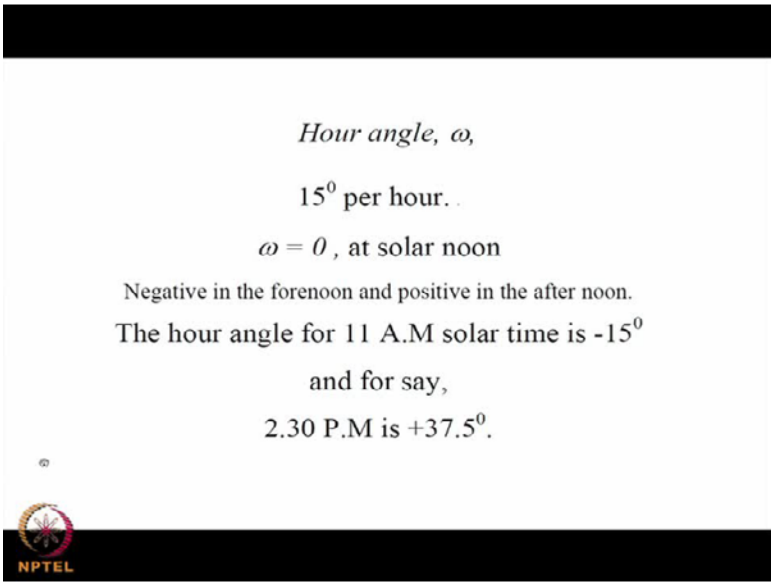
(Refer Slide Time: 27:50)



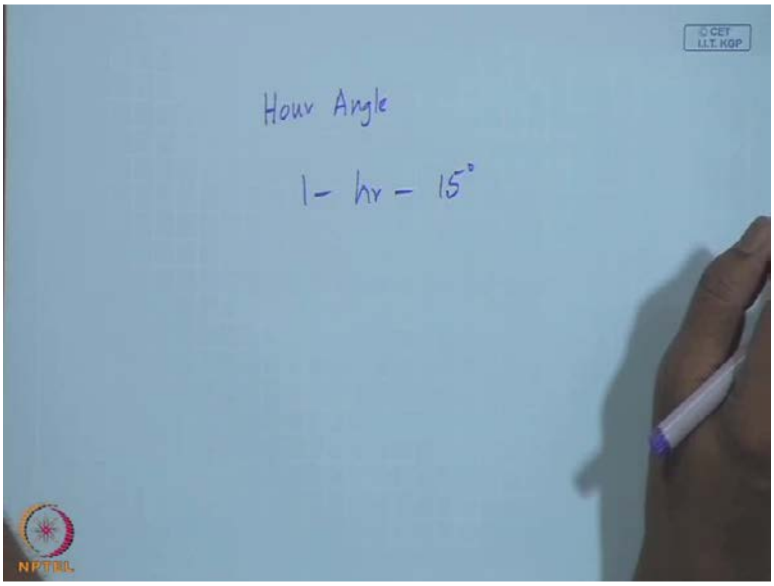
So, solar time is the so called standard time, whatever your clock says, plus or minus 4 times, L st is the longitude, based on which your standard time is made and L loc is the locations longitude. For example, in India L st will be 82.5 and Calcutta may be 84 degree also and you have to use the plus sign for the west latitudes and minus sign for east longitudes sorry plus for, you can see that, if you have Calcutta, you should add minus and minus, it will add up.

And this E is actually a sort of non-uniform rotation of the earth, which will change the solar time by, even up to plus minus minutes. That is given by equation where, that angle B is 360 into n minus 1 81 by 364 so that is how, the solar time is calculated and that E is, that 4 is nothing but 4 minutes. Because, 24 hours in a day and 360 degrees of the longitude so 1 degree will correspond to 4 minutes and E also is given in minutes.

(Refer Slide Time: 29:12)

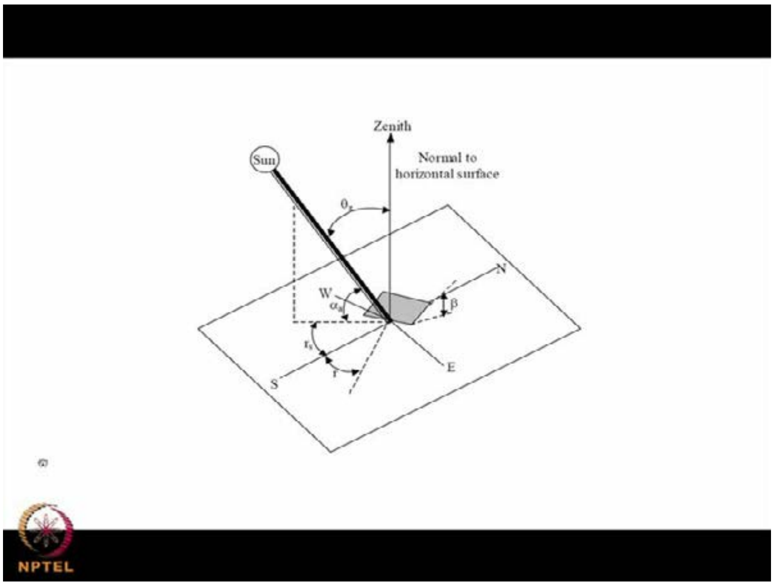


(Refer Slide Time: 29:18)



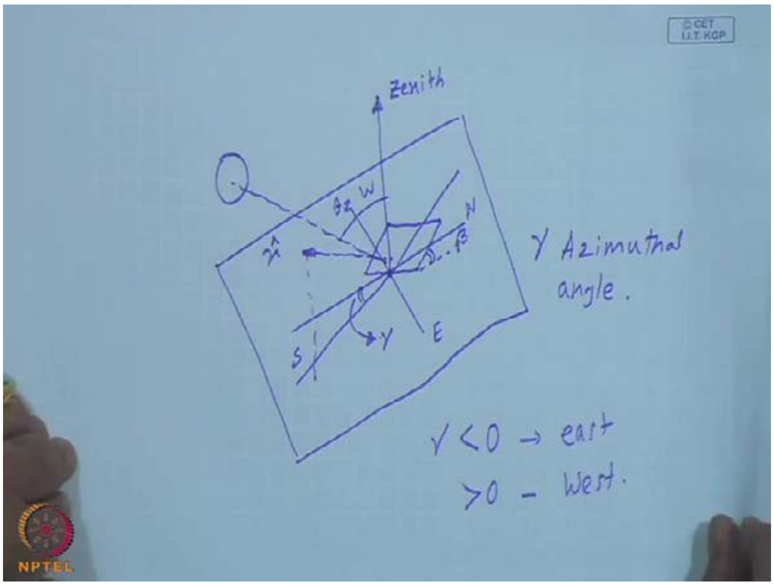
So, we also define a hour angle in other words, instead of saying 10'o clock, 11'o clock, 12'o clock, we will specified by the hour angle omega and because it is again 24 hours for 360 degrees of rotation, each 1 hour will correspond to 15 degrees. And by notation, omega equal to 0 at solar noon, negative in the forenoon and positive in the afternoon, some books write the other way around also. But, what we follow is like as I gave an example 11 AM the solar time actually so it is not solar time, hour angle is minus 15 degrees and 2:30 PM for example, is plus 37.5 degrees.

(Refer Slide Time: 30:08)



Now, here is things get little more complicated.

(Refer Slide Time: 30:21)

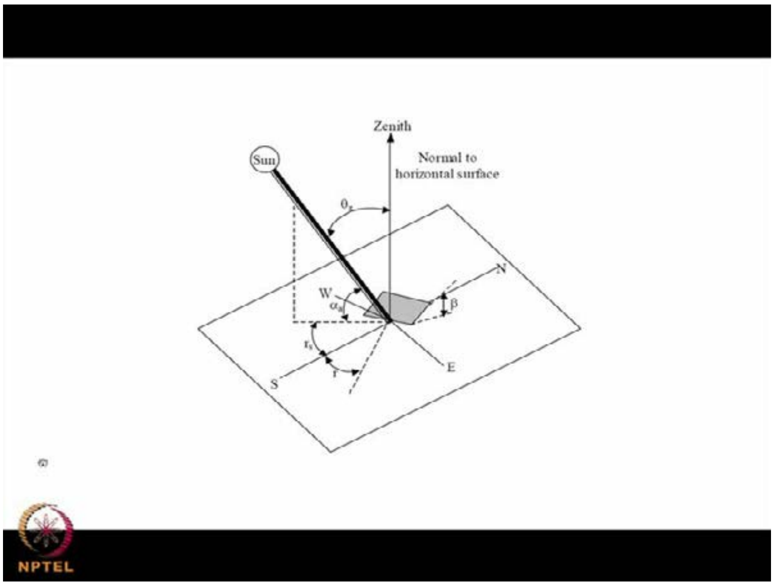


That is, a piece of earth that big rectangle and of course, north-south and you got that, W should be in continuation with E, west and east, and we have got a surface with a slope beta, which will completely use. This slope always measured from behind the surface in other words, sun is somewhere here, as shown in this and this is the zenith. Zenith is nothing but vertical line to the horizontal and if this is the sun's ray or the angle is, this should be theta, angle of incidence sorry this is theta z, with respect to the zenith.

And I take this outer normal to the surface and make a projection of that, this is so called gamma or the azimuthal angle. I can demonstrate it with a small piece of book or something, if this is my south direction, if I am exactly orienting it with a slope beta then, the outer normal will be along the north-south direction. But, if I turn it towards the east then, the outer normal projection will make an angle like this, I have shown here, that will be the azimuthal angle.

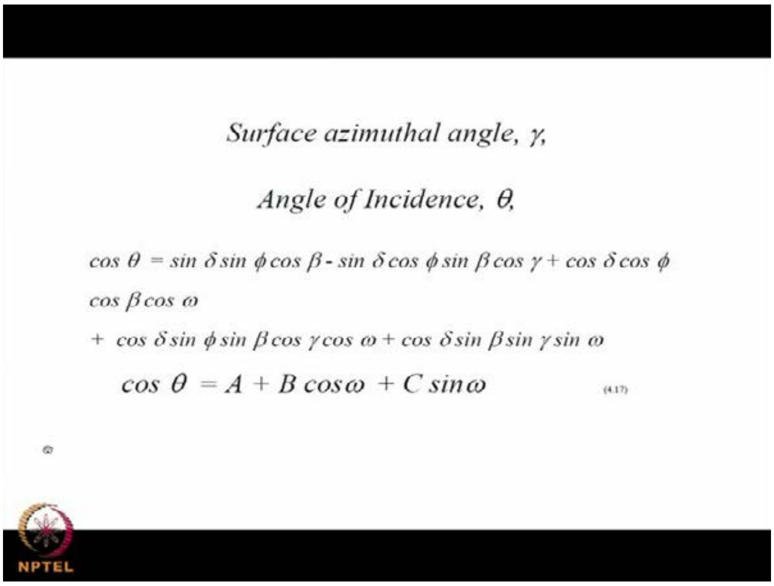
If it is towards west, it will make a positive or negative way convection and if it is horizontal, the projection of the outer normal will be a point right, there is no azimuthal angle. And interestingly, you will find when once the surface is a horizontal, azimuthal angle does not come into the picture, and which is should not also and this azimuthal angle is gamma negative towards east and towards west, it is positive. This is consistent with that time notation, hour angle being negative in the morning and positive being in the afternoon, azimuthal angle also towards east is negative, towards west is positive.

(Refer Slide Time: 33:31)



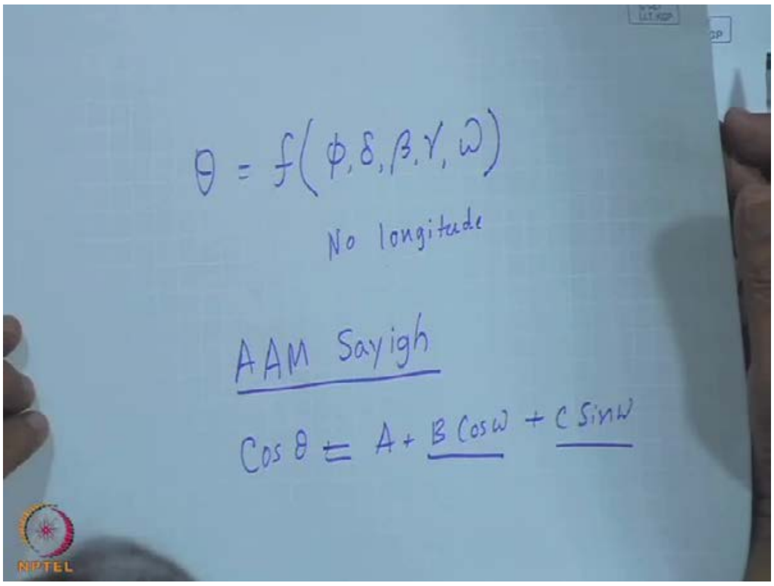
So, if you go towards north via south, you can have a gamma plus 180 and if you come the other direction, it would be minus 180. So, your angles and equations, when it is juiced out, whether you put gamma plus 180 or minus 180, you should get the same answer.

(Refer Slide Time: 33:47)



So, surface azimuthal angle is gamma and the general angle of incidence is theta.

(Refer Slide Time: 33:55)

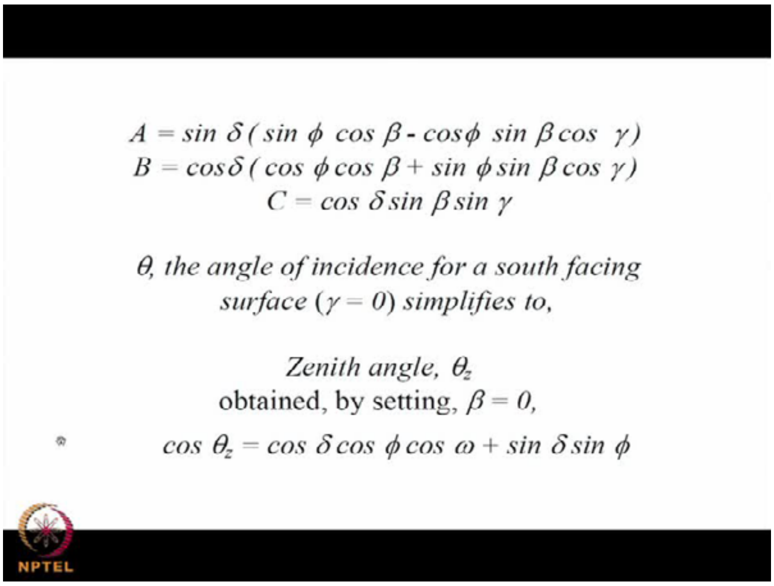


What I can expect is, theta to be a function of where, I am that is, the latitude and on what day, given by the declination and then, how the surface is oriented the slope and the azimuthal angle, is it towards (( )) east or west or something else and then, the hour angle. You will find no longitude, it does not depend upon the longitude because if you are at a particular longitude and another longitude will occupy exactly the same location, after the earth has rotate by 1 hour or half an hour or whatever is the time.

So, when once the hour angle in terms of sun, for that location specified, the longitude will not be dependent upon, I mean influence the angle of incidence. In other words, all the latitude, same latitude locations will experiences same angle sooner or later, depending upon the sun rise and sun set. And this is a long expression, you can see another book by AAM Sayigh, there is one copy, there used to be one copy in the library.

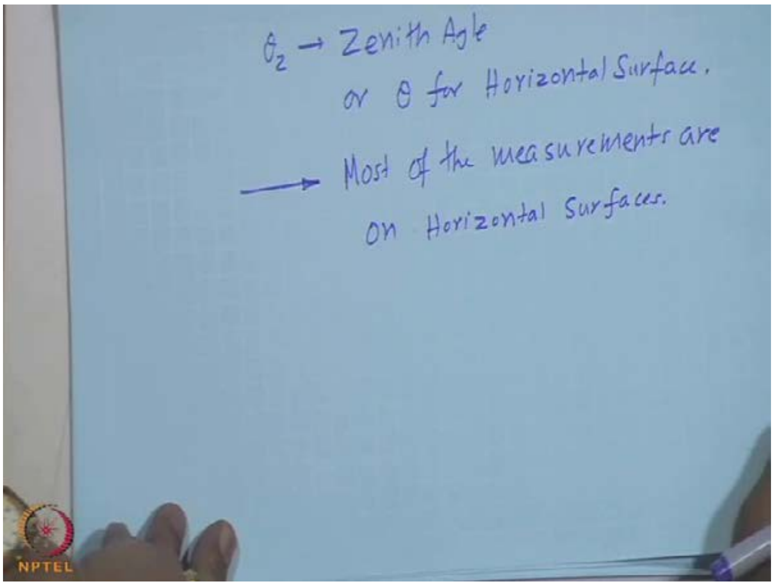
And this involves physical set trigonometry, with a sun being at the center and the celestial figure you have to construct, that will take about 3 to 4 classes for derivation. Then I thought, I shall give up and take the relation as per say and this is quite conveniently written as, cos theta equal to a plus b cos omega plus c sin omega. In other words, there is a symmetric component, there is an anti-symmetric component, which basically will make the distinction, whether gamma is positive or gamma is negative.

(Refer Slide Time: 36:16)



So, of course, a b c are defined in terms of the remaining things.

(Refer Slide Time: 36:28)

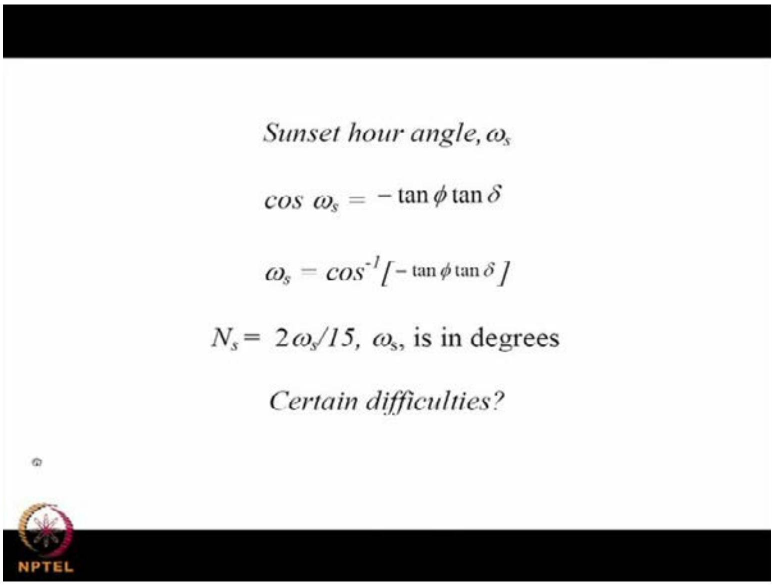


And that, so called zenith angle, the angle between the vertical and the sun's ray is theta z that means, it is the angle of incidence or theta for horizontal surface. Basically, zenith angle is nothing but the angle of incidence in general, if the surface had been horizontal. Now, this horizontal surface instead of, the general theta or angle of incidence, we keep on referring main reason is, horizontal surface are also important. But, most of the measurements are on horizontal surfaces and there is a good reason for it, the instrument can be just kept horizontal.

The second part is, if you choose a particular angle right, that may not be the only application, that you are thinking of, you may have a vertical wall, you may have a angled solar collector and if it is some other application, you may choose any angle cause so many measurements are not possible. So, most of the measurement are on a horizontal surface, from which we try to find out the conversion factors, to calculate on any desired surface.

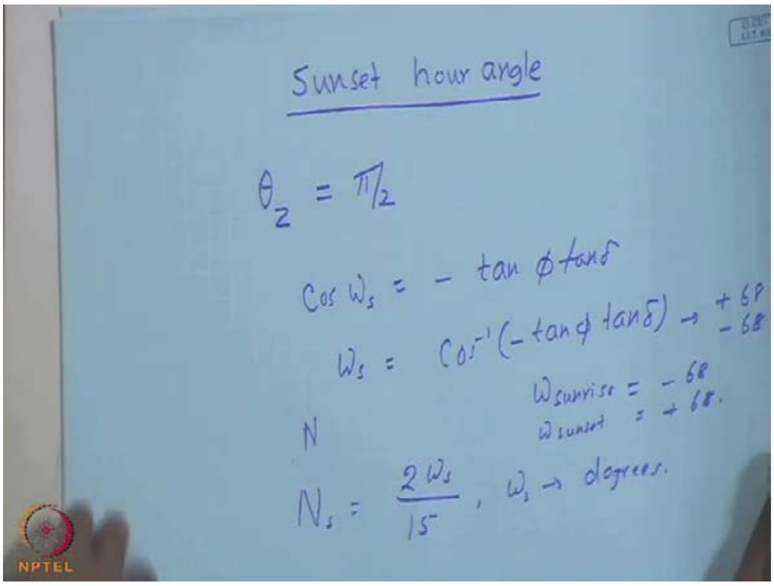
The second type of measurements generally done are on a normal surface that means, if the instrument sensor is normal to the sun's ray, that will be used most of the time as a check against the horizontal measurements. Otherwise, the instrument has to keep on tracking the sun, if you want to be continuously normal to the sun's rays so zenith angle theta z is simply obtained by putting beta equal to 0 that is, the horizontal surface, and which is given by very simple formula.

(Refer Slide Time: 38:50)



Now, we go for, one more thing should be there.

(Refer Slide Time: 39:11)



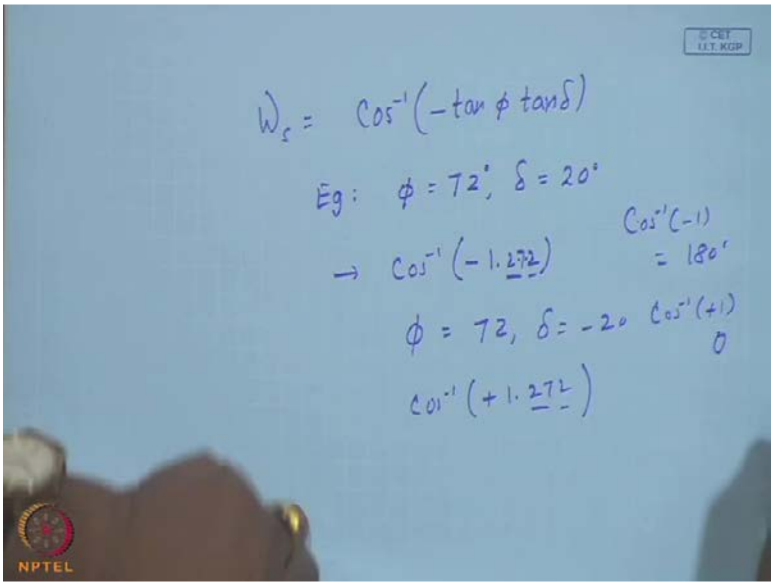
The sunset hour angle, how do you define, it can be called as sunrise hour angle or sunset hour angle, it is symmetric as long as solar time is followed. When the sun's rays are horizontal, the rays passed the horizontal surface then, it is either sunrise or sunset at any other time, they will make a particular angle with respect less than pi by 2, with respect to the horizontal surface right. In other words, as a sun appears to be moving from east to west, when it first appears at the horizon, their rays are parallel to the horizon.

So, you put theta z is equals to pi by 2 because remember you are measuring from the vertical so horizontal ray will be at an angle of pi by 2 and not 0. Then, if you solve that theta z, you will get cos omega s, the value of omega, for which the sun raises or sun sets, which is minus tan phi tan delta and omega s will be cos inverse minus tan phi tan delta. Now, number of sun shine hours so this can be plus or minus right, I can have answer or say for example, for a certain location, it will be plus 68 minus 68, agreed.

By our notation, omega sunrise should be minus 68, omega sunset to be plus 68 that is reason, why we give the terminology, as sunset hour angle rather than the sunrise hour angle. So that, omega s, a positive number that I take, is the sunset hour angle then, number of hours of sunshine N s will be twice omega s by 15, when omega s is in degrees.

This you have to be careful or whenever we are using trigonometric relation that, degrees or radiance, as a process of integration. If you get a omega, that has to be always in radiance whereas, sin 30 or sin pi by 6 is one in same thing, whereas if I multiply by omega sin omega s, this omega which resulted from sum process of integration, differentiation, I have to use only in radiance that, you have to be in the memory.

(Refer Slide Time: 42:25)

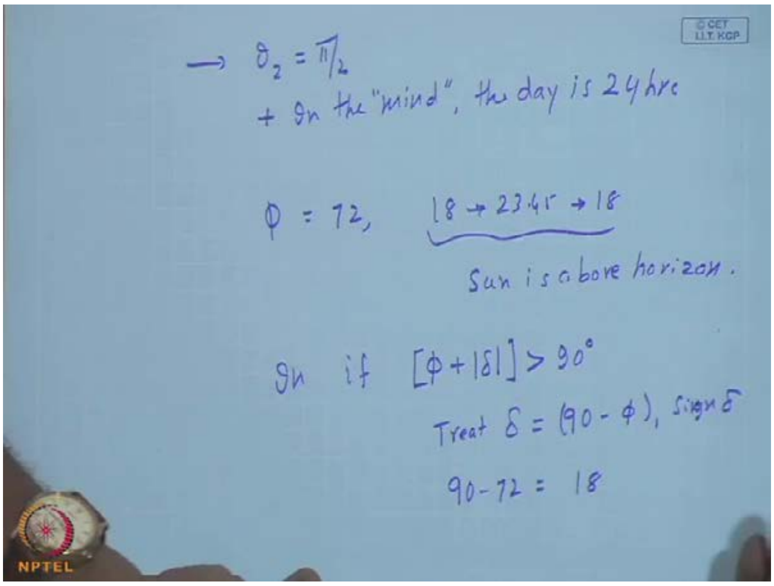


Now, this equation gives some problems, as an example later on, we will formulize it mathematically. Let phi be 72 degrees, delta be 20 degrees high latitude and somewhat higher declination. Obviously, I will have a cos inverse minus, something like 1 point, that 0.272 may not be correct but I know it will be cos inverse of something less than minus 1.

And another example, I can take phi is equals to 72, delta equals to minus 20 then, I have cos inverse plus 1.272, with the same pinch of sort, for the 0.272. Obviously, you do not know cos of minus 1.272 right, maximum you can define as cos minus 1 is equals to 180 and cos inverse plus 1 will be how much, 0 right 180 multiplied by 2 will be 360, which will be 24 hours, and this 0 is 0.

So but this is a real situation there is people, there are people at 70 degree latitude also and declination is there right. Somewhere, we are making a mistake, nothing wrong in this equation as such but then, we are unable to calculate because cosine inverse is not defined.

(Refer Slide Time: 44:40)



But, what happened was, in our process of derivations we said that, theta z should be pi by 2 plus in the mind, it is not satisfying both of them that is all, nothing wrong with that equation. We are psychologically thinking, that sunrise and sunset should take place within 24 hours and then, theta z should be equals to pi by 2. So, when you have a example like 72 degrees latitudes and 20 degrees delta, one way of limiting is, I do pass through cos inverse of minus 1, when delta is 18 degrees exactly, right.

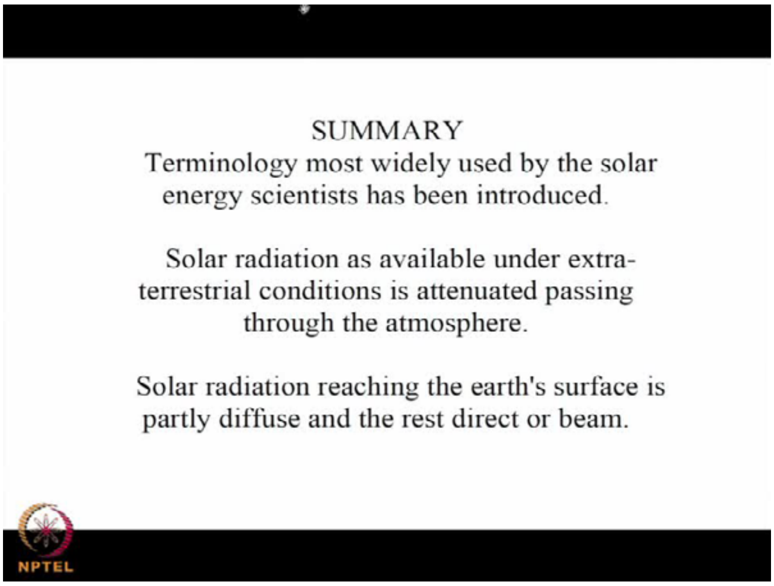
Then, it continues to be above the horizon and again it will come down to the horizon, when once the declination becomes 18 so plus 20 degrees, for the case of, for phi equal to 72, for delta 18 go to 23.45 goes back to 18. So, all this days, there will be sun above the horizon in other words, if you go to north pole, 6 months will be there will be sun, 6 months there will not be sun.

With that, we know commonly and actually, mathematically nothing wrong but we are subconsciously imposing another condition because of, our feeling that the day should end within 24 hours but the condition that where, I said is only the theta z should become equal to pi by 2. It does become theta z equal to pi by 2 from declination being 18 degrees and continuous above the horizon, and again becomes pi by 2, when declination becomes 18.

Similar argument you can built for negative or in other words, if phi plus mod delta is greater than 90 degrees treat. So, you calculate 90 minus phi and treat the delta as equal to that number, with the sign associate with the originally delta. I think, this is computer language, sign delta magnitude of 90 minus phi, in this case, if you have got a 90 minus 72, you will get it as 18. If it is originally minus 20 or plus 20, you will use it as minus 18 or plus 18.

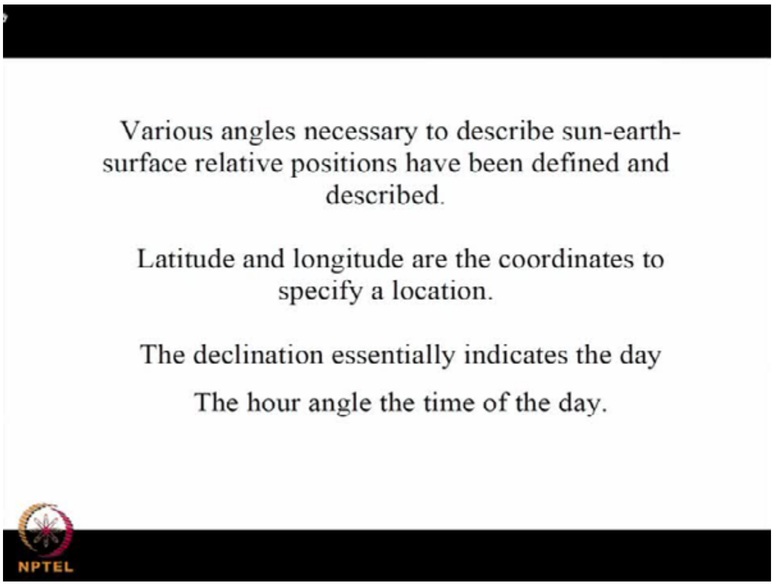
In other words or without much confusion, whenever you encounter less than minus 1, t theta sunrises, means sunshine hours 24 and if it is greater than 1, 0. But, the angle you have to calculate it correctly and it remains to be less than pi by 2, from the declination being 18, coming back up to 18.

(Refer Slide Time: 48:46)



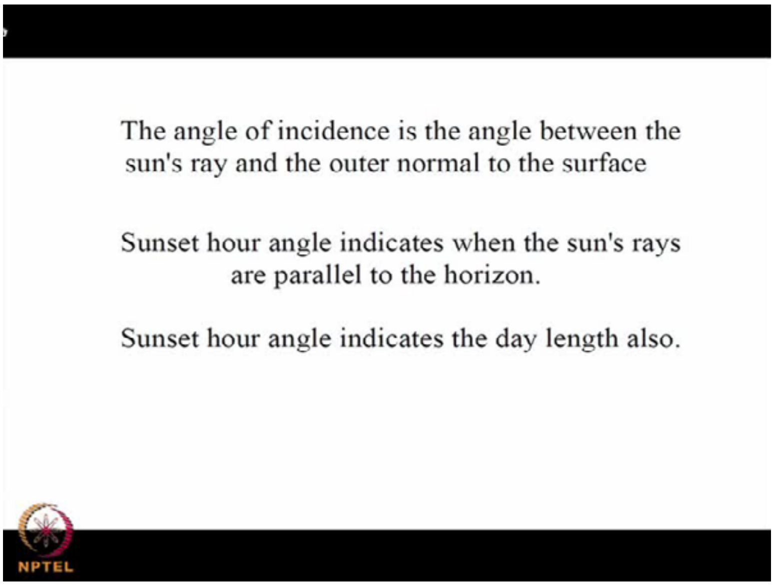
So, we summarize here, terminology most widely used by the solar energy scientists has been introduced, solar radiation as available under extraterrestrial conditions is attenuated passing through the atmosphere. Solar radiation reaching the earth's surface is partly diffuse and the rest direct or beam.

(Refer Slide Time: 49:10)



And the various angles, necessary to describe sun-earth surface relative position have been defined and described. Latitude and longitude are the coordinates to specify a location, the declination essentially indicates the day, the hour angle, the time of the day.

(Refer Slide Time: 49:32)



The angle of incidence is of course, we have defined between the sunrays and the outer normal to the surface, and this indicates the sun’s rays are parallel to the horizon and sunset hour angle also used to the total number of sunshine hours.