Optical Engineering
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Lecture – 08
Lab 2 – OSLO

Good afternoon. So, we are starting a second lab for this course and in today's lab you will be doing an exercise on actually designing a lens with a specific focal length and you will also be looking at how you trace rays through the system. So, I want to give a brief talk a little before that so that you have some background that helps you carry out the lab exercises ok.

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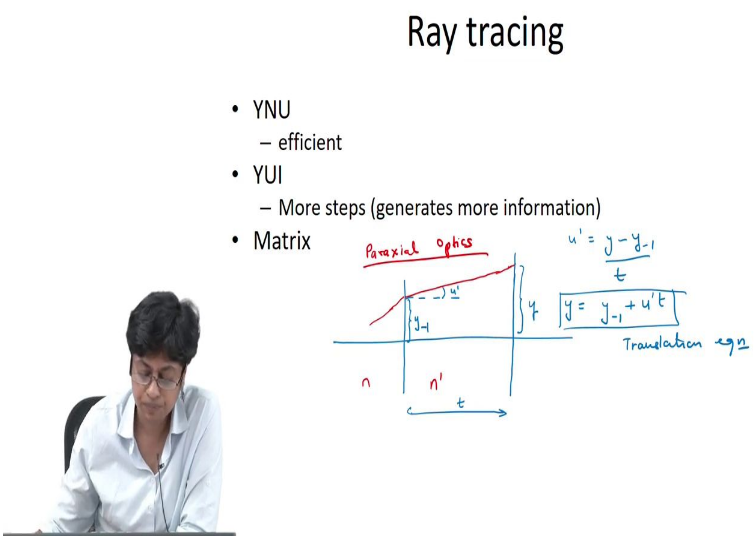
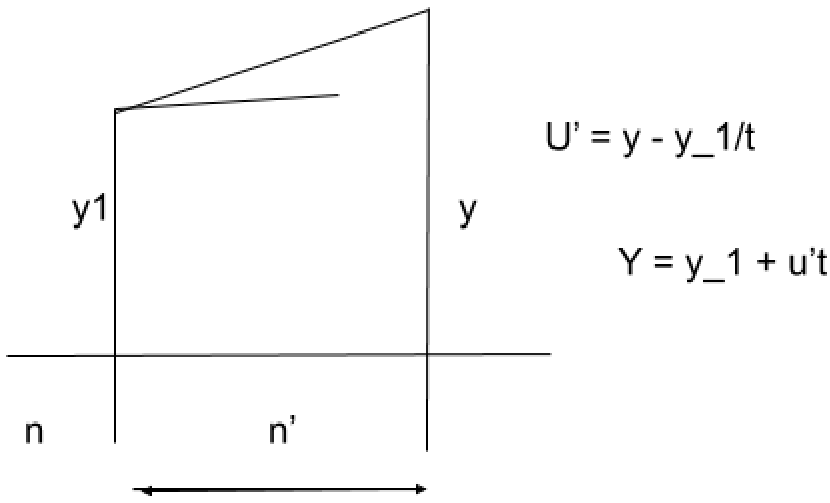


So, when you look at ray tracing there are actually several ways you can trace rays through a system ok. So, there are three different ways that are used predominantly; they call the YNU technique or the YUI technique or the matrix method. The YNU is considered a very efficient method because the number of steps you take to trace an ray is less. The YUI uses one more equation, but because it does not it gives you a little more information and in fact, that is what a program like OSLO does; it uses this technique.

And the matrix method has a slightly different approach to it and we will in fact spend some time in this course looking at matrix techniques for tracing arrays. If you think about it you are tracing a ray through a system; that means, at one point you know the height and angle ray mix and at one point at that is at one interface. And then with that information and with any refractive index or curvature information; you then have to find a way to calculate what happens to these rays so that at the next interface you know what its height and what its angle; what its slope is.

And then you use this information and then find that for the next interface and basically that is what you are doing when I say tracing a ray ok. So, let us look at the YNU method just to give you an idea. Now, since we are dealing with paraxial optics; I can imagine that my optical surfaces are actually straight lines. I can make this assumption. So, I am going to consider every interface in my assumption of paraxial optics as a plane surface perpendicular to the optical axis.

So, if I have a ray that is incident here and then it is an interface so that means, there is one refractive index on one side, let us say n and on this side is n' . So, because of this change in refractive index; the ray bends and lets us travel to this interface here. So, I know the height of the ray here ok; let us call this y_because it is the height at the surface previous to the surface. This is y and of course, the angle; now how do I define this angle? I could define it with respect to different directions, I am going to define it with respect to the optical axis; so, this line is parallel to the optical axis. So, I am going to define it with respect to the optical axis and I will say this is u' ok. Now, the distance between these two surfaces or interfaces let us say has this value. So, I know the height at one interface; I know the angle it the ray makes with the optical axis just after the interface and I want to find out the height at the next interface.



So, I am going to write this in terms of this angle which is nothing, but this height y minus the previous height divided by the thickness or if I am writing it in terms of the new height that is going to be nothing, but the previous height plus this ok. So, this is nothing, but a kind of translation equation which tells you; if you know the height at one interface; given some information, you can find out the height at the next interface ok. So, this is one equation; so this is the y of the YNU method ok. Now, what if I want to take the curved surface into account? What, what do I do that ok?

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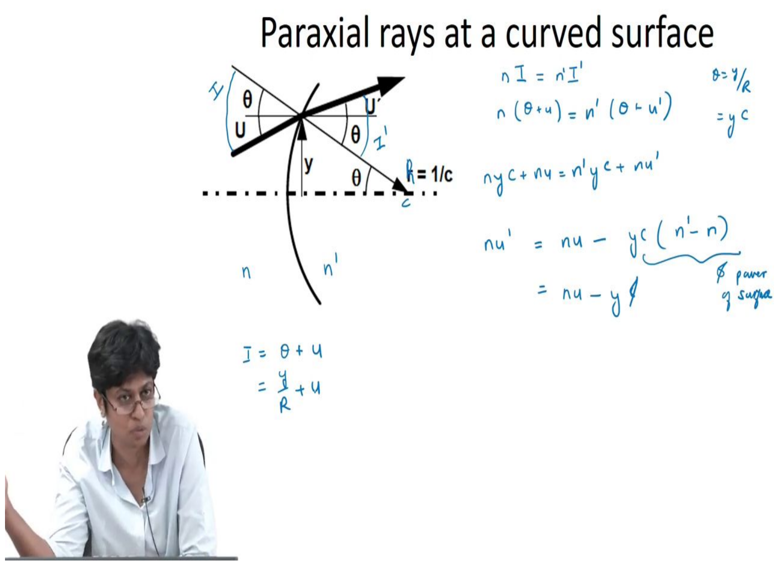

So, let us say I now look at my interface and say I am; I want to take this curvature into account. So, I am going to look at this. Let us call this R. So, this is a spherical surface of radius of curvature capital R right; I can consider. So, the thick black line is the ray; it is incident on the surface and because of the difference in refractive indexes indices, let us say this is n n'; the ray bends according to Snell's law.

So, I have in fact, if I write Snell's law; I will say n into the angle of incidence is equal to n dash into the angle after refraction. I am leaving out the signs because I am still considering these rays to be paraxial and so theta is almost equal to sin theta ok. What is I? It is always the angle with respect to the normal; so that is this in this case and this in this case because this is the center of curvature of this surface.

So, n$(\theta + u) = n'(\theta + u')$ plus u that is n dash which is theta plus u dash, but theta is nothing but y by R right; the height of the ray and I could or I could just say y into the curvature 1 by R is the curvature. So, if I expand this I have nyc + nu $= n'yc + nu'$. And I can write this again just in terms of the angle after the interface and that is going to be

$nu' = nu - yc(n' - n)$

So, let me write it in terms of y c first right. So, this is the second equation that gets used for tracing rays through a system ok. And I could further simplify this because I recognize that this in a sense is the power of this interface because it takes into account the refractive index difference on either side; as well as the curvature of the surface. So, I could in fact say let us write this more simply as this where phi represents the power of the surface ok; so, this is another equation that I would use ok.

Now, OSLO will use a slightly; if it use these equations, it also uses the simple equation of $I = \theta + u = \frac{y}{R} + u$ So, OSLO uses this equation for I, the equation for y, the equation for nu dash and some form of YUI or YNU is what OSLO uses to trace rays through the system.

But you can clearly see that with these parameters given the information at one plane, you are able to trace the ray through the system and then find out the slope of the ray, as well as the height of the ray at the next interface and then you will calculate what happens at that interface, use those parameters as input and calculate what happens at the next interface and so on. So, that is basically how your ray tracing is going on.

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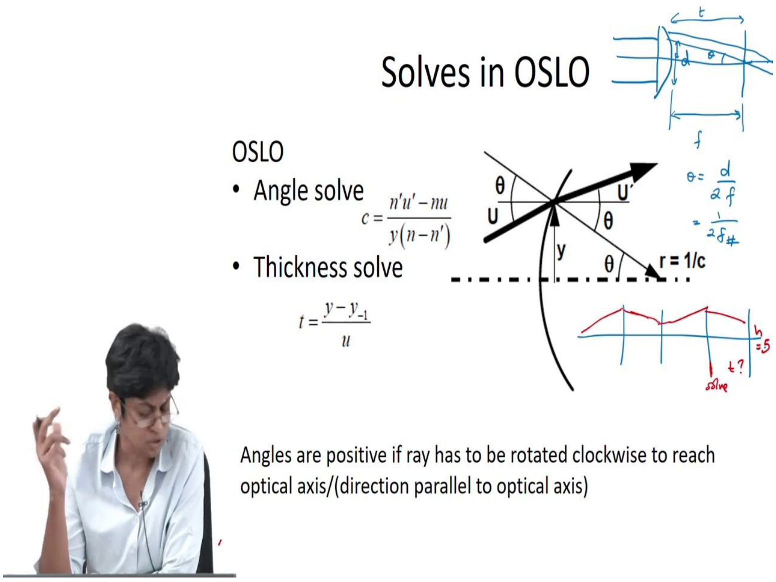

Now, if I look at it in a little more detail; in OSLO, I said there are different ways of entering information; you could go into the software into that spreadsheet and you could manually enter values. So, what are the values you typically enter? You might be entering the radius of curvature, you might be entering distance which they call thickness, you might be choosing a material or glass type and so on.

But sometimes, it is convenient for you if you are able to tell OSLO to calculate a value and say please assign the value for the curvature or for the thickness such that the ray does something specific ok. So, though the act of doing that is called using a solve in OSLO and there are two solves that you will use very commonly; one is the angle solve and you should recognize this equation we just derived this now. So, what are you doing with the angle solve? You are saying I want the curvature of a surface to be or to have a certain value such that the ray that traverses it will have a certain angle.

So, you are going to say; this is the angle I wanted to have, in order for it to have this angle after the surface what should the curvature of the surface be ok? So, rather than go to the column where you enter radius of curvature and enter directly a value of curvature; you will say choose the curvature, give me the value of curvature such that the ray has this angle afterwards. Why would you do that? You are going to do it in today's exercise and I will give you one example of why you would do that.

Let us say you have rays coming in from infinity. So, they are coming in from infinity and you want to choose the distance here. So, you want to choose this thickness such that this is equal to the focal length ok. However, if the rays are coming from infinity; I know that this angle here $\theta = \frac{d}{2f}$.

In other words, this is nothing but 1 by 2 of the f number of your system right. Now, if the ray coming through and I am not talking about any ray, I am talking about the axial ray because the axial ray starts are from the object point that is on axis and focuses at the image point on axis. So, I am saying let the axial ray angle after this second interface be d/2f and in doing so, I am choosing the focal length of the lens right. So, that is the key to what I am doing; I am choosing the curvature such that I am actually choosing the focal length of the lens right.

If I changed the value of f; I said let it be I calculate so that it is here; I am then saying what is the curvature for this new focal length of the lens right. So, this is one place where I would use an angle solve. The other solved that is commonly used as the thickness salt and again I am using the equation that we just derived we are seeing choose the thickness. So, maybe I have many interfaces, many optical interfaces in my system and the ray is traveling through these bends at each interface; it's continuous right.

And I am now saying; I put a solve here, this plane I put a salt and say choose this thickness; tell me what is thickness t, such that the height at this interface is equal to let us say 5 mm right. I do not know where that height happens, but I am saying put the next interface wherever that height happens right. And again depending on what I want to do, I will say choose the axial ray height or choose the chief ray height; I can choose which ray and work ok.

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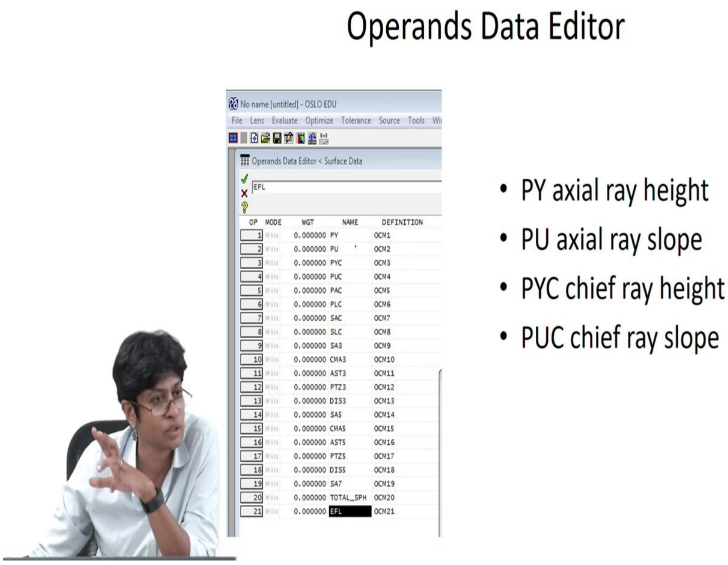

So, this is basically what we are going to be doing in today's lab class and one of the things you will need to do is to go and pick operands that you want to work with. This will become clearer as you work out the exercise I just wanted to show you; this I will also run through it in OSLO so it becomes clear.

But this window shows you a bunch of operands that you can work with and the first few operands PY and PU are the axial ray height and the axial ray slope and PYC and PUC are the same parameters, but for the chief ray and the remainder; so you see it starts from something called PAC; all the way to this total SPH; these are all different kinds of aberrations.

So, the first few are chromatic aberrations and then SA3, these are the third order monochromatic aberrations and then you have the fifth order monochromatic aberrations and this last parameter here is actually the effective focal length. So, the way we used PU, we calculated the u angle right; we were in effect saying what should be the curvature so that I get a certain focal length?

So, in some cases I will use the PU operand in order to control or design a lens of a particular focal length. You could also use the effective focal length; we will learn what effective focal length means. So, there are two operands we can use and we; I would like you as we go along in this course to try to understand why there are two operands and are they exactly equivalent and if not what are the differences ok. So, keep that in mind; go to OSLO.

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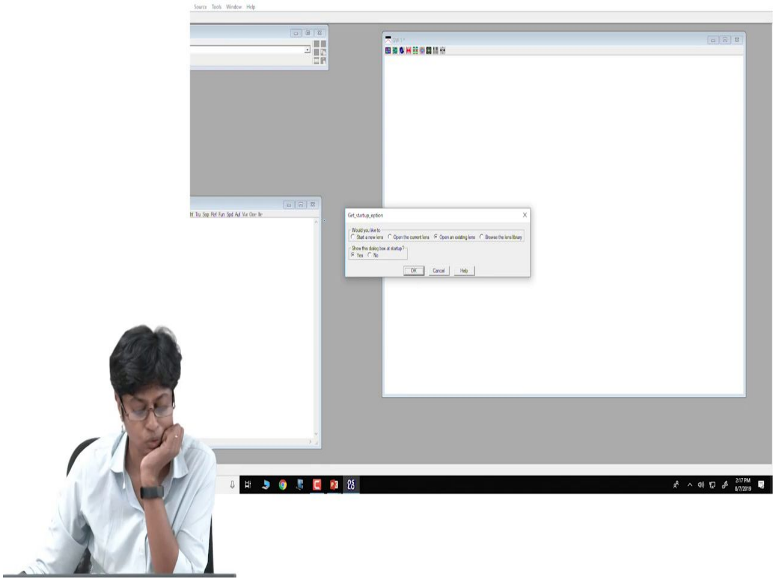

So, if you open OSLO; you always of course get the startup option; we want to start a new length. So, that is what I am going to do.

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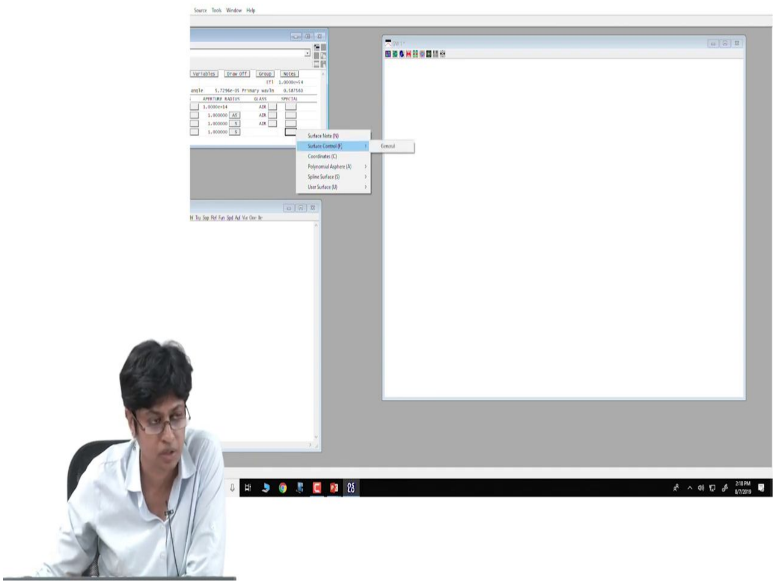

And let me just enter something randomly. So, let us say the first radius of curvature I take is 100 and I am going to insert one more row. Let us make it a convex lens; so the next radius of curvature, I will make it negative minus 100. I want to see what happens on the image plane, so I am, of course, drawing the last surface.

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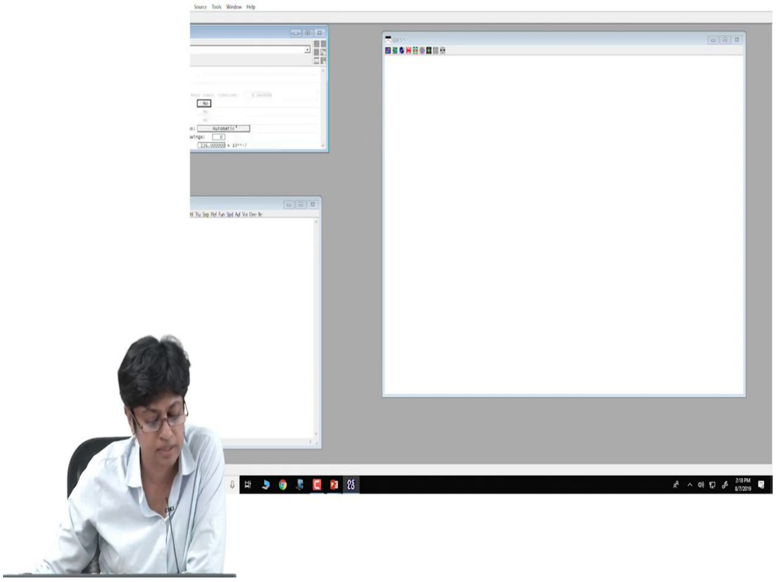

So, we go to the last column; the special column surface control, general and say we want this surface to be drawn, always accepting inputs with this green tick mark.

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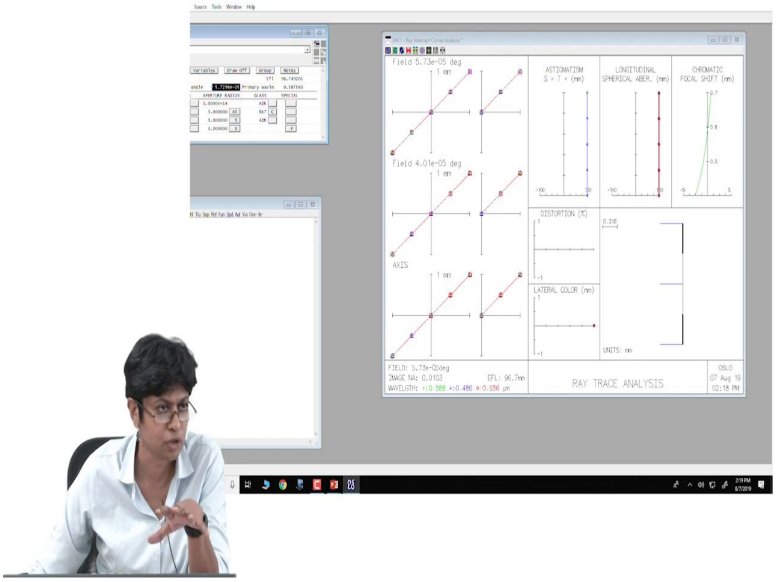

Of course there is nothing here yet by clicking on this red set of lines; I am getting all the aberration curves drawn. But the system isn't shown because although I have entered radii of curvature, I have not yet entered any material; there are no interfaces yet in this. So, I am going to enter as I said BK 7 which is a standard glass type.

I still do not see anything very much; now my lens is there, but the image plane is bang after the lens. I have not given any distance between the image plane and the lens and I have not given much; there is no field angle, there is no entrance beam radius. So, a couple of things to note here; I would start by entering the beam radius of the beam size that I want to work with. So, let us say we say we have a 3 mm radius beam and this number indicates 0 for OSLO. This is a truly paraxial ray there is this; there is no angle at all, let us give it a small angle of 2 degrees ok.

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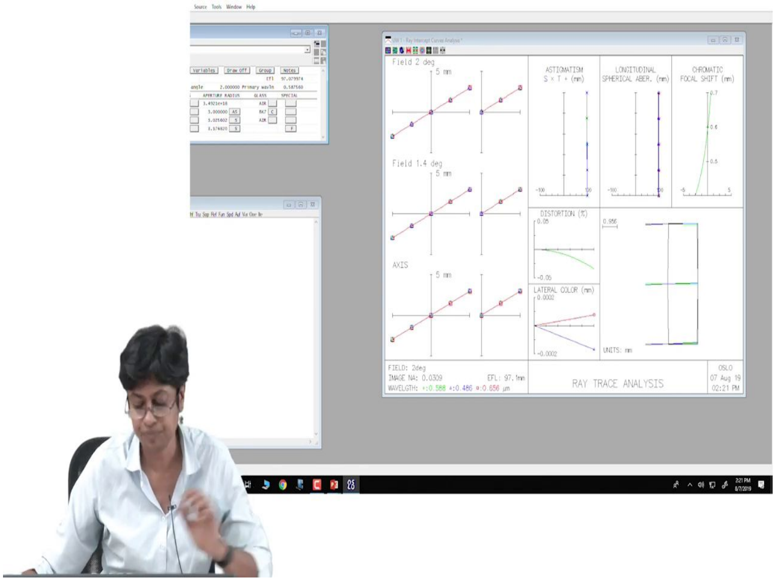

Now, you should notice that when I change the entrance beam radius by default OSLO will make the first surface always the apertures stop. So, that is why you have this A/S right and now you should understand what that aperture stop means. If I want I can change, if I have a number of elements I can pick some other element to be the aperture stop, but by default the first element is going to be the aperture stop and you should notice that when I change the entrance beam radius; the radius of the aperture stop also changes.

Because so let us see; let us say if I gave it 5 mm; this also changes to 5 all right. Why is that happening? Because OSLO works in the principal that the entrance beam radius that you give, you say I want my beam to have this size. In other words, you want the beam that makes it through the system to have that size and we now know that the element that controls what goes through the system is the aperture stop.

So, it is going to control the size of everything else such that this size beam goes through and that is why when you enter it there that is what gets changed at the aperture stop ok; I do not want such a large ray. So, I am going to go back to 3 mms ok; let us also give the lens a finite thickness, it is not 0. So, I see that thickness now, but of course, I still have not got my image plane moved away, my image plane is right after the lens because the thickness here is 0.

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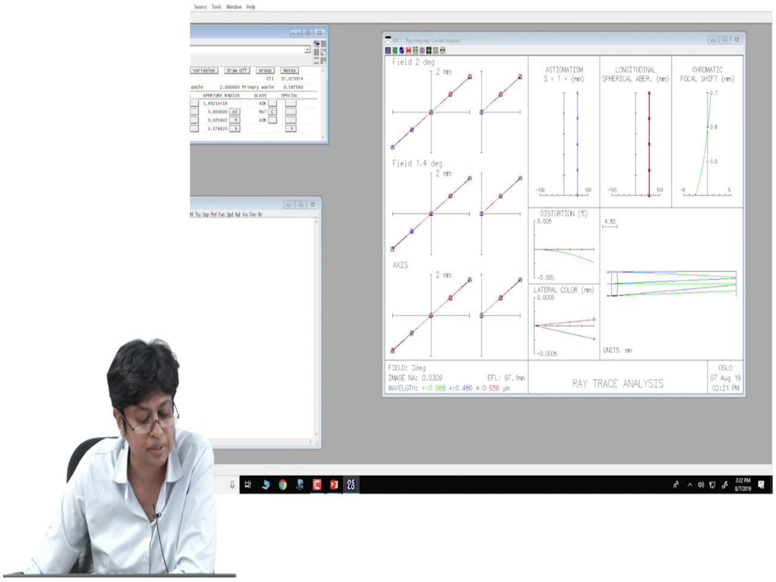

Let us say I moved it some distance. Now, I can see now the image plane is moved, but this is clearly no. I am calling it an image plane; in OSLO that really means the last plane you are looking at. It does not necessarily mean that is the plane where the best image is formed ok.

You might have to do something different in order to get to the plane where the best image is formed. And you can see very easily here you are not at all near the plane where the best image is formed. We have a parallel beam coming in; the best image in this case is definitely going to be formed at which plane? At the focal plane, right.

So, you can clearly see this is not near the focal plane. Now, you do not yet understand all these aberration curves; all these other curves here are aberration curves, but if you look at them, you can see that the scales on these just keep an eye on the scales you have about 2 millimeters here, you have -100 to 100 in this scale; a fairly large numbers.

Now, let us go closer to the focal plane and how would I know that? Well, I have the effective focal number listed up here; it gives me the effective focal number, it says 97 mm. So, let us go to 97 ok.

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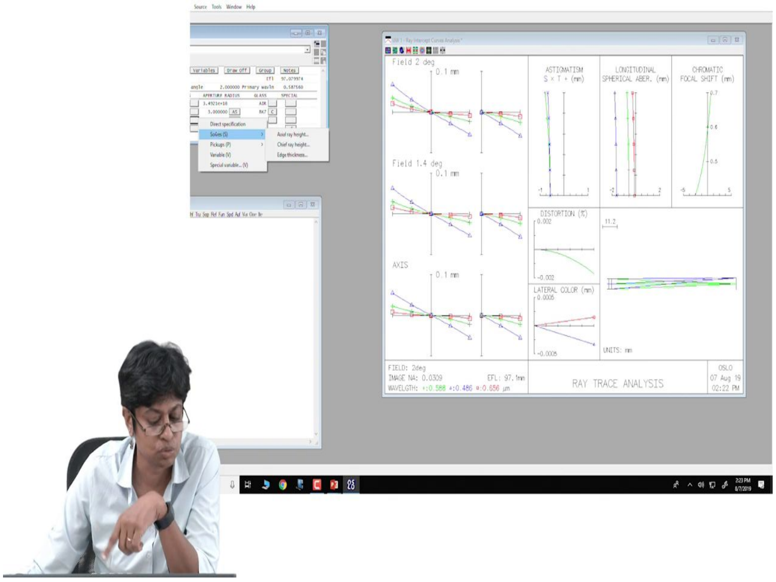

And you can see these numbers have come down drastically; the aberration this astigmatism was going from -100 to +100 and now it is - 1 to +1 right; this was 2 mm and you have seen it's now 0.1 mm. So, let us every time it's plotting this curve; it changes the scales to fit what are the values being generated. So, do not just look at the shape of these curves, you also always need to keep in mind the scale or the values right.

And we will anyway come to these curves later, but you can see even from this image that the image plane is now clearly closer to the focus. I entered a number very close to this effective focal length, I did not actually enter the exact number; I am now going to use a solve. So, I will click on this little square button next to the thickness; I am going to ask OSLO to solve for the thickness such that, so I am choosing a solve I am interested in finding where purpose perfect focus happens. So, it is the axial ray that will have 0 height at perfect focus. So, I am going to pick axial ray height.

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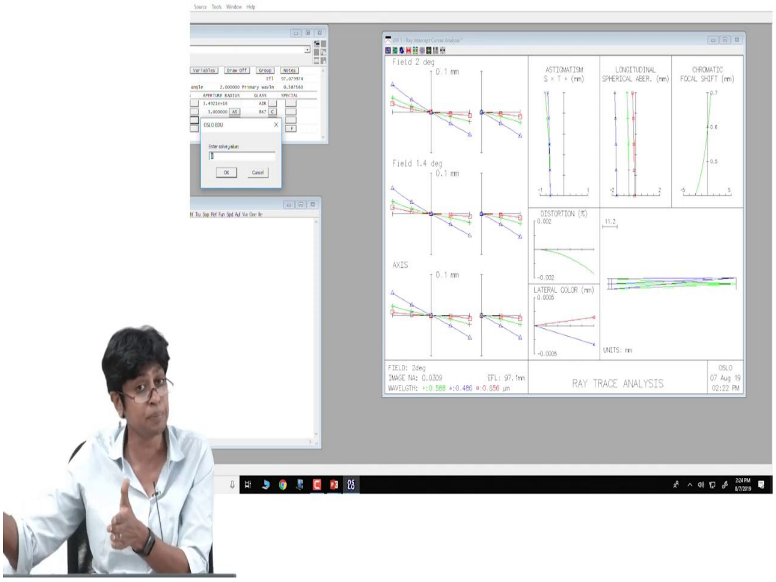

But I want the plane at which the ray height is 0; I could pick the axial ray and say choose a plane where the height is some other value, I want the place where it is 0, where it crosses the axis.

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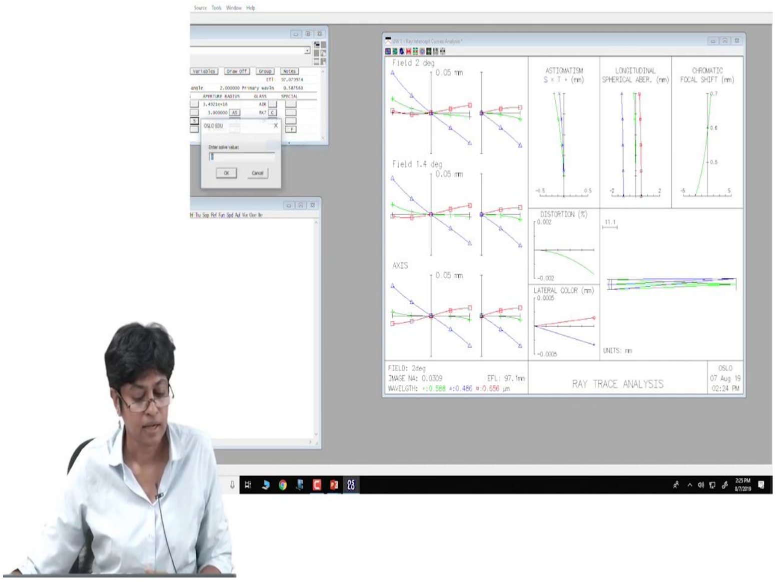

So, if I do that you can say it has picked a value 96.4 and if we go to the image now; it is really at the focus and you see the scale values here they have even come down. So, the aberrations have decreased further right because you are now at the perfect focal plane ok. Do you have any idea why this focal length and this number here are not exactly the same? Because the lens has a certain thickness and we will also; it basically that we will go into that in a little more detail over the next few classes ok.

I need not solve for axial ray height right; I could solve for chief ray. So, let us say I took chief ray height; where will the chief ray height be 0? Where if I click 0 now; now I am saying solve for the thickness such that the next plane is the place where the chief ray height is 0, where will that next plane happen?

Student: (Refer Time: 24:12).

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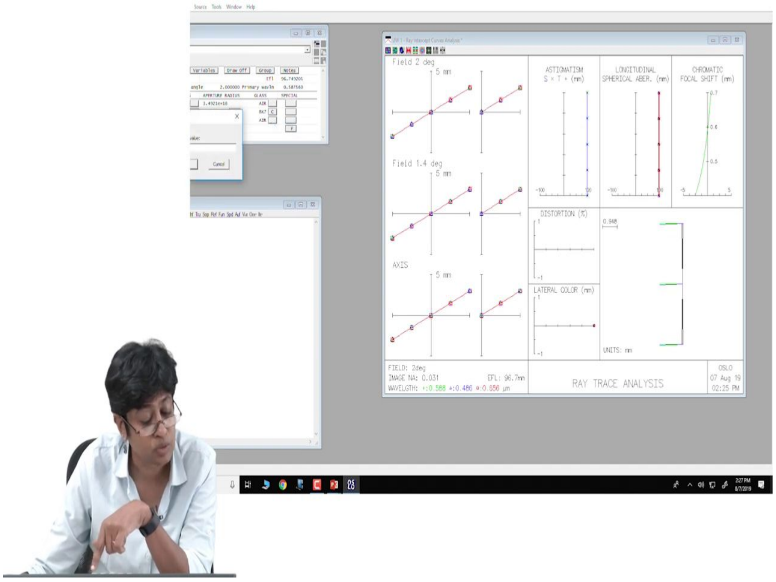

It will happen at the lens itself because how did we define the chief ray? We said the chief ray goes through the center of the exit pupil right; does it? Yes no?

Student: Yes.

And what is an exit pupil in this case? You imagine anything that comes after the aperture stops it, here the lens is the aperture stop and there is nothing after the aperture stop. So, the back of the lens is going to act as your exit pupil. So, if you choose to solve where the height is 0 for the chief ray; it is exactly at the aperture stop itself which is the lens itself right. So, these are just tools that allow you to calculate thicknesses or curvatures right. I can go here again. There is a solve here; let us say solve and say solve for which ray?.

You are seeing solve give me the radius of curvature of this surface such that a ray has a certain angle after it. But I have to tell OSLO which ray to solve for? So, you can see there are a number of rays that its; number of axial rays and a number of cheap rays you can choose. If you choose that you have to say what is the angle that I want and then it will choose the curvature such that that happens. So, these are some tools that will help you carry out today's exercise as well as the exercises in the future labs.

So, I think with that background; I will let you start the lab exercises, please go through the first part of the exercise or what has been given to you in the PDF file and then start working out the exercise.