Optical Engineering
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Lecture – 18
Monochromatic Aberrations – part 2

Good morning. So, bright and early we start with our Aberrations again. We saw in yesterday's lab exercise you were asked to optimize some systems for certain aberrations, so since we looked at spherical aberration and coma that is what you did in the lab exercise yesterday. And you might not have finished the exercise yet, but you have also been asked to change the shape of a lens so; that means, keep its focal length constant and then see how the aberrations vary or depend upon the shape; and once you do that you need to plot a graph of this kind.

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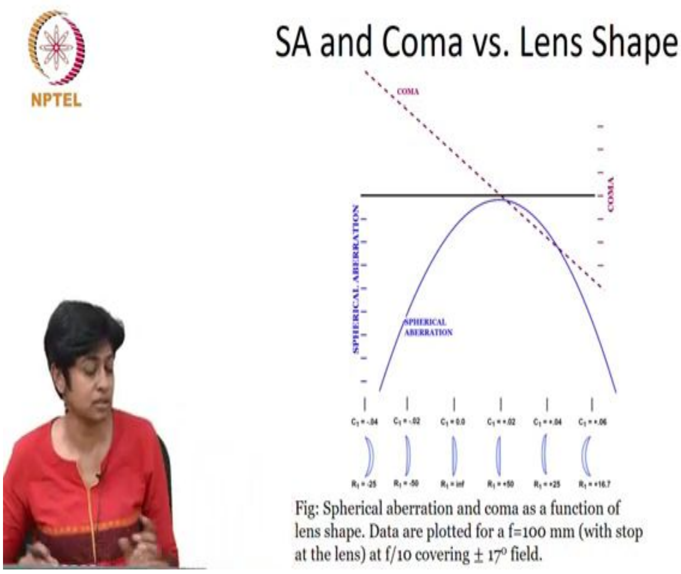

When although the x axis is plotted against so, the what you are wearing along the x axis is the shape there are very specific instructions on what you actually plot along the x axis. So, please go through the document carefully otherwise you will not get this form of the curves ok.

Has anyone finished the exercise? One of the reasons of plotting curves like this is you are able to see, where your you can minimize more than one aberration; or in this case you see for a particular focal length you are not changing that, you find that there is one shape that gives you a minimum of spherical aberration and coma and clearly that would be a good shape to use in that case right.

So, if we only plotted the two aberrations here but of course, you can plot the other aberrations you can look at astigmatism, and distortion, and color, and see how they are affected by this parameter ok. So, I encourage you to do that since it gives you an idea of what affects a certain aberration or not ok.

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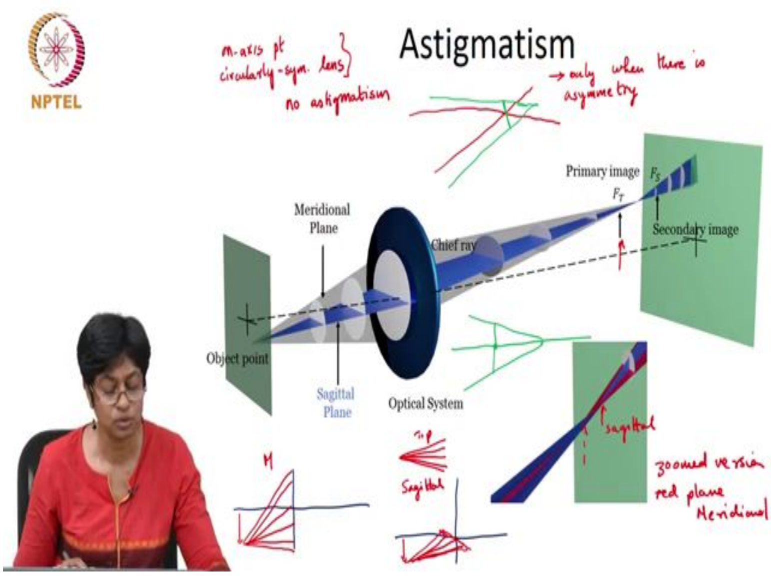

So, we move on to the next monochromatic aberration; which is astigmatism ok. What is astigmatism? And you can see several of you wearing glasses, so I am sure you would have heard the term astigmatism before right ok. So, you have got the idea that; well, this is what every aberration is doing right, different annular zones are doing something, different apertures are doing something.

So, where does astigmatism arise, first of all astigmatism arises when there is asymmetry ok, so it is an aberration that arises only when there is asymmetry. So, if I have an on axis point and a circular lens circularly symmetric lens, then you will have no astigmatism. We will see in this particular figure the astigmatism is arising because you are looking at an off axis point and that is where the asymmetry of the lens is circularly symmetric, but you have an off axis point and that is where the asymmetry is arising.

Now, I hope I have this figure. This is just a zoomed in version of what is happening over here, so if you look at this there are two different; the planes have been two different colors used to designate the planes ok. So, the Sagittal plane is in blue and that is the rays that lie in the horizontal plane and the Meridional plane is in gray and that is the perpendicular plane. So, you can imagine you have a fan of rays that lie in the meridional plane and a fan of rays that line the sagittal plane and they come from this off axis point and hit the lens.

Now, you already know that the meridional rays; if this is your lens this is the optical axis, the meridional rays are coming from this off axis point and you can see they all hit the lens in a very different manner there is no symmetry in the way they hit the lens so, this is for the meridional plane. On the other hand the sagittal rays are all would be, I cannot really draw it, but let us see this is my sagittal they are all hitting this. So, when I look at it from the top they are going to look symmetric, this is the top view for the sagittal right.

So, there is symmetry still with the sagittal rays and there is not any symmetry with the meridional and there is a difference between these two ok, for an off axis point. So, it may not be obvious in this figure, if I look at these two if it seems here that both the sagittal and the meridional rays are coming to focus here, but if you look at this you zoom in and you look closer this is what is really happening right. And what is happening here is the set of fans of rays that lie in the sagittal plane they are coming to focus over here at this point.

So, the blue are the sagittal and unfortunately the color has changed so, in this zoomed version the red plane is the meridional ok, what was gray over here. They are coming so, this is like a sagittal focus, but the red rays are focusing somewhere over here right. So, the rays that are coming from the meridional plane they come to focus at one point; after focus they go on diverging, the sagittal rays come to focus at another point after focus they go on diverging.

Now, ideally these two points should be the same point and if this was an on axis point this would be happening, the focus would be happening at the same point, but because of the asymmetry this is not happening at the same point, so, what does that mean? At this plane where the tangential rays come to focus the sagittal rays have not yet come to focus. So, if I were to look at that image at that point of course, the image is formed by all the rays that are there not just by the rays that happened to be in focus there.

So, if I were to look at the image at that point what do you think that image would look like? I have a point object my ideal image is a point image, and when I look at the tangential rays they have all come and focus to a point so, the tangential rays are forming a point at that place at that location the sagittal rays are coming like this and they form a point later on. So, at that plane where the tangential rays are focused, what do the sagittal rays look like? So, I have my tangential rays coming to focus, at this point and my sagittal rays are focusing at this point.

So, what does the sagittal look like here, what is the focus of the sagittal rays? It is a line right. So, I have this the fan of rays in this plane they are coming to focus, just think of if I am looking from a top view I have a fan of rays coming to focus here, if I look at them at any other plane it is a line, at this plane and I cannot draw it because, it is a top view now so, I the tangential rays is just going to look like this. But there is a whole fan of rays there they are coming to focus at this point, at this point what will the tangential rays look like?

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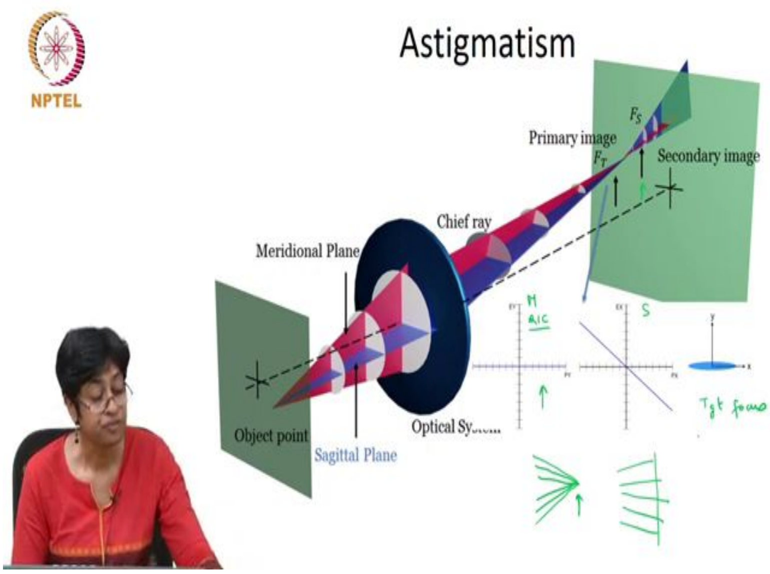

Another line, but will the lines be exactly the same? So, maybe this image helps you a little bit, in this case I am my focus; so, I am now looking at the tangential focus, this is the line which is basically caused by all the sagittal rays right. So, the tangential rays have come to a point focus, but the sagittal rays are spread out and I get a line like this. What will I see if I look at this surface? It is still a line, but it is a vertical line ok.

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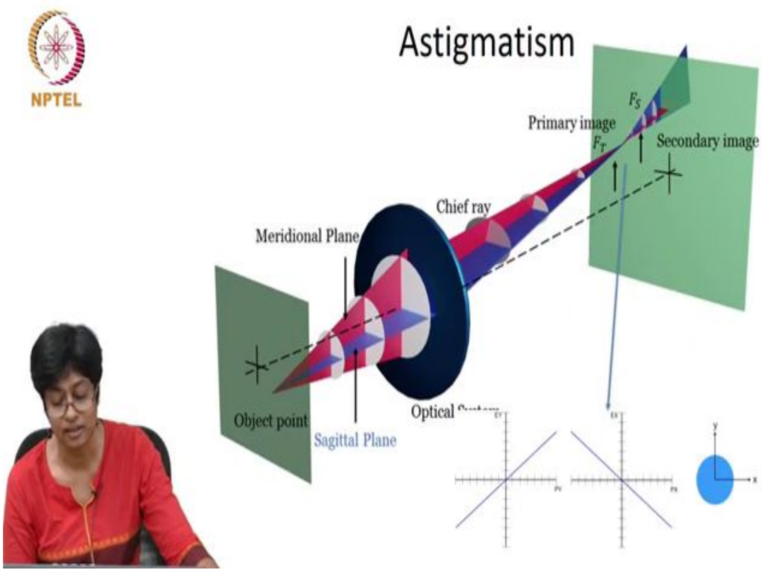

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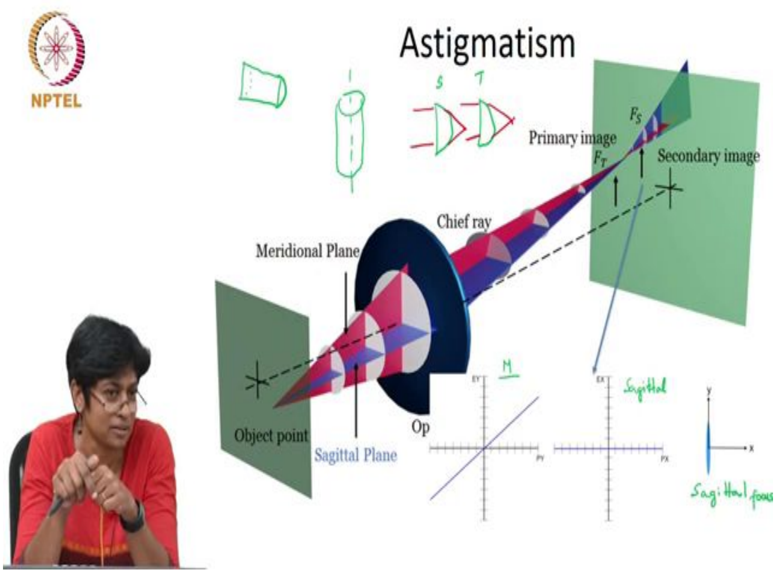

So, remember now even in spherical aberration we said the focus happens for the paraxial rays at some point, the focus happens for the marginal rays at another point and I can consider that there is a focus that has happened everywhere between these two points, so, it was as if the focus was spread along the optical axis right.

And we then decided that the paraxial focus although we keep saying that is the ideal focus, it actually does not give us the best focus point, because the tangential or the marginal rays are so far spread there that your spot is overall very large at the paraxial plane. And then we moved along the optical axis till we found the plane or the circle of least confusion and we said that is the best focus if your system has spherical aberration. Again in astigmatism you find that the focus varies along the optical axis, but it is not a bearing in terms of a circle of different diameters, here it is varying in terms of an ellipse.

So, the tangential focus, I call this the tangential focus, but this line is caused by the spread of the sagittal rays here, I call this the sagittal focus; that means, of all the sagittal rays, all the sagittal rays have come to focus, but the tangential rays were focused much earlier they have continued to diverge and so, their rays are spread out like this so, I have a vertical line here right. And somewhere in between I will have the circle of least confusion ok.

Now, this arises because the object point was off axis, the moment I moved to an on axis point, I cannot tell the difference between the meridional and sagittal rays, you should be able to see that. If I can always rotate my object and what I am calling meridional and sagittal I can interchange that right. So, for an on axis point if my lens is symmetric there is no question of having astigmatism right.

So, astigmatism each aberration you can see affects the system very differently, spherical aberration yes it was an aberration that affected focus along the axis, but it was symmetric you could identify a nice center of gravity to your image you could find a plane where the spot is minimum and that was not the paraxial plane. Coma you had no longitudinal error you have only a transverse area error, but the center of gravity is not easy to locate. You have to use some other means and you get this strange comet-like shape that makes your image really bad quality.

And now we are saying in astigmatism again you have a longitudinal variation, but it is not symmetric about the optical axis, you have this ellipse and this ellipse is rotating as you move along the optical axis. So, at the tangential focus this is what you will have and I have drawn the RIC curves for the meridional or the tangential plane as well as the sagittal plane. Now, you can see we call this the tangential focus so, if I look at the RIC for the tangential rays there is 0 error, because they are all at focus yes the rays are all so, they are all coming to the focus point.

So, all these different tan use, but the error at this point is 0 and that is what is indicated in this curve right. On the other hand if I look at the sagittal rays right, at this plane they are spread out like this. So, I have this spread over here right, and that is why you see a variation in the sagittal. If I move a little further down the axis, I have the best focus, so it is neither that this is the best focus its like a compromise neither are the sagittal rays focused here nor at the tangential rays focused here, but this is where I get the minimum spot or the most circular spot right.

And both RIC curves of sagittal and meridional show variation, on the other hand if I move further down, now I have come to the plane where all the sagittal rays have come to focus. So, each ray coming to focus has a different angle, but at that point of focus they are all at the same place so, the error is 0 which is why the sagittal here shows 0 error for all rays irrespective of their angle, the meridional rays on the other hand have now spread out in this direction and so, this is why the meridional rays the RIC curve is nonzero.

And, as you move for increasing angle you see the height is increasing so, you have a linear variation in the error ok. Is that clear? Take some time and picture it, once you picture it, it is pretty straight for once you see this fan of rays which is why it is so important to get your definitions and understanding of the meridional and the sagittal rays. Now, you see if you understand what those rays are, this aberration becomes easy to picture because; you know we are talking about the fan of rays in a particular plane right.

Now, up till this point we have always assumed or imagined or talked about aberrations as if aberrations are a bad thing, but we can use aberrations or not all aberrations, but we can use astigmatism to help us do something and in fact, I said if you have an on axis point and a circularly symmetric lens you will not have astigmatism, and that is clear because, your sagittal and meridional for on axis do not have a difference. So, sometimes in an optical system people will actually use what is called a cylindrical lens. Now a cylindrical lens breaks the circular symmetry.

So, if I were to attempt to draw a cylindrical lens, this would be one phase of the cylindrical lens and the other phase would be curved ok. It would be like, if you took us a cylinder and then you cut it in half at the diameter and then you use that surface as an x. Now, how is this different from the lenses we have been looking at all this while, well the lenses that we have looked at the spherical lenses they had curvature in this direction and they had curvature in this direction right what did that mean?.

When you have a beam of light, let me draw the side view that is just a side view of our spherical lens. So, remember in this view you only see the curvature in this direction, but if I were to look at the top. So, this is a side view, if I were to look at the top view it would look the same right. Now, if I have a light incident on this lens it comes to focus because it is bent by this curvature in this the same beam would come to focus because it's bent by the other curvature there is this curvature and this curvature.

So, these rays are getting bent, the sagittal rays are getting bent, the tangential or meridional rays are getting bent, but in a cylindrical lens this curvature only in one axis there is no curvature in this axis. So, the bending happens only in one. So, every ray that bends here, it bends here, it bends here, but there is no sideward bending. What is the focus I will get? You will get a line focus right, and you know you must have seen optical systems where you have a line of light right.

So, sometimes you do not want a point if it is an imaging system you want every point on the object to be a point on the image, but you are not using optical systems only as imaging systems sometimes you use them to scan or some you use them for a variety of reasons maybe you need to heat up a certain regions we have a powerful beam of light.

Sometimes, you need a line of light rather than a point of light and a cylindrical lens does that. Now I can further use that in some systems where I want to have astigmatism now why would I want to have astigmatism? The clue to that is thinking about what happens as you move along the optical axis in a system with astigmatism. So, you tell me that what happens we have just gone through that, but I will ask you again what happens when you move along the optical axis in a system with astigmatism what are you going to observe as you move along.

So, the focus, but the focus is a line which is strictly speaking if you consider all the rays it is not really a line, but it is like an ellipse, but the ellipse rotates as you move along the focus. So, the major axis of the ellipse lies in one plane and as you move that is rotating and finally, the ellipse of major axis of the ellipse is in a orthogonal direction and in between somewhere that ellipse has changed to a circle and then again it becomes an ellipse and that is right can I not use this? If the focus is changing as I move along the optical axis. Can I not use this? Say I wanted to find out in a particular system where the focus was right.

And many systems actually do this. So, they may use some inherent astigmatism that is present in the system, but if they do not have inherent astigmatism present they will actually introduce a cylindrical lens. So, you are introducing astigmatism now please note I said on axis points do not suffer astigmatism, but that is not true if I introduce a cylindrical lens because I also added the rider on axis points do not experience astigmatism if the lens is circularly symmetric and the moment you introduce a cylindrical lens you are breaking the symmetry.

So, even on axis points will have astigmatism right because this behavior of the sagittal rays is going to be completely different from the meridional rays even for an on axis point right. What happens in a CD system is in that. So, one of the common places where this is used is in focusing on a CD system ok.

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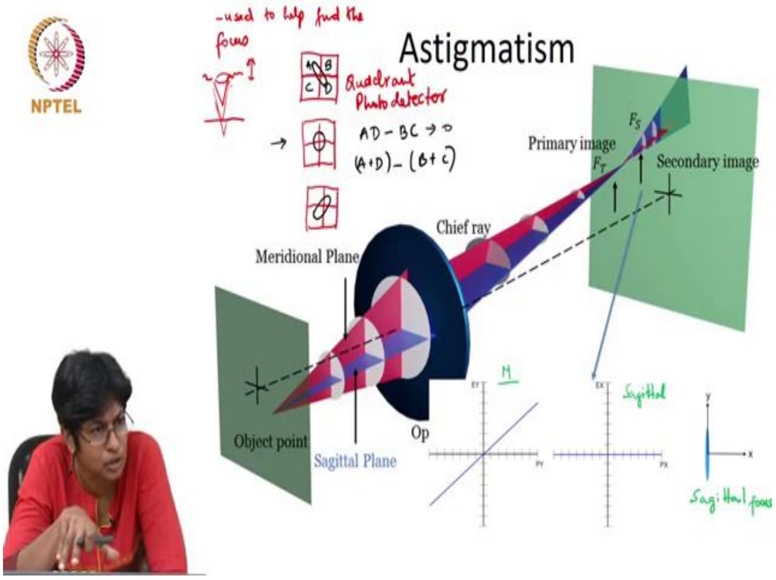

So, astigmatism can be used to help find the focus. So, the CD and we will look at that in more detail, but basically the CD system and other similar systems have a lens which has the ability to move up and down ok. So, you can control that movement. Now as its moving you are changing where the focus may be the focus happens here then you move it down then the focus will happen here if you move it further down the focus right.

So, you are changing by moving the lens. You are changing where the focus happens. I want to adjust the height of the lens with respect to the surface such that the focused point lies on the surface. Now, how do I do that automatically? If I have a detector which has four quadrants. So, it is called a quadrant photodetector now let us imagine so, let us say we will call these AB or CD right. I have to orient my system or I have to orient the detector such that the tangential focus initially is like this.

So, as I move the lens the detectors here and it sees this if I move the lens further, let me just keep these ready. If I move the lens further I am going to go through this region and if I look move it further I am going to go through this region. Now the electronics the quadrant photodetector basically means you are able to acquire the image from each of these quadrants independently and so, the people either do an operation of AD minus BC or A plus D minus

B plus C and you can see that if you have aligned your system correctly when you are at this position you will get a 0 over here.

So, when that signal is 0 you know you are at the best focus. So, you can use that for automatic focusing. This is exactly what is used in a CD pickup or DVD pickup and in many other optical systems as well. So, you are actually using an aberration to achieve something useful.

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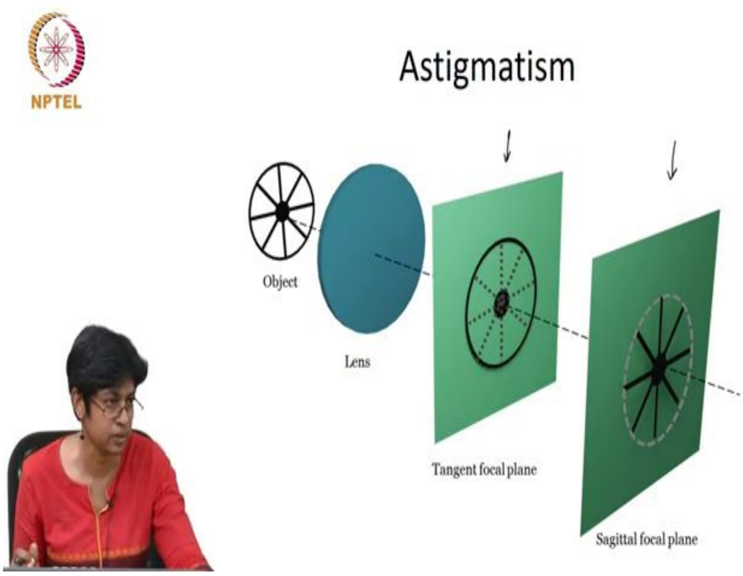

So, you can also think of astigmatism as. So, what the explanation we looked at was right. Now is this is what is happening this is why it is happening sagittal and meridional rays behave differently we use these two fans of rays or the fans of rays that lie in these two planes to make it very clear why there is a different in focus, but clearly this effect is being felt through all the rays in every plane.

So, we have taken only this plane and this plane, but you have a whole host of planes of rays right and you can think of it in another way if this was the object. So, you had like a bicycle wheel with spokes astigmatism causing one set of features to be in focus at one plane and another set of features to be in focus at another plane. So, if I was trying to imagine such an object, astigmatism is going to prove a bad thing because clearly where I get best focus for some feature I am getting the worst focus for the others and I would have to find some plane in between where I say I do not get best for either.

I get something that is acceptable for both or the different sets of features ok, but in the previous example of searching for focus using this then I am taking advantage of the aberration or I am actually introducing the aberration. So, that I can use it to find the best focus point ok.

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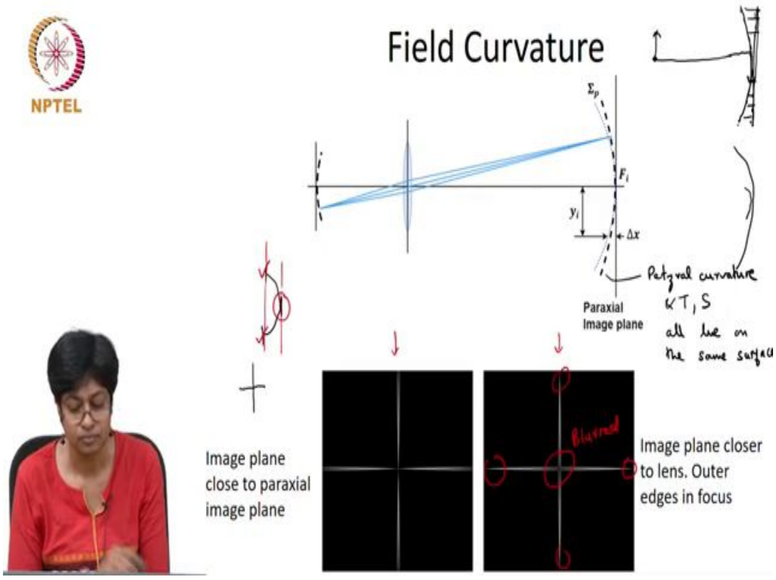

Now, the final aberration we look at is field curvature. So, again if we go to an off axis point it should not be surprising that the ideal image surface is not actually a planar surface, but a curved surface right we have always been talking about I if you have an optical system if you have an object then and I look at let us say I have an object which has some height.

We have always been drawing the image like this; that means, we are saying what happens on this plane, but the spherical surface is not the surface that gives us the best image. So, it should not be surprising that the best image plane is actually a plane with curvature which itself is part of a sphere, now we are compromising and using a planar image why do not I use a curved surface is the curved surface is the best surface if my image is being formed on a curved surface why am I capturing it on a planar surface?

I remind you of something else that will help you answer that why did we go to spherical, if spherical is not the best surface why are we using spherical? It is easier to imagine if every screen we are seeing the image capturing screen should be curved. Now imagine it every single phone of ours has a screen every camera has a screen, every imaging system has a screen its. So, much easier to manufacture flat screens and if I start saying manufacture curved screens well the curvature has to depend on the optical system.

Here whether you are buying a smartphone of certain size or a slightly larger smartphone everything is flat I do not have to worry about what is the optics that I am going to use what is the size of the camera what is the curvature therefore, that I need I may make my sensor slightly larger or smaller yes, but it is always flat. So, I do not have to worry about the curvature of the system if I change the size of my optics well maybe my screen has to be this big or maybe my screen has to be like this I would have to custom make it and anytime you have to custom make some make something the cost shoots up.

Plus it is just so much easier to fabricate flat screens right. So, again we are living with the fact that the best image is being formed on this surface, but we are going to capture it on the surface; that means, this d focus everywhere now if this d focus is within the depth of focus its acceptable. So, I have to design in my system such that this error and it is called the petzval curvature this.

Now, if you have an on axis point the tangential rays the sagittal raised and this petzval curvature these three surfaces all lie on the same surface they are all the same surface, but the moment you go to an off axis point these three surfaces separate ok. So, I have like you could consider the petzval curvatures like the paraxial curvature the best curvature you get even for on axis then the tangential rays will focus on one curved surface which is different from where the sagittal rays focus and you can see this two images over here.

The first image is when you are at the plane closer to the paraxial image point and you can see it you are imaging something like this across and closer to this you are at this plane where these rays are in focus right and if you move away here sorry these rays are in focus and if you move away then you find these rays are in focus. So, you can imagine if your surface was like this and you see the paraxial rays are in focus here and the outer rays are in focus here if I move my screen when they are here I will see these rays in focus and when the screen has moved here I will see these rays in focus and that is what you are seeing in these two images over here.

So, my image is formed on a curved surface the paraxial rays are focused closer to the axis. So, when the screen is here you get those rays in focus and then I move the screen and the outer ones become in these regions are in focus and this is all blurred right.

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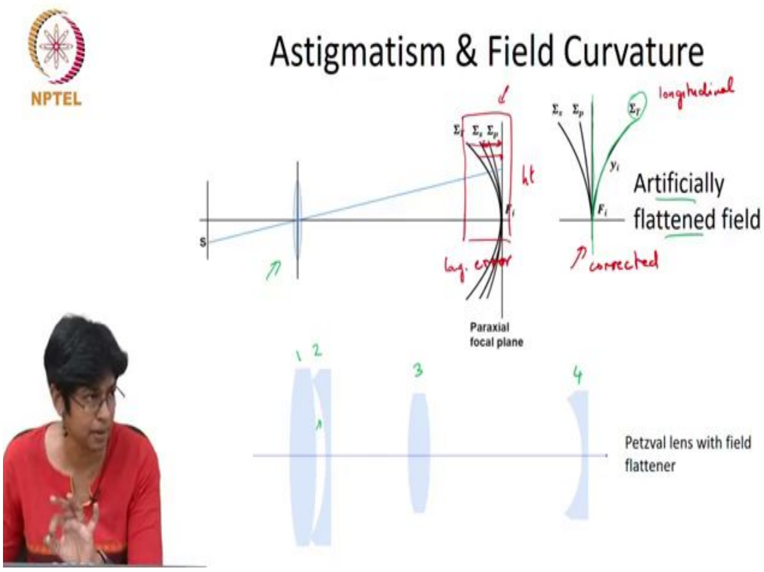

So, for an this is what I was saying for an off axis point these three planes start to separate out with the tangential rays for a convex lens the tangential meridional rays they come closer to the lens and they are roughly three times away from the paraxial plane as the sagittal rays are. So, you can see I first have all the tangential rays focused here. I have all the sagittal rays focus and this is the petzval curvature plane.

If it is an on axis point these three will all merge and become one curved surface. Again if I look at the longitudinal error this graph is now showing the longitudinal error if I can somehow add a lens or set of lenses to the system that pulls this away right this is actually a nice figure this shows the longitudinal error and you can see it is a this is for a corrected field ok. So, if I was looking at the longitudinal error of an uncorrected field plot would be exactly this right this is the height of the ray and this is the longitudinal error how much does it deviate from the paraxial plane right.

So, this tangential has the largest error, the sagittal has smaller error right. If I go to a lower height let us say I met this height the error is less, but always the tangential has more error. So, this graph itself gives you the longitudinal error and again you can just look at this and get an idea of correction with this kind of lens. This is the kind of error you get.

So, if you could replace or change the optical system, so, that the tangential rays now did this then I get in what is called an artificially flattened field and you can see this single length he has caused this kind of astigmatism and the diagram below which has four lenses in it is used to flatten. So, you are adding convex concave. You have something that slightly concave over here. So, these sets of four lenses are required to flatten the field and get something where your best image will form here ok.

Now, you can buy adapters or objectives for a microscope and the amount of money you pay for that objective depends on how much aberration correction has been done and some of the most expensive objectives are the ones that give you flat field over large area and of course, it depends on your application if its a simple lab demo or school exercise you are not going to worry about flattening the whole field, but people who are using it for medical diagnostics or studying biological phenomena you know you will pay lakhs of rupees for an objective because it is been designed with the optics that will actually flatten the field.

That means on your flat screen you get everything in focus ok. Any questions? When I ask questions there are no answers when I ask four questions there are no questions ok. So, these aberrations as I said, so, up to astigmatism they actually there is clear d focus right field curvature yes if you are at the paraxial plane there is going to be d focus, but there is actually a surface what field curvatures same the field curvature is basically giving you the deviation from the paraxial plane and in when you talk about field curvature there is the surface where there is perfect focus right in spherical aberration and in coma and in astigmatism there is no surface where there is perfect focus.

You are finding a surface where there is or an plane or a point where there is minimum aberration it is not that there is perfect focus, but in field curvature if you use the paraxial plane the; so, called paraxial plane yes you will see d focus, but if you developed a curved screen or a curved sensor you would be able to get perfect focus right you are not making compromising there is perfect focus.

So, that is why right at the beginning I had differentiated these three spherical coma astigmatism they actually affect they deteriorate the image whereas, in field curvature distortion there is perfect focus although often in field curvature means because I am using a planar surface I am losing out on that perfect focus ok. However, because there is perfect focus I can actually do something to my system and change that curved surface to a flat surface and get my perfect focus.

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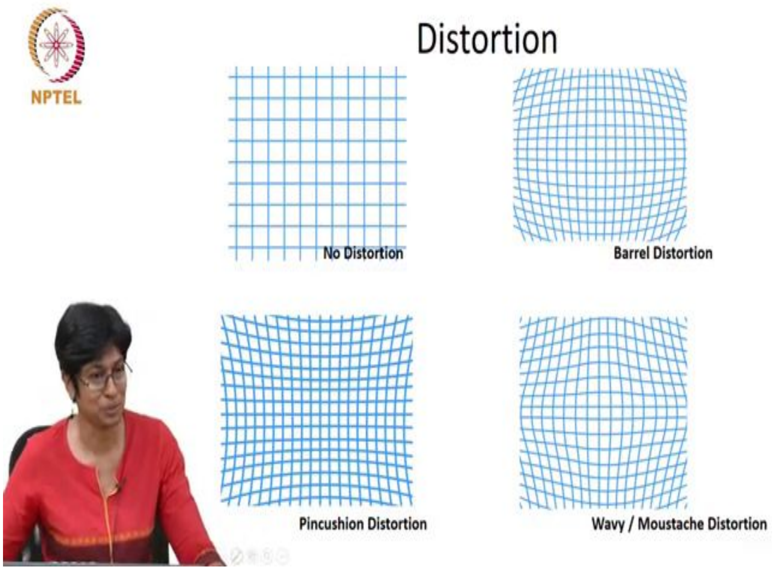

Distortion is where I have perfect focus nothing looks blurred, but you can see this top image here is what should have been the image. So, I am imaging a set of grid lines and I should have and they are perfectly perpendicular square areas between these grid lines this is what I should get as an image and because of the distortion of the system I get any one of these other three images nothing is blurred nothing is hazy nothing is out of focus, but the points are no longer perpendicular I do not have nice square areas.

So, it is almost like this was image was stretched it is in focus, but it is been stretched or its been pushed right and so, this is called barrel distortion it is pretty obvious, why it looks like a big wine barrel this is pincushion distortion because if you consider a pin cushion when you stick the pins into it the way it deforms and well sometimes optics people be a little bit adventurous. So, they call this mustache distortion. I leave it to you to figure out why ok.

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And so, an idea of what this is an image taken it does not have distortion, but with certain lenses in this case we have just digitally adjusted the image to show you what it would look like with distortion, but it's sometimes in an optical system you will actually see the lens will itself give you distortion. I mean certain software have digital tools to give you with netting for example.

Or this because they may use it to enhance something in a photograph, but often your optical system itself will give you that effect right and it may not be a desired effect and we will see where that arises ok. So, you can see that this image is kind of like everything is there, but it is slightly stretched or out of proportion.

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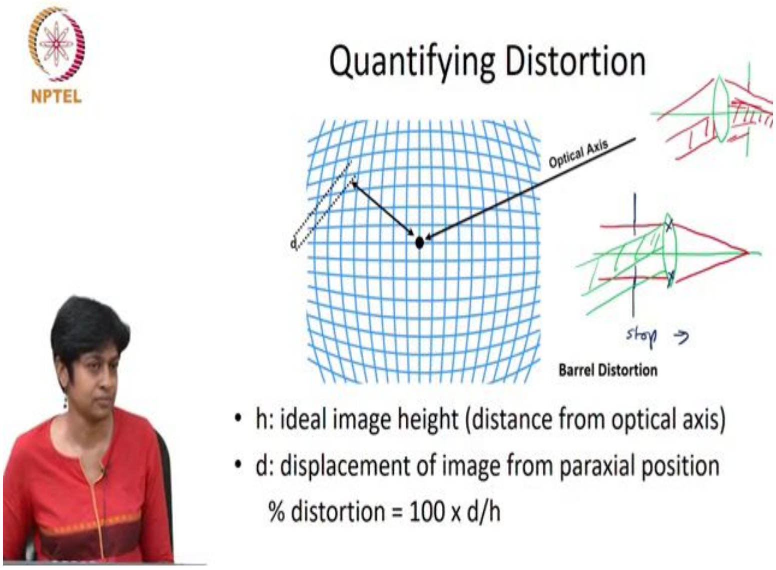

If you will, how do you quantify distortion? Well let us say from this is an optical axis a point should have lain at some position this is the ideal paraxial point the image, but instead of lying here it lies a distance d away. So, the distance from the optical axis the ideal distance from the optical axis if you said that, was h and the extra distance is d then we call distortion just the ratio d by h and it is a percentage. So, it is d by h into 100 ok.

And if d moves further out it will be positive if it moved closer it would be negative and that tells you whether you are stretching or compressing your image ok. So, now when you go and look at your abrasion curves you will. Now see the distortion curve and many systems may have very low levels of distortion. So, up to a percentage or. So, is fine right, but you really do not want a typical system to have high values of distortion ok.

So, we have looked now at a number of different aberrations and maybe in yesterday's lab class you also started looking at what affects those aberrations ok. So, I want to ask you a question now let us say I had a lens and I am looking at an on axis set of rays.

So, it is coming to focus here now I take a stop and I move the stop. So, I have a stop and I now move the stop what do you think happens to the spherical aberration in the system nothing happens, spherical aberration is independent of the position of the stop it is not independent of what are the parameter of the stop the size because, if you change the size you are then seeing these rays are not going through and we know spherical aberration is variation in focus with aperture height. So, if you change the aperture height you are affecting the aberration.

But if I am, but for an on axis spherical aberration is on an axis that is unaffected by the locations of I keep the size of the stop the same and I move it up and down it does not affect spherical aberration. On the other hand let us say I took the same system and I had a set of off axis rays coming. Do you think it would be affected by the location of the stop? Yes, it will be affected by the location of the stop in this example itself you can see that if I had the aperture here one the ray that goes through is this is what goes through, but let us say I took the same system and I put the stop here.

Which set of rays are going through this goes through here, but then finally, what is passing through is this part of the system right, it is this part of this ray that is going through. So, which part goes through; which part goes through which part of the lens is determined now by the location of the stop when it is an off axis beam coming right. So, now to understand how I optimize and remove aberrations from my system I must know what they depend upon and to do that I must understand the aberration.

So, I hope I am looking at these five aberrations you have slightly better understanding the lab exercises are aimed at helping you get that link between the different tools you have and what are the tools you have? You have the shape of the lens, you have this location of the stop you have the size of the stop these are some of the immediate tools that you have and some of the exercises are going to give you or the exercises will give you some of these links I want you to play around with. So, that you understand all of these links because that is how you are going to be able to correct the aberrations.

And you should not get surprised if you say I have put a variable I have put an operand I am optimizing I am aberrations not decreasing well spherical aberration is not going to decrease. If the variable you put was the position of stop right; however, if you put shape, kept the focal length constant and changed the shape then you will affect the spherical aberration and you will affect coma.

So, the next class and what you should finish for yesterday's exercise are all now to do with how I get rid of aberrations by choosing the appropriate parameters to adjust and then we will also in the next class look at chromatic aberration.