Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer

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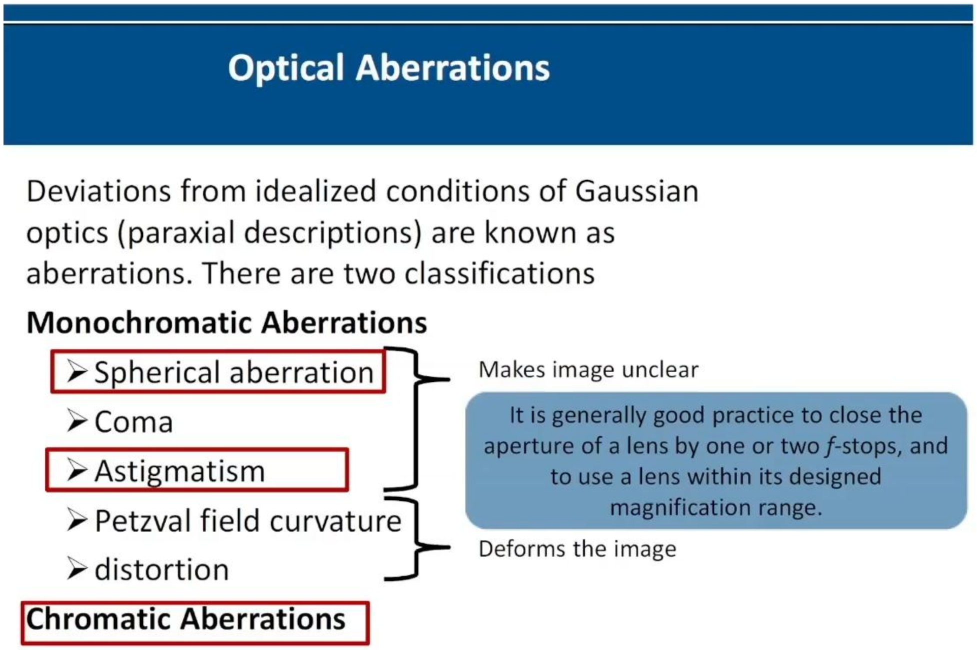
OK, so now that we have talked about diffraction, the diffraction greeting, and what diffraction is, in this particular talk, we are going to discuss the other kinds of problems that happen when trying to image something. So this falls under the category of optical aberrations. The optical aberrations are basically deviations from the known optics. These are basically based on the idealized conditions of Gaussian optics. So these are also called paraxial descriptions. Now there are two major classifications we can think of for optical aberrations.

First ones are the monochromatic aberrations. Under this, two things that we are going to discuss today are spherical aberration and astigmatism. And there are other kinds of monochromatic aberrations as well. So what these aberrations actually do is make the image, the image that you are actually filming, very unclear.

And in some cases, the image is distorted as well. So it is generally good practice, therefore, to close the aperture of a lens by using one or two f-stops and to use a lens within its designed magnification range. So the usage of the lens becomes an important parameter in this particular exercise. But the main things are that when you talk about chromatic aberrations, you also know about these from your lens formula, the prescription glasses that we wear. There is also another type of aberration that is called chromatic aberration.

It comes from the color, the color that is contained in the light. So basically, we are going to talk about these three aberrations, and these are, remember, deviations from the idealized condition of Gaussian optics, which we know a little bit about already.

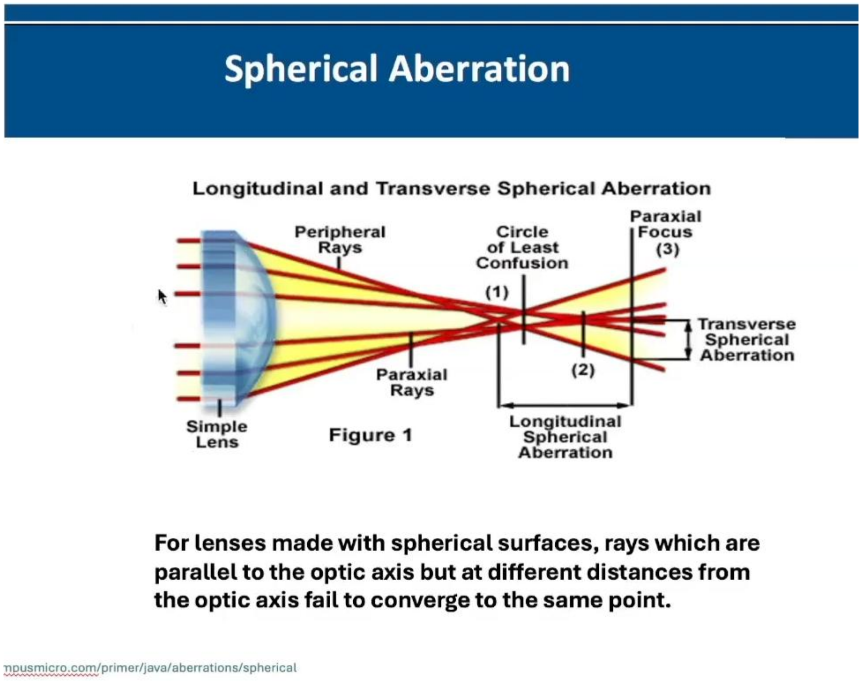


So when we talk about spherical aberration, let's look at this particular plot, this particular figure in detail. This is a simple lens. So the rays that are going towards the center of the lens and the rays that are coming from the edge of the lens, which are basically called the peripheral rays, are focused at two different points.

So the lens is made of spherical surfaces, and the rays that are parallel to the optical axis initially, but at some distances from the optical axis—the optical axis is the central line—fail to converge; therefore, they fail to focus at the same point, or the lenses are unable to focus at the same point. As a result, you get what is called spherical aberration. So take a look at this here; for example, these are the paraxial rays, which are focused, say, somewhere around two, at this point two. And then there are certain peripheral rays, which are focused at a point. So the distance between, and there are certain rays that, you know, go away from after focusing, and they diverge by the time they reach point two.

So if we now consider this particular arrangement, the ray that is farthest away from the optical axis, the farthest peripheral ray, is going to have a certain distance from the optical axis at this paraxial focus point three. And this is called transverse spherical aberration. This is the transverse spherical aberration. And the paraxial focus three that you see over here, and the distance from that to the first converging point, which is here and given as one, is called longitudinal spherical aberration. So the lenses with spherical surfaces, the rays that are parallel to the optical axis but at different distances, fail to converge at the same point.

As a result of that, they give rise to this aberration. All right? All right. So, as we can see, what we did was identify this as spherical aberration. So if you look at it in this particular picture, it will be even clearer.



This occurs due to the dependence of focal length on aperture for the non-paraxial rays, which are basically rays that are away from the optical axis and not close to it.

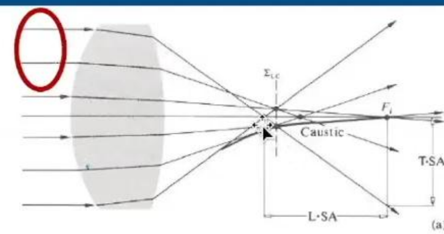
As you can see, rays converge here, and those rays converge there. So this is what we call longitudinal spherical aberration. The longitudinal spherical aberration is this: LSA over here. As you can see from this point to that point. So this is where the peripheral rays actually meet on the axis, and this is the far axis.

So you can see that this is basically the LSA, which is the envelope of the reflected rays. And then, of course, there is transverse spherical aberration as well, which is from the optical axis, from F1 basically, and how far this particular ray is actually deviated. So this particular distance is called the TSA. So the incident ray will undergo minimum deviation when it makes more or less the same angle as the emerging ray does. Simply turning a lens around can markedly reduce spherical aberration.

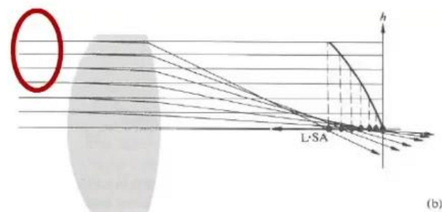
The incident ray will undergo minimum deviation when it makes more or less the same angle as the emerging ray. So this is a spherical aberration. In other words, it is nothing but the inability of the lens to focus at the same point as the non-axis or off-axis rays, which are non-para-axial rays, essentially.

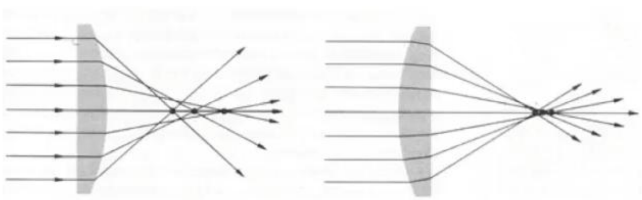
Spherical Aberration

Spherical aberrations occur because of the dependence of focal length on aperture for nonparaxial rays, i.e. rays not close to the optical axis.



Spherical aberration for a lens. The envelope of the refracted rays is called a caustic: L·SA (Longitudinal Spherical Aberration), T·SA (Transverse Spherical Aberration)





The incident ray will undergo a minimum deviation when it makes, more or less, the same angle as does the emerging ray. Simply turning a lens around can markedly reduce the SA.

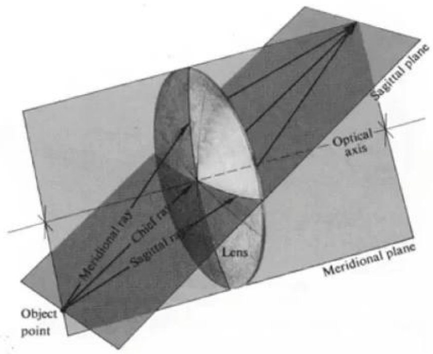
So astigmatism arises when an object lies at an appreciable distance from the optical axis. So, for example, here is the object point.

It is not lying on the optical axis. It lies at an appreciable distance from the optical axis. So the configuration of an oblique parallel ray bundle will be very different in the meridional and sagittal planes. As a result, the focal lengths in these planes will also be different. So this is what happens.

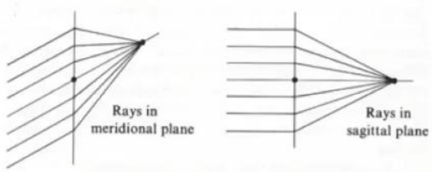
This is the object that is away from the, you know, away from the optical axis. And these are the rays in the meridional axis, the meridional plane, and this is the plane in the sagittal plane. So the configuration for an oblique parallel ray bundle will be different in this plane versus that plane. As a result, the focal lengths in these planes will also be different, which gives rise to astigmatism. This is very common when you are taking your prescription classes.

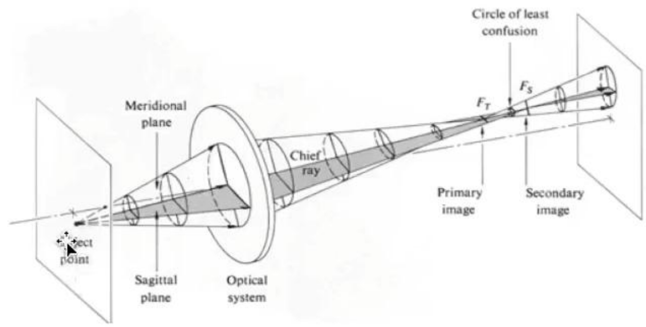
This is something that you are well aware of. If you look at this, this is your meridional plane that you see over here, and this is your sagittal plane. All right, so this is your sagittal plane; this is your meridional. All right, so it is well marked over here, and this is the object point away from the optical axis, right? And this is the primary image, this is the secondary image, and this is the circle of least confusion. So all this leads to image blurring essentially. So, the fuzziness of the images comes from this. So you can see, it's a very clear idea that the sagittal plane and the meridional plane will have focal lengths that are different because of astigmatism. So this is what it is, and this should be something that you already know.

Astigmatism



Astigmatism arises when an object lies an appreciable distance from the optical axis. The configuration of an oblique, parallel ray bundle will be different in the meridional and sagittal planes. As a result, the focal lengths in these planes will be different as well.





Hecht E, Zajac A (1979) Optics, Addison-Wesley Publishing Company, Reading Massachusetts

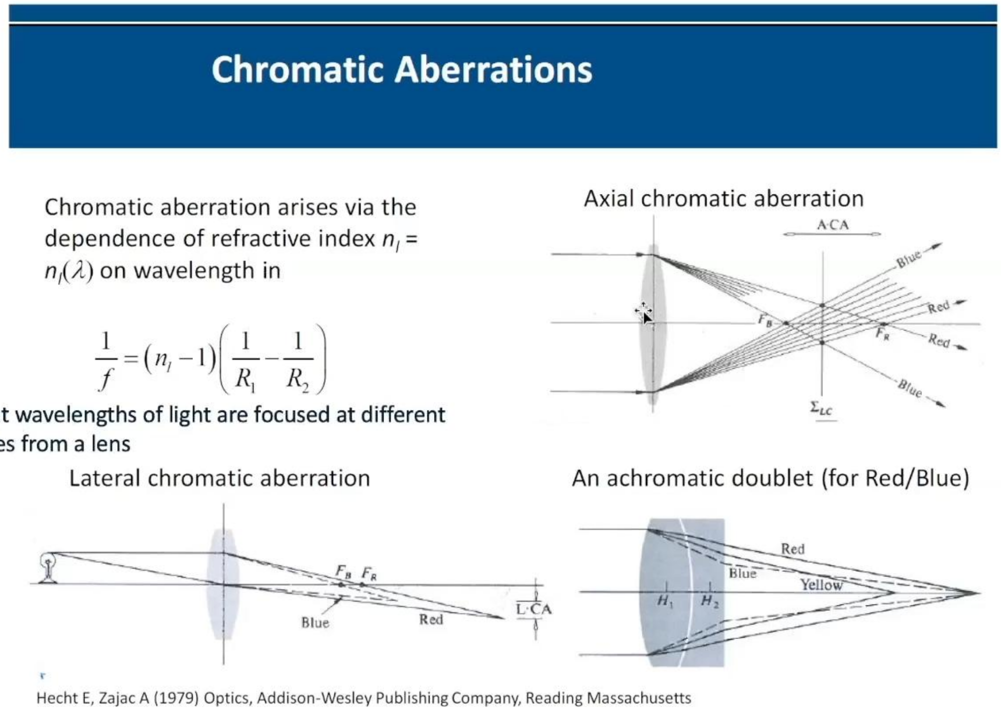
So next comes what we call chromatic aberrations. Now, chromatic aberrations arise due to the dependence of the refractive index on wavelength.

In this particular equation, that means different wavelengths of light are focused at different distances from one another. If you look at this particular picture, you will see that this is a singleton ray, one single ray, not a monochromatic ray. So it comes and hits the lens. Now this is blue, and this is red. So they are focused at different points of the optical axis.

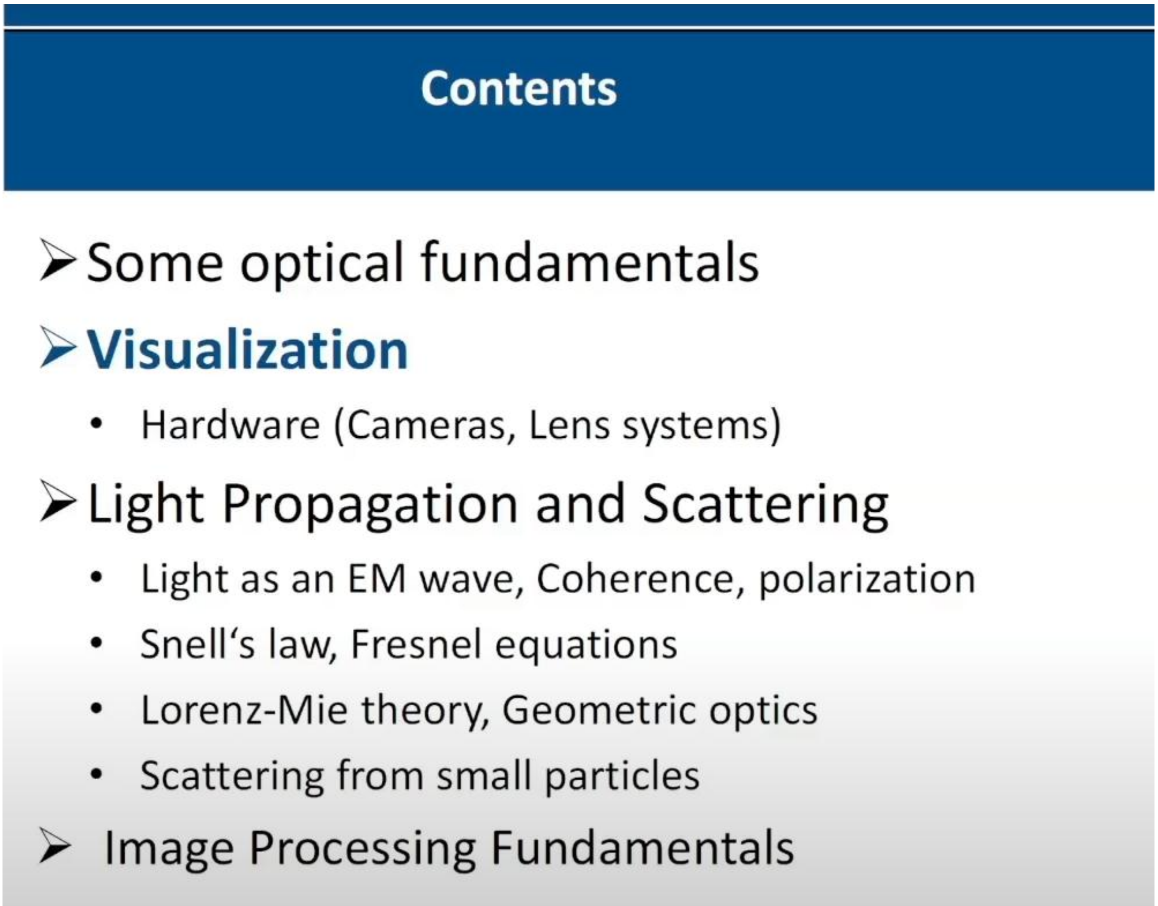
So, for example, blue is focused here; the red is focused there. So there is a difference in how the different lights are focused at different points on the optical axis, done both in the vertical and in the horizontal direction. So, if you look at this, this is axial chromatic aberration. So this is axial because this is how the focal points of blue and red are different. As a result, you get an aberration right over here.

You also get what we call lateral chromatic aberration, which is the distance between the blue and the red. So this is blue. And this is also, you can see that this is red. So it is this difference. The red converges somewhere over there.

And the blue converges here. So it is the difference between the two convergent points of red and blue that actually gives rise to LCA, which is lateral chromatic aberration. So this is how the chromatic aberration part actually works. So you have both lateral, like spherical aberration, and actual chromatic aberration. And remember, in the case of spherical aberration, it has longitudinal and transverse aberration.



Right? So that is what this is. So that is what it is. So, this is the chromatic aberration. So apart from this, of course, now you have some visualization equipment like camera lens systems, et cetera. So we are still in that visualization part before we go to the light propagation and scattering parts.



The cameras, if you look at high-speed cameras, are typically equipped with CMOS sensors and have a resolution of 1280 by 800 pixels.

gives rise to a 28-micron pixel size. And that is something around 36 mm by 22.4 mm. It's a 12-bit depth. Okay, and really it is heat pipe-cooled, and there can be thermoelectric cooling as well that can actually happen.

So these are the two competing companies, Fortron and Vision Research's Phantom. So you can see the camera pixels and the corresponding framing rate at full resolution. So, this gives, for example, about 22,500. And as you go on reducing the pixel, as you go on reducing the media, you can imagine, for example, at 512 x 512, you can get almost 70,000 frames per second. Remember, your normal cinema is somewhere around 60 hertz or maybe 30 hertz, so this frames per second is quite a lot, and they are actively cooled cameras as well.

High-Speed Cameras

- CMOS sensor 1280 x 800 pixels
- 28 µm pixel size
- 35.8 mm x 22.4 mm
- 12-bit depth
- TE and heat pipe cooled

VISION RESEARCH

Pixels	Frames/s
1280 x 800	22,500
1280 x 720	25,100
1024 x 800	26,900
1024 x 512	41,800
640 x 480	62,600
512 x 512	67,800

Photron
HIGH SPEED CAMERAS

There are different makes of high-speed cameras. IDT makes one, then NAC, then Phantom, then Fortron, and then Shimadzu. And these are the different models. You can see the latest models as of 2016.

This has changed quite a bit. IDT has, for example, a 600 x 1200 frame resolution with an FPS of about 8,000 frames per second. And the memory is about 2 GB. This is the on-chip memory.

It costs about 80,000 euros. Expensive. The Phantom can go up to about 7,500. This memory can be changed. And this also costs about $56,000. Then, Fortron SA-X2 is about 1 megapixel.

This is rectangular. So this can go up to 13,500 frames per second. This is, again, something of which the function of the memory chip can be changed. and about $70,000, 70,000 euros. You can see that there are Shimadzu, which is HPV2; it has a very low pixel count, but the framing rate is a million, and the memory can hold up to only 100 frames.

Price: more than 150K euros. This is a very small pixel resolution, but it can take a million frames, so this is appropriate for very high-speed images or high-speed events that last for a very short duration. That's why in memory it can hold up to 100 frames at a million frames per second at that kind of resolution, so this is a particular feature of Shimatsu; no other camera can actually go up to that. See, all these cameras, even at reduced resolution, like I showed over here, can go up to very high framing rates, but not 1 million frames per second.

High-Speed Cameras

Typical data (2016):

Make	Model	Pixel	fps	Memory	ISO	EUR
IDT	Os8 V3-S3	1600x1200	8000	256 GB		78,200
NAC	HX4	1280x960	6250		10000	
Phantom	V711	1200x800	7530	32 GB	10000	56,000
	Flex	4096x1960	1000			
Photron	SA-X2	1024x1024	13,500	64 GB	25000	70515
	Mini AX200	1024x1024	6400	32 GB	40000	58140
Shimadzu	HPV-2	312x260	10^6	100 frames		>150000

There are high-resolution cameras as well. So, for example, PCO4000 is about 4 megapixels. So, 4000 by 2600 pixels. FPS is rather low at 5. It takes images at 5 frames per second.

IDS, for example, has a 2.5-megapixel. It is only 12.5 if and h5 this is a good one, so this actually has a 2.5-megapixel resolution and the fps is about 7500 with on-chip memory of about 32 GB. This can change quite a bit, and they're all very costly; this is 56,000 euros. You can see all these cameras are very expensive, but they are capable of very high frame rates and they incorporate most of these optics.

They correct for spherical and chromatic aberrations and all those things. The lenses also come with the camera as per your requirement, basically.

High-Resolutions Cameras

Make	Model	Pixel	fps	Memory	ISO	EUR
PCO	PCO.4000	4008x2672	5		10000	
	Edge 5.5	2560x2160	7530	32 GB	10000	56,000
IDS	U3-3582LE	2560x1920	12.5			

So the signal-to-noise ratio, if you look at it, comes from Tropia's paper and Christian Koehler's paper on the comparison of CCMOS and intensified cameras. So this, you can see the PCO SensiCam; for example, it has a resolution of 1 megapixel, 1.

2 megapixels, and 8 FPS. And this is the... Interframe time is the time between two frames when you can take the next one. So, these are all different types of cameras. And this black line is the SensiCam. So you can see the signal-to-noise ratio that you have over here.

And that is what has been plotted. You can see that these are the kinds of features you get. So the other cameras are all plotted over here: Nantec Dynamics, iNanoSense, 100. These are all different types of cameras that are being plotted.

So this is the kind of signal .. In some cases, even at low signal, you get a very improved signal ratio, achieving a high level of signal-to-noise ratio; even at very low signals, this means you can recover very mild signals as well. This means that even if the image, uh, the illumination is poor or the intensity, you can do that, okay? Very, very good at these very low signal values. And at high signals, of course, all the cameras show the signal-to-noise ratio. But it is at the low end, if you see, and you can see the Sensecam over here does a very good job in ensuring that you have a very high signal or an acceptable signal-to-noise ratio.

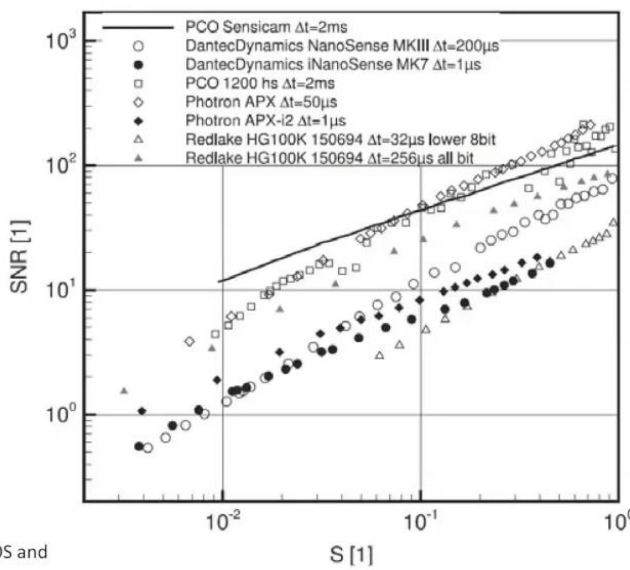
In other cases, the noise becomes very acute. And that is what happens. The signal is actually very low. So these are things that one needs to consider when one uses cameras. It's not just about the frame rate.

It is not just about the pixel size. It is not just about the interframe distance and interframe time. But it is also about the signal-to-noise ratios.

Signal-to-Noise Ratio

Camera	Resolution (px^2)	Pixelsize (μm^2)	fps (1/s)	*IF* (ns)
PCO Sensicam[a,d]	1,280 × 1,024	6.7 × 6.7	8	300
DantecDynamics NanoSense MKIII[b]	1,280 × 1,024	12 × 12	1,024	100
DantecDynamics iNanoSense MK7[c,f]	1,280 × 1,024	12 × 12	1,024	100[e]
PCO 1200hs[b]	1,280 × 1,024	12 × 12	638	75
Photron APX[b]	1,024 × 1,024	17 × 17	2,000	2000
Photron APX-i2[c]	1,024 × 1,024	17 × 17	2,000	2000[e]
Redlake HG 100K[b]	1,504 × 1,128	12 × 12	1,000	3000

fps frames per second
IF interframe time
[a] CCD
[b] CMOS
[c] Intensified CMOS
[d] This camera is indentical with the LaVision Flowmaster3S
[e] CMOS interframe time
[f] This camera is identical with the IDT XS5-i



Hain R, Kähler CJ, Tropea C (2007) Comparison of CCD, CMOS and intensified cameras. Exp in Fluids **42**:403-411

These are actually long-distance microscopes, so for example, there are many companies that make it; Infinity K2SC is one option. So these are basically working distance, field of view, and magnification. That is, this is what we are talking about: transverse magnification all the time.

So, as you can see, these long-distance microscopes allow you to image from a long distance. It essentially acts like a microscope, but from a long distance. Microscopy, you really need to bring the objective very close to your body. So, that is what it does.

And this is used for measurements in the environment. You cannot get too close to your measurement window, but you want to measure a very small area. Therefore, the magnification becomes.

.. So that is what we need to do. So there are near, mid, far; all these things are actually given.

Long-Distance Microscopes

Infinity K2/SC
Photo-Optical Company

WD – Working distance
FOV – Field of View
MAG – Magnification (Transverse)

K2/SC	STD w/o S Lens			CF-1			CF-1/B			CF-2			CF-3			CF-4		
	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far
WD mm	360	510	980	265	365	580	222	290	418	138	190	205	92	105	125	55	60	63
MAG	0.95	0.64	0.31	1.28	0.86	0.52	1.4	1.07	0.71	2.29	1.52	1.36	3.05	2.56	2.06	5.33	4.74	4.27
FOV mm	6.74	10	20.5	5.0	7.4	12.2	4.6	6.00	9.0	2.80	4.20	4.7	2.10	2.50	3.1	1.20	1.35	1.50

NOTE: The K2/SC has greater potential magnification than previous models. The data above *DO NOT* assume amplifiers in-system.

*FOV based on 1/2" video format (6.4mm horizontally). See Video Format Page.

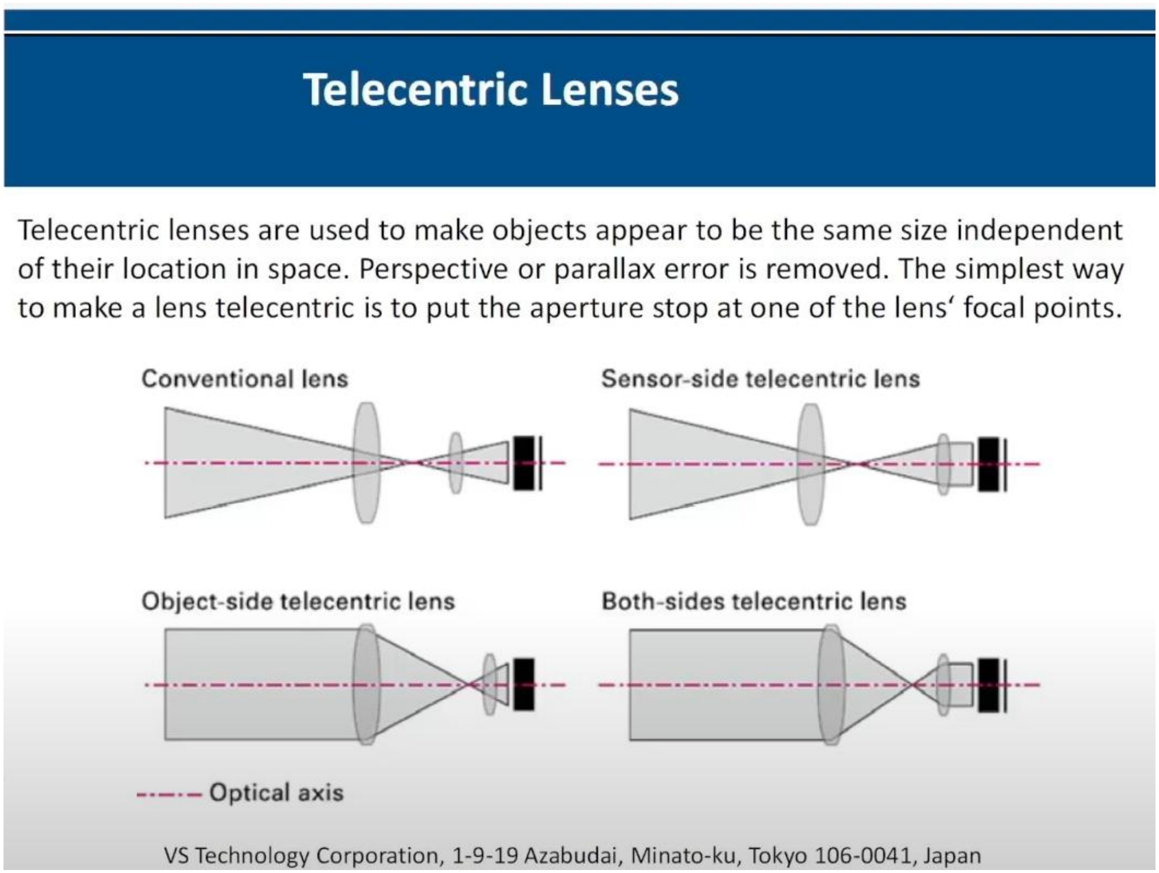
Model K2/SC	STD w/o S Lens			CF-1			CF-1/B			CF-2			CF-3			CF-4		
	Near	Mid	Far	Near	MID	Far	Near	MID	Far	Near	MID	Far	Near	MID	Far	Near	MID	Far
WDmm	360	510	980	265	365	580	222	290	418	138	190	205	92	105	125	55	60	63
MAG	0.95	0.64	0.31	1.28	0.86	0.52	1.40	1.07	0.71	2.29	1.52	1.36	3.05	2.56	2.06	5.33	4.74	4.27
NA	0.053	0.037	0.019	0.072	0.052	0.033	0.086	0.066	0.045	0.138	0.100	0.093	0.207	0.181	0.152	0.200	0.183	0.175
Resolution (lpmm)	158	112	58	215	156	98	257	197	136	413	300	278	620	543	456	600	550	524
Resolution (microns)	6.3	8.9	17.2	4.6	6.4	10.2	3.9	5.1	7.3	2.4	3.3	3.6	1.6	1.8	2.2	1.7	1.8	1.9
DOFmm	0.20	0.39	1.45	0.11	0.20	0.51	0.07	0.13	0.26	0.03	0.05	0.06	0.01	0.02	0.02	0.01	0.02	0.02

There are also telecentric lenses. The telecentric lenses are used when you want to make the objects appear to be of the same size, independent of their location in space. So what it does is basically remove the parallax of the perspective error, and the simplest way to make a lens telecentric is to put an aperture stop at one of the lens's focal lengths.

Focal points, basically. So, this is a conventional lens. Here you have the image. What happens is that the images may not be of the same size for a normal conventional lens, but telecentric lenses are used to make the objects appear exactly to be of the same size, independent of where they are located in space. If you have two objects, one behind the other, for example, a conventional lens, they will appear to be of different sizes. But in the case of a telecentric lens, that is not the case.

So, for example, this is a sensor sight telecentric lens. So in the central size of the telecentric lens, what you have is this object; you basically have this particular image that is formed. This is a telecentric lens for object sight. Which does things in a slightly different way. And this is a both sides telecentric lens.

So these are the different telecentric lenses that are available. Many of these materials are available on the Internet. You are free to read about all of them. So, that is what the telecentric lenses actually do. So it's basically to make the objects appear to be the same size.

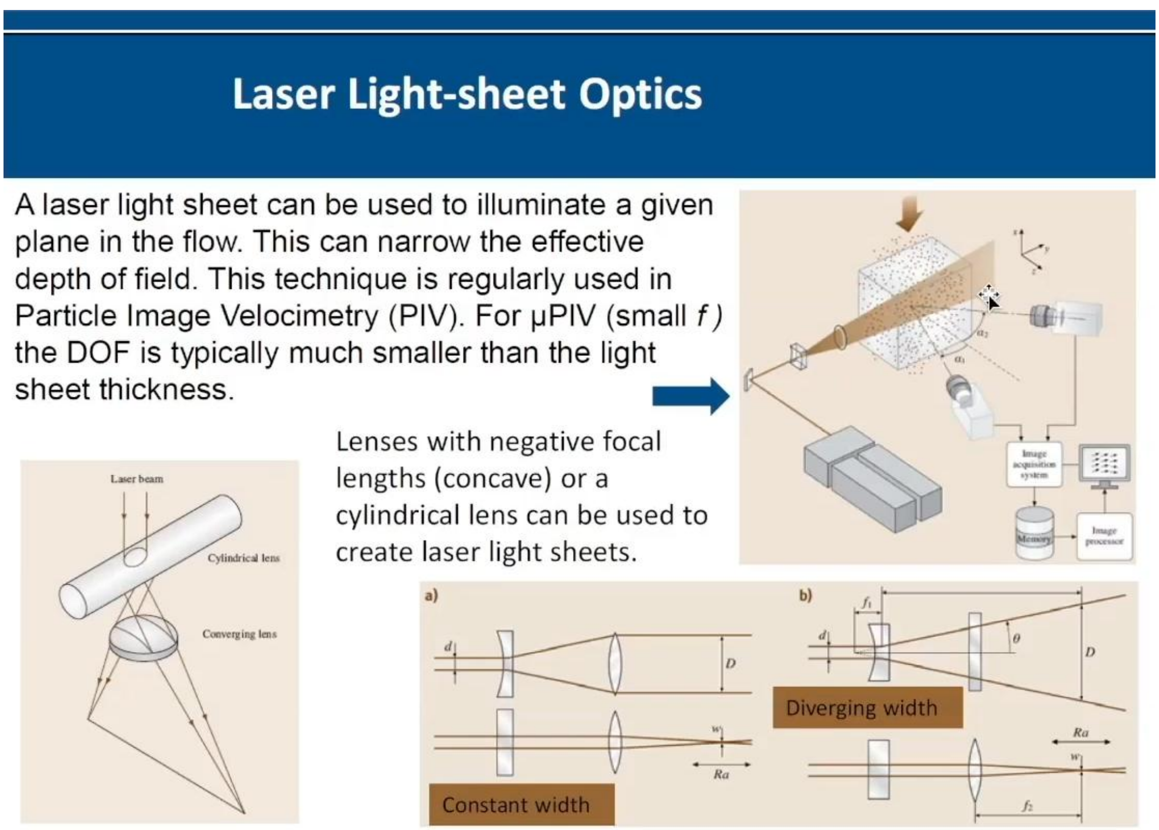


Now, we will talk a little bit about the laser sheet optics. Now, the laser sheet optics are regularly used to illuminate a given plane in a flow field, though the laser sheets actually have a finite thickness. Now, this is routinely used in measurements such as particle image velocimetry. For micro-PIV, of course, it is more of a volumetric illumination, as we will see. What happens is that in these cases, the laser, the lenses with negative focal lengths, which are basically concave lenses, or a cylindrical lens can be used to create this laser sheet.

So, this is the laser beam. This is a cylindrical lens. And there is a converging lens that basically creates the laser sheet. Okay, so you can also see it with a concave lens with a negative focal length. There are parallel beams. It basically opens up the beam using a convex lens of a certain constant width. So you can see that this, for example, diverging width, is routinely used in measurement; typically, this is like an NDAG laser, which is basically expanded first, routed, or deflected and guided.

Then you use this arrangement of cylindrical or concave lenses, and then use a convex lens to basically open up and form a sheet, and the flow is laden with tracer particles. And as this trace of particles passes through the laser sheet, it actually scatters light. And that is what you monitor with a camera. If you monitor with a single camera, we get a 2D PIB field. If you do it with two cameras looking at a single object, this is what gives rise to the three-dimensional effect or the vector field.

And then, of course, there is image processing and other things that you do. But this is light sheet optics, which basically consists of nothing but a cylindrical lens or a concave lens. And you use a convex lens basically to create a sheet of constant width or divergence. We will talk more about these sheets and how they are actually made; that is a topic in itself. We talked a little bit about this in LDV and will discuss it more in DIV. Okay, so now that we have done that, you have seen that we have covered some optics fundamentals, visualization hardware, cameras, and lens systems, and now in the next lecture onward, we will cover light propagation and scattering.



Just a quick recap: we did spherical aberration, which is basically the off-axis parallel rays that are off-axis, which basically get focused at different points. Which are away from the axis that is focused on at different points. As a result of that, you get both longitudinal and transverse spherical aberration. This essentially leads to image blurring. You can also have astigmatism, which is basically when the object lies away from the optical axis.

As a result of that, the meridional plane rays and the sagittal plane rays, which are shown over here, actually focus at different points. The focal lengths of these planes are actually different. As a result of that, you have astigmatism. And then we talked about chromatic aberration, which is nothing but the colors resulting from the dependence of the refractive index on the wavelength.

OK, and this leads to, you know, differential focusing of the different colors of light. And this can also have lateral as well as axial chromatic aberration. And then we talked a little bit about the different types of cameras that are available, from high-resolution cameras to lower medium-resolution cameras. And then we talked about the signal-to-noise ratio and said that when the signal is small, if the noise is also small, the signal-to-noise ratio is small; in some cameras, the noise and the signal will have comparable values. So the signal-to-noise ratio is not that great, but it can improve even for low signals if your signal-to-noise ratio is pretty high. Then we talked about the long-distance microscope, the telecentric lens, which is important because it makes the objects appear the same size.

So this is used in the industry, even in machine vision and things like that. And you also use laser light sheet optics, where you have to create a sheet from the light using a combination of cylindrical and positive focal length lenses. In the next lecture, we are going to talk about light propagation.