Optical Design Lab

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1. Introduction and Objective

Optical design is a critical part of astronomical instrument development. It is a process where one determines the parameters of the optical components to be used in the instrument, such as the shapes and sizes of lenses, glass material, and the number of optical components. Given a set of scientific/system requirements and real-life physical constraints, the designer needs to determine what is the best (i.e. possible to fabricate, cost-effective, and robust) optical layout that satisfies all of the requirements. Every instrument is different, so each optical design needs to be uniquely tailored to its needs. However, it is necessary to borrow ideas from years of optical design as a starting point. It is worth stressing that optical design is really an art, and experience is clearly a virtue.

At present times, almost all complex optical design work is done using software. Of course, software is no replacement for thinking. There is a common phrase you will encounter from seasoned optical designers when it comes to using optical design software: "Garbage in, garbage out!" It is up to the lens designer to know what they are doing when using this software because it is very easy to produce unrealistic or incorrect designs. It is often worthwhile to check if the numbers make sense by carrying out hand calculations. A good understanding of basic optical principles, aberration theory, and optical fabrication is a necessity when designing optical systems.

<u>The primary objective of this lab is to gain a familiarity of optical design software.</u> The very basic form of this software uses sequential ray tracing to determine the properties and performance of an optical system. This form of ray tracing launches rays from the object plane and traces their path through the optical system all the way to the image plane. Typically, only refraction or reflection affect the path of the rays. In sequential ray tracing, rays only travel in one direction through the pre-defined sequence of surfaces. Scattering and diffractive effects are not considered or directly modelled. This method is very powerful because it is computationally efficient and is well suited for designing imagers and spectrographs. *(Note: these programs also often have the ability to model diffraction gratings in a rudimentary fashion by using the grating equation to compute the diffracted ray angle.)*

We will use a free MS Windows-based software called OSLO-EDU, which is essentially an educational version of a fully featured lens design software. There is sufficient functionality in this software to learn the basics of using lens design software. The main limitation of OSLO-EDU is that you **cannot exceed ten surfaces**. If you wish to play around with this software on your own time, you can download OSLO-EDU from this website:

https://www.lambdares.com/edu/

The main drivers of optical design are factors such as field-of-view, focal length, etendue, and physical dimensions (especially length). The figures of merit for optical performance for astronomical imagers and spectrographs are often image quality, which is principally affected by diffraction and geometric aberrations, and throughput. Diffraction is a fundamental property of the optical system and is directly related to its f/# or the numerical aperture (NA) and operating wavelength. Diffraction sets the ultimate limit on system performance, which is also known as diffraction-limited performance. However, the image quality of most optical systems are dominated by geometric and chromatic aberrations that can be controlled through careful design. This design lab will focus on identifying and controlling geometric aberrations. The activity is organized into three different parts:

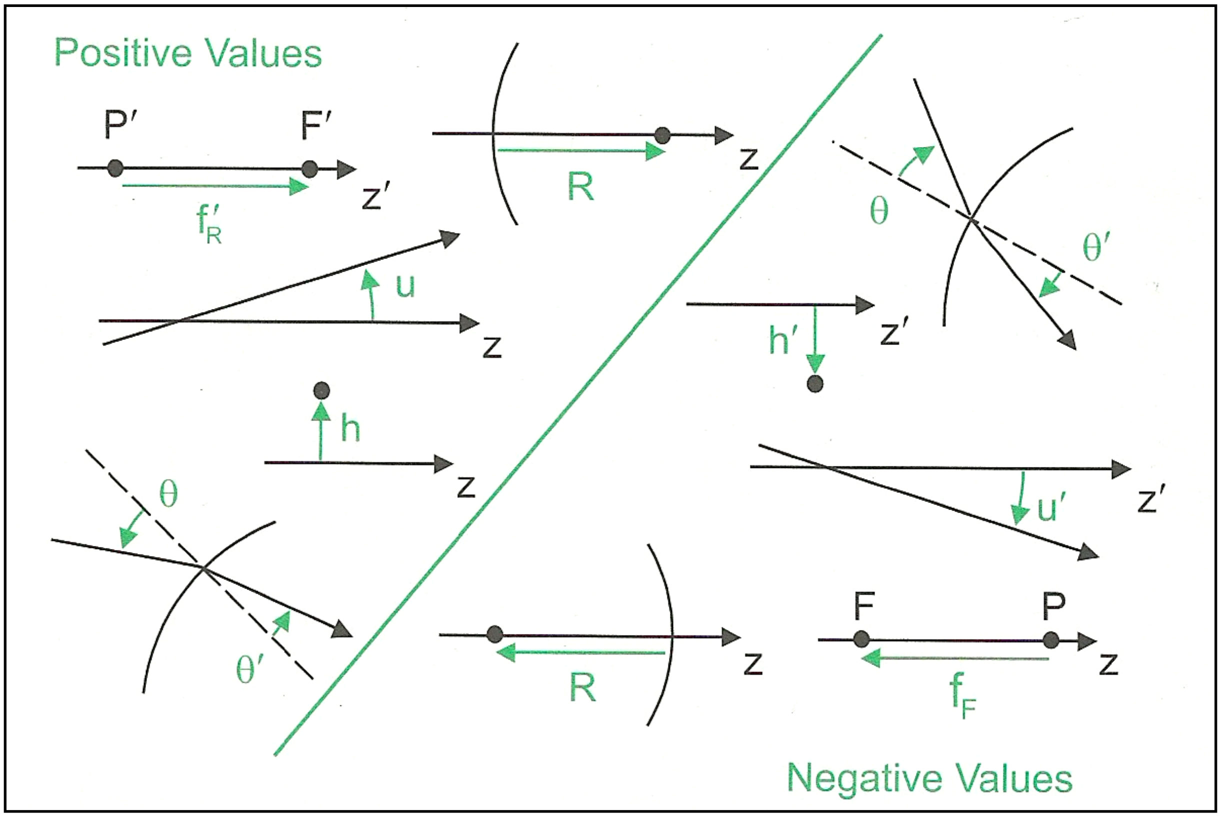
1. **In the first exercise, you will familiarize yourself with the OSLO user interface and some of its capabilities.**
2. **In the second exercise, you will construct a Wollaston landscape lens, which one of the simplest lenses that controls for geometric aberrations.**
3. **In the third *(bonus)* exercise, you will model the David Dunlap Observatory (DDO) 1.88-meter telescope, which you will be visiting as part of a tour.**

A good lens designer is able to identify the dominant geometric aberrations in an optical system and has in his/her/their toolkit a list of techniques to correct/balance for each individual kind of aberration and how the choice of optical materials affect the performance of the system. This lab will give you a taste of these techniques. ***For a crash course on aberration theory, please refer to the Appendix.*** For this lab, you can use the following cheat sheet to interpret the aberration coefficients output by OSLO. There are two different ways to quantify aberrations, one measures the optical path differences (OPD) aberrations introduce compared to a perfect wavefront and the other measures how much a ray in the image plane is offset from where it would have been had there been no aberrations, which is also known as the transverse ray aberration.

Cheat sheet for identifying aberration coefficients

Geometric Aberration	OPD Coefficient	Transverse Ray Aberration Coefficient	Field Dependent
Spherical	W_{040}	SA3	No
Coma	W_{131}	CMA3	Yes
Astigmatism	W_{222}	AST3	Yes
Field Curvature	W_{220}	PTZ3	Yes
Distortion	W_{311}	DIS3	Yes

Sign Convention in Optics:



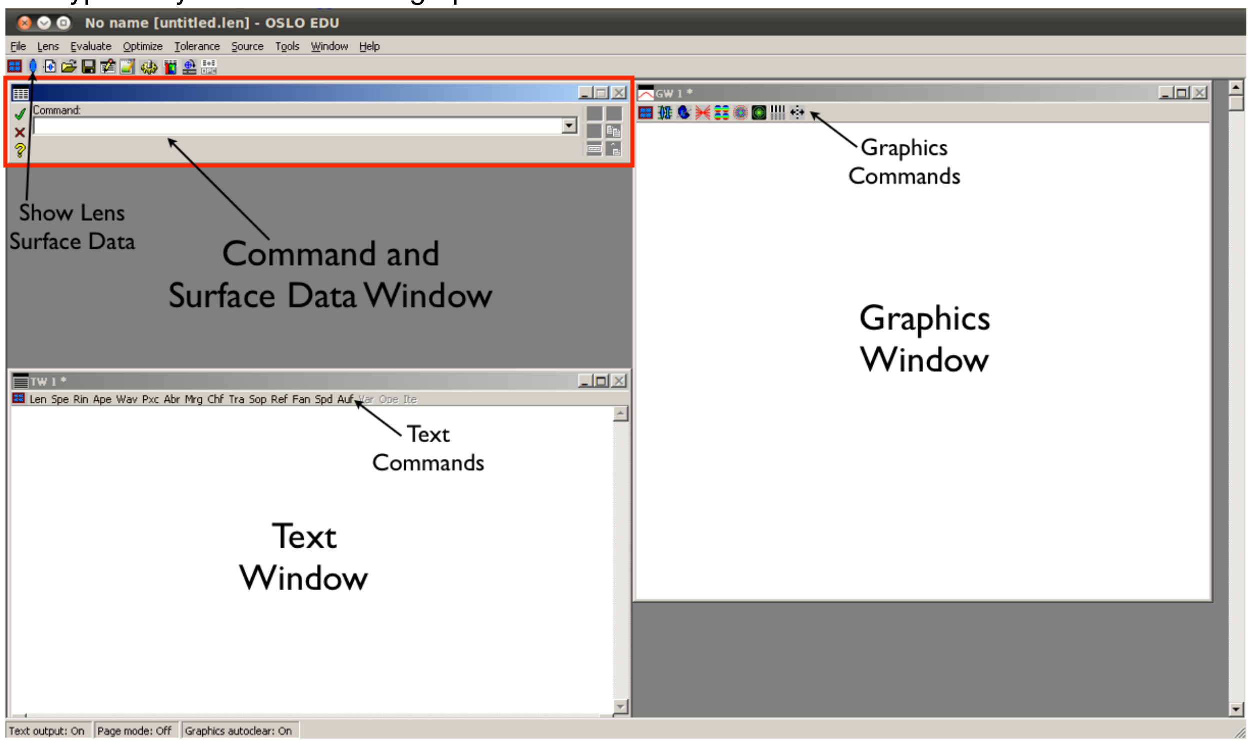
The z-axis is the optical axis of a system (Credit: Field Guide to Geometric Optics).

Note: This lab is meant to be interactive. Some of the activities are deliberately open-ended so you will learn how to use the software. Please don't hesitate to ask us for assistance. We want to make sure you will learn as much as possible.

2. Getting Familiar with the OSLO Interface *(60 minutes)*

To start OSLO, navigate to the Start Menu and select **OSLO7->OSLO EDU**.

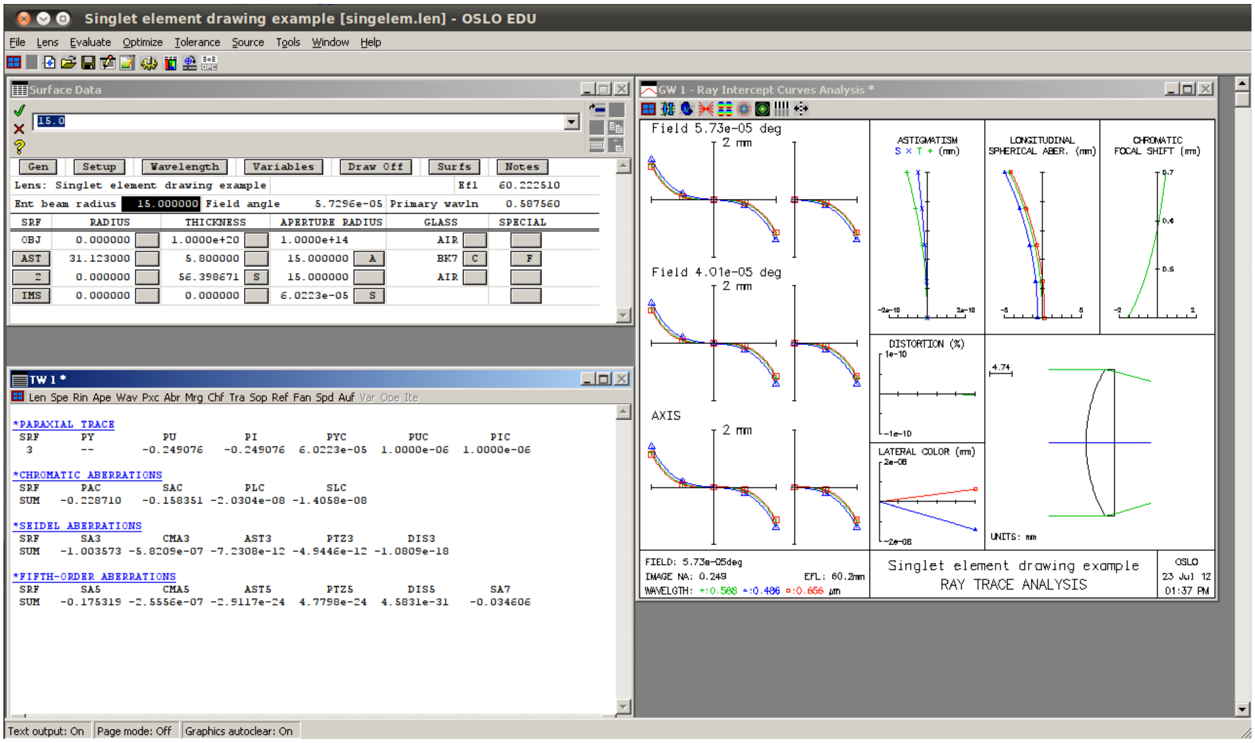
The typical layout of the OSLO graphical user interface is shown below:



For the first exercise, you will start by looking at a simple lens in the lens library. When you start up the program, you are given the option to browse the lens library. Choose that option. A number of optical design examples will pop up in the Command Window. You can scroll through a number of the designs and see their optical layout in the graphics window. Even the Hubble Space Telescope is a design example.

For the purpose of this exercise, we are going to focus on a planoconvex lens example:

A. Scroll down the lens database and select the "**Singlet element drawing example.**"
B. Maximize the OSLO window and select from the menu bar **Window->Tile Windows** to arrange the sub-windows within the main OSLO window.
C. Having done that click on the "Show Lens Surface Data" button shown in figure above to reveal the lens data input spreadsheet. If everything went well, you should see the following in OSLO (*Note: in your case the text window should be empty; in the screenshot, the "Abr" command was run in the text window which prints out the transverse ray aberration coefficients for the optical system)*:



2.1 Surface Data

The surface data window is used to enter the optical system parameters. The display format is in the form of a spreadsheet with each surface getting its own row including the object plane, which is the very first surface, and the image plane, which is the very last surface. Each surface has a radius of curvature, thickness, aperture radius, and material. In this case, we have a BK7 glass planoconvex lens with an effective focal length of 60 mm and an input beam radius of 15 mm. **This particular system only views on-axis rays, which is evidenced by the very small field angle given in units of degrees.** The little grey boxes beside each input field allow you to change the properties of a field or solve for its value. Click on them to find out what options each field has.

Investigate the following questions:

1. What are the radii of curvature of the lens surfaces?
2. What is the thickness of the lens?
3. How far is the image plane from the rear surface of the lens?
4. What is the operating wavelength of the lens *(Hint: Look for the Primary wavln parameter. Its units are in micrometers)*?
5. Where can you find the effective focal length of the lens *(Hint: Look for the Efl parameter)*?
6. Which surface is the aperture stop *(Hint: Look for the surface marked "AST")*?

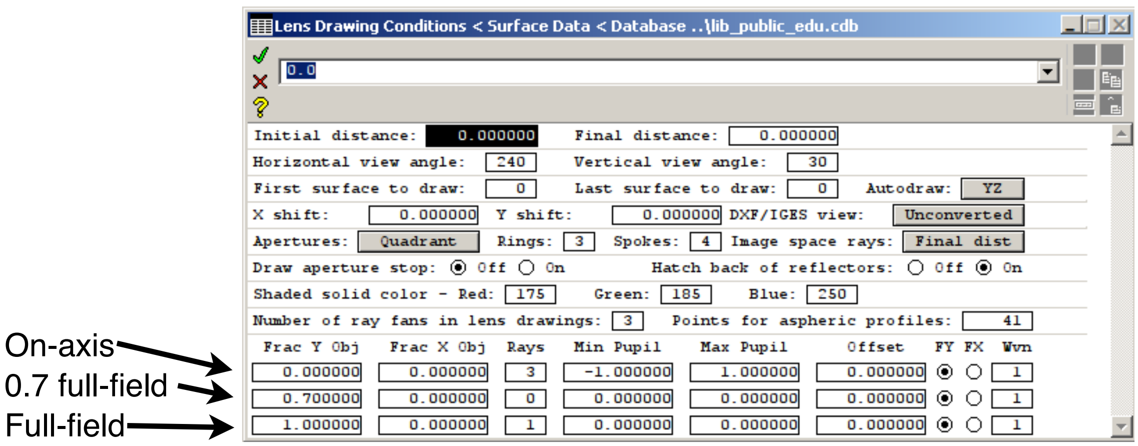
The units for wavelength and dimensions are microns and millimeters, respectively.

2.2 Graphics Window

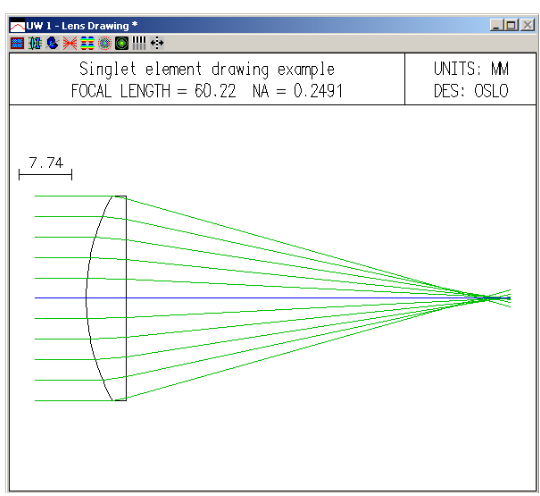
The graphics window provides a lot of information about the layout of the system and its performance. The default output shows you the transverse ray aberration plots of the system in the left most panel. The transverse ray aberration plots are for three different field positions: on-axis, 0.7 times full-field, and full-field. Astigmatism, longitudinal spherical aberration, and chromatic focal shift are plotted on the top right panel. Distortion and lateral colour plots in the middle, and the layout of the lens on the lower right. Try out different graphics commands found below the menu bar of the graphics window to see what result each one produces.

The graphics commands of interest are the “Draw system (2D plan view)”, wavefront analysis , and spot diagram analysis . The 2D plan view shows a profile of the lens system and ray traces from different field position. Unfortunately by default OSLO does not draw the rays all the way to the image plane. For the purpose of our exercise, we need to see the rays all the way to the image plane:

A. This can be changed by first clicking on  and selecting “Operating Conditions” in the menu. The surface data window should now change to show the following window.
B. Change the “Image space rays” parameter to draw rays to the image surface.
C. Click on the green check mark to close this spreadsheet.
D. Double click on the graphics window to refresh the 2D view of the optical system. It is worth noting that the lens drawing conditions window can adjust the number of rays, colour of rays, etc. drawn in the lens layout. The three rows at the very bottom of the window signify the rays drawn out for three different field positions over a range of pupil positions.
E. Try more rays for the on-axis field position.



Below is an example of the same system with 11 rays traced for the on-axis field position.



You can zoom into a specific area by dragging a box around a region of interest. Do that in the region where you see all of the rays converging. Double-clicking on the graphics window will return you to the unzoomed version of the layout.

Investigate the following questions:

1. In a perfect optical system, one expects all on-axis rays to converge to a point at the image plane. Do you see this in this optical system? Do you have an explanation for what you see?
2. What is the peak-to-valley optical path difference (OPD) of this system? Do you think it is diffraction-limited? *(Hint: Use the Wavefront Analysis function to obtain these values. According to the Rayleigh condition, a diffraction-limited system has a peak-to-valley OPD of 1/4 wave)*
3. What is the approximate size of the in-focus spots? How does it compare to the expected Airy disk size? *(Note: it is possible to overlay the Airy disk on the spot diagram. Right click on the Spot Diagram window, click "Re-calculate using new parameters" and select "Show Airy disk in plot". You can try changing the scale parameter of the plot to see the Airy disk. Hint: You may need to reduce the scale by a lot)*
4. What is the dominant geometric aberration? *(Hint: A guess is sufficient)*

2.3 Text Window

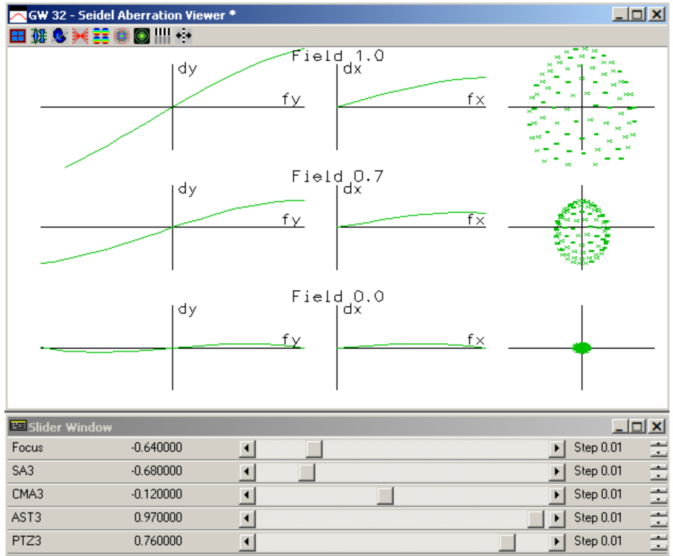
It is entirely understandable if you were unable to answer the last question of the previous exercise. For the untrained eye, it is difficult to determine the dominant geometric aberration. Even for the trained eye when there are more than one dominant aberrations, it can be quite challenging to ascertain which ones they are. That is why it is very useful to compute the Seidel aberration coefficients *(See the Appendix for more information)*. There are two methods for computing these coefficients. One can compute the transverse ray aberration coefficients in millimeters. This is the default output of OSLO when you click on the "Abr" button in the text window. I prefer the wave aberration coefficients, which can be accessed from the main menu bar by clicking **Evaluate->Other Aberrations->Seidel Wavefront**. This gives you the aberration coefficients in waves (measured at the operating wavelength) including the contribution from individual lens surfaces. Try clicking all of the other commands on the text window to get a sense of what they do.

Investigate the following questions:

1. What is the dominant aberration of the system?
2. How many waves in OPD does this aberration cause? How does this compare with the value you measured in the previous section?
3. Why do you think the other aberrations do not dominate *(Hint: think about field dependence)*?

2.4 Seidel Aberration Viewer

The Seidel Aberration Viewer is a neat demo in the OSLO program that allows you to visualize the expected spot diagram and the transverse ray aberration plot by giving you the ability to change the magnitude of different aberrations. **This demo is not related to the previous optical system.** It simply sets the appropriate coefficient for the aberration and computes the spot diagrams and plots. This is what you would see if you know the aberration coefficients of a system. This demo can be accessed from the main program menu by selecting **Tools->Demo->Seidel Aberration Viewer**.



Try playing around with different magnitudes of aberrations by changing the sliders and see how they change the spot diagram. Try to gain an intuition on how different aberrations affect the spots. *(Hint: Set all aberration coefficients to zero and try increasing one aberration at a time. Also, "Field 0.0" is what you would see on-axis, and "Field 0.7" and "Field 1.0" represent the 0.7 full-field, and full-field performance, respectively.)*

<u>Investigate the following questions:</u>

1. How does each aberration affect the spot size and shape as a function of field position? Why is distortion not included in this viewer? *(Hint: What does distortion do to an image? Does it change the spot size?)*
2. Suppose you have a system dominated entirely by spherical aberration. Can the spot size be improved by defocussing the system? Remember, a focus value of 0 is the nominal paraxial focus of the system.
3. Now consider the case where you have a system dominated entirely by field curvature. What happens when you change the contribution of astigmatism. Can you improve the final spot size?

It is important to note that oftentimes in optical design one tries to "balance" the aberrations and achieve partial cancellation without eliminating them entirely.

2.5 Spot Diagram

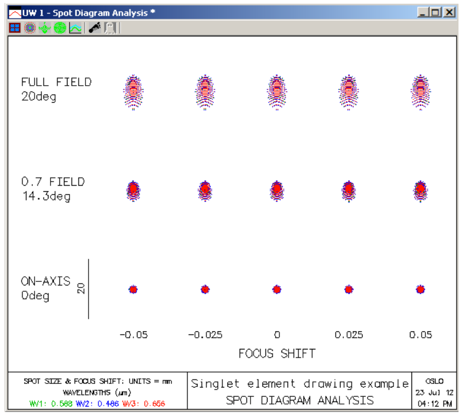
As you may have noticed in the previous activity, a spot diagram is a useful way of evaluating image quality and determining the performance of an optical system. In addition to evaluating image quality, the spot diagram can also be useful for identifying the dominant aberrations in a system *(There are also other methods for identifying aberrations such as OPD plots, and transverse ray diagrams, but we do not focus on these for this lab.)*

For this exercise, change the field angle of the planoconvex lens system to be 20 degrees. This means the system will observe field angles ranging from -20 to 20 degrees.

A. Generate a spot diagram for this new system (see figure below). The different colours represent different wavelengths (see bottom left of plot for the wavelength legend).

B. You can get more command options on your graphics window by clicking on the button. Click on that button and select “Spot Diagram”. You should see a new set of commands associated with the spot diagram.

C. Try plotting the RMS spot radius as a function of field position (Fractional Object Height).

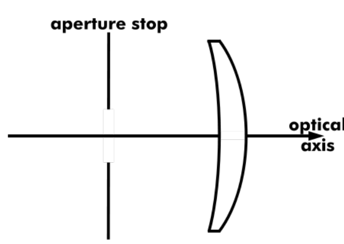


<u>Investigate the following questions:</u>

1. How does the size and shape of the spot diagram change as a function of field position?
2. Can you guess what the dominant aberrations are now?
3. Confirm the dominant aberrations by computing the Seidel coefficients. What are the OPDs introduced by each one of these aberrations?
4. Try reducing the entrance beam radius to 10 mm, how does this change the magnitude of aberrations? What does this say about how the f/# affects aberrations in optical systems? What can be the disadvantages of reducing the entrance beam size?

3. Building your first real lens: a landscape lens *(90 minutes)*

The landscape lens, also known as the Wollaston meniscus lens, is a very old lens design. It was designed by William Wollaston in 1812. It was one of the first lenses that controlled for geometric aberrations. Even though it is fairly old, it is used to this day in some form within relatively cheap cameras. A schematic of the landscape lens is shown below:

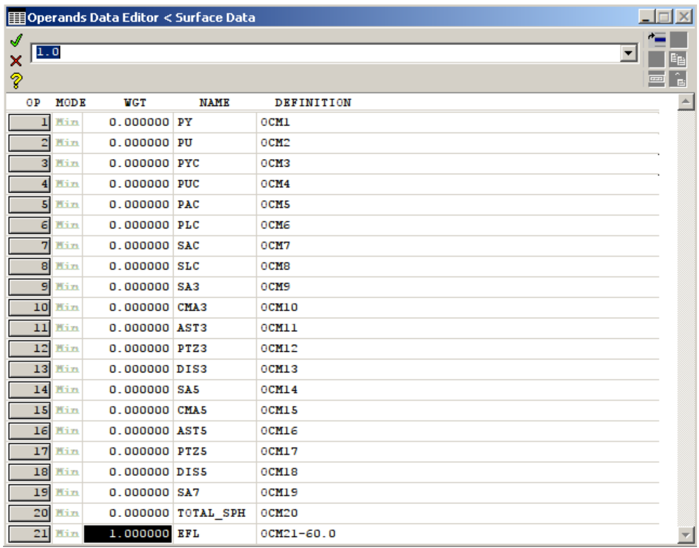


Light enters through the left. (*Credit: wikipedia.org)*

The landscape lens is a fairly slow (high f/#) single element lens with an offset stop that controls for spherical aberration, coma, astigmatism, and field curvature. Distortion is not corrected for. The primary purpose of the lens is to produce decent image quality over a reasonably large field on a flat image plane. This is not trivial to achieve by any means, and this activity will show you the trade-offs a lens designer has to make in order to achieve the required goal.

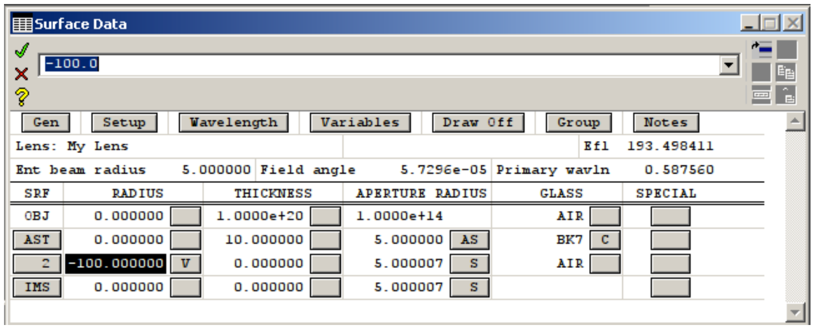
3.1 Using the optimizer

In this activity, you will learn an additional tool that a lens design program offers the designer: the optimizer. The optimizer is essentially a least squares algorithm that minimizes a merit function that you specify. For example, using this method you could force a lens system to have a specific focal length. You might allow the radii of curvature of the lens to vary and run the optimization routine to find the optimal radii of curvature that produce the correct focal length. Or you can minimize a specific aberration. The possibilities are endless. However, you needs to be careful in what you do with the optimizer because it is easy to produce poor and unrealistic results. The EDU version of OSLO only exposes a limited number of operands. Fully featured lens design software typically offers many more possibilities for merit functions.


Operands Data Editor < Surface Data

OP	MODE	WGT	NAME	DEFINITION
1	Min	0.000000	PY	OCM1
2	Min	0.000000	PU	OCM2
3	Min	0.000000	PYC	OCM3
4	Min	0.000000	PUC	OCM4
5	Min	0.000000	PAC	OCM5
6	Min	0.000000	PLC	OCM6
7	Min	0.000000	SAC	OCM7
8	Min	0.000000	SLC	OCM8
9	Min	0.000000	SA3	OCM9
10	Min	0.000000	CMA3	OCM10
11	Min	0.000000	AST3	OCM11
12	Min	0.000000	PTZ3	OCM12
13	Min	0.000000	DIS3	OCM13
14	Min	0.000000	SA5	OCM14
15	Min	0.000000	CMA5	OCM15
16	Min	0.000000	AST5	OCM16
17	Min	0.000000	PTZ5	OCM17
18	Min	0.000000	DIS5	OCM18
19	Min	0.000000	SA7	OCM19
20	Min	0.000000	TOTAL_SPH	OCM20
21	Min	1.000000	EFL	OCM21-60.0

At this point you want to start a new lens. You can access the merit function from the main menu under **Optimize->Generate Error Function->Aberration Operands**. The program opens up a window with the available operands, which is shown in the figure above. Some of the operands are familiar; they are the Seidel transverse aberration coefficients. The only other operand that we will concern ourselves with is the "**EFL**" operand, which stands for effective focal length. Remember that the merit function is like an error function that you minimize. To obtain an effective focal length of 60 mm, you would have to minimize EFL minus 60 to obtain the appropriate value. You will also notice that all of the weights are set to zero. You will have to weight the appropriate parameters you want to minimize with 1. In the figure shown above, the merit function is set up to yield a lens with an effective focal length of 60 mm. You can add more than one parameter to minimize by making its weighting factor non-zero. Of course, in order to change the system to meet your constraints, you require free parameters in your system. OSLO has the ability to make design parameters variable. For example, you can vary the curvature of surfaces by making the surface radii variable. This can be done by clicking on the grey box beside the radius parameter in the spreadsheet and selecting "variable." Try setting up the lens parameters using the example given below.



To insert a surface, you can right click any field of the spreadsheet and either "Insert Before" or "Insert After". Set up the merit function above. Then run **Optimize->Iterate**. This will bring up a dialog box asking how many iterations of the minimization routine you wish to run. You may need more than 10 iterations to converge. You do not need to change any of the other parameters. After the iteration is complete and if everything went well, the EFL of the system should be 60 mm.

Now let's start with the lens you will design for this exercise. Create a new lens in OSLO. The lens has the following parameters:
1. Focal length = 100 mm
2. f/# = 10
3. Thickness = 15 mm
4. Material = BK7 glass
5. Operating wavelength = 0.58756 microns (default value)
6. Front surface is flat and is also the system stop (a curvature of zero means it is flat)
7. Object at infinity (a thickness value of 1e20 means the object is at infinity)
8. Field angle = 20 degrees

Remember the entrance beam radius is related to the f/# and focal length of the lens (r = 0.5*f/(f/#)). Use the optimizer to determine the correct radius of curvature for the rear surface of the lens. After doing so, determine the right distance to the image plane. You can do so by clicking on the grey box beside the image plane thickness and clicking on one of the autofocus functions. For now choose the paraxial focus. OSLO will automatically place the image plane at the paraxial focus of the lens. If your optimization was done correctly, the image plane thickness value will be close to 100 mm. Now that you have working lens.

<u>Investigate the following questions:</u>
1. Look at the plan view of the lens. Where do all of the rays of the different field position come to focus?
2. What are the dominant aberrations of this system?
3. How do the spot diagrams look like? Do you think this is a good imaging system?

Save your lens file! In the next few steps, you may accidentally mess up your lens model, so it is good to have a backup. Remember to save a new file in each following step.

3.2 Correcting for spherical aberration through lens bending

The previous investigation of your lens would have shown that its performance off-axis was very poor. On axis, the lens would have been dominated by spherical aberration. The lens should have had approximately 1.1 waves of spherical aberration (SA). We can try to correct for this a number of ways. We can increase the f/# of the system; however, at some point this is prohibitive since the sensitivity of that system will suffer from the smaller aperture and therefore collecting area. Let's say we are forced to stick with an f/10 system. The other alternative is to bend the lens. Lens bending, i.e. changing the radii of curvature of the front and rear surface so the focal length is not changed, can be an effective way to reduce spherical aberration. There is a well-defined set of equations that allow you to determine the optimal radii of curvature that minimizes SA, which is given below. One needs to first calculate the optimal Coddington shape factor, *C*, given the refractive index of the lens, *n*, the image distance *i* and object distance *o*. *C* is simply a function of the radii of curvatures where R_1 and R_2 are the radii of the first and second surfaces, respectively.

$$C = \frac{-2(n^2-1)P}{n+2}$$
$$P = \frac{i+o}{i-o}$$
$$C = \frac{R_2 + R_1}{R_2 - R_1}$$

P is simply -1 since our object is at infinity. The index of refraction of BK7 is 1.52 at 0.587 um. You should be able to calculate the optimal *C* from the top left equation.

However, we know how to optimize the lens given a merit function. It is possible to define one that both ensures a focal length of 100 mm and minimizes spherical aberration (the SA3 parameter). Of course, you will have to vary the radii of curvature for both lens surfaces. Use the optimization routine to find the best combination of radii to minimize spherical aberration. **Make sure to readjust the focus after this step.**

Investigate the following questions:

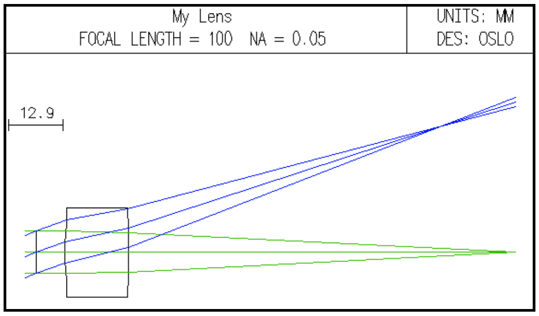
1. Is the choice of lens radii close to the computed optimal Coddington shape factor? *(Note: if you are within 0.1 of the computed value, you can declare victory)*
2. How much has spherical aberration been reduced through lens bending? *(Note: You may notice that the lens shape does not match that of the landscape lens. More on that in Section 3.4)*

Save your lens file!

3.3 Correcting for coma by a stop shift

It turns out that if a lens system has some spherical aberration, it is possible to eliminate its coma entirely by shifting its aperture stop. For this exercise, you will create a new surface in front of the lens which will act as an aperture stop. An aperture stop is often just a plate with a circular hole. Modern cameras use adjustable irises as stops. Try moving the stop to see how much it affects coma. You will have to force OSLO to draw the stop by clicking on the "Special" section for the aperture stop. Select **Surface Control->General**. In the displayed spreadsheet under "Surface appearance under lens drawings" select "Drawn."

To determine the optimal stop position, you can make the distance between the stop and the first surface of the lens variable, and use the optimizer to minimize coma (CMA3). Make sure you turn off the variability of the two radii of curvatures by selecting "Direct Specification." Shifting the stop should not change the focal length of the system. Now you should have a system corrected for spherical aberration and coma. Your system should look something like this:



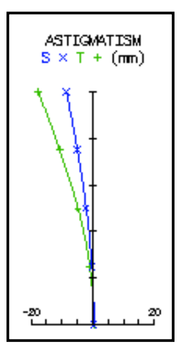
Look into what the dominant aberrations are now. You will notice the off-field performance is still quite poor. You have not quite arrived at the landscape lens design yet. It is worth comparing its performance with the final step.

<u>Investigate the following questions:</u>
1. What are the dominant aberrations?
2. What do you notice about the flatness of the field?

Save your lens file!

3.4 Flattening the field and making your landscape lens
Landscape lenses are used in systems with flat image planes. Poor off-axis performance is unacceptable. This is largely due to field curvature. The solution to this problem can appear counterintuitive. One needs to trade-off on-axis performance for improved off-axis performance. For this reason, landscapes lenses do not directly correct for spherical aberration. By bending the lens into a meniscus shape (as shown in the original figure of the landscape lens), one can reduce field curvature and balance it with astigmatism. This comes at the expense of increasing spherical aberration because the lens will deviate from the optimal shape determined in Section 3.2. However, the off-axis performance is greatly improved while the on-axis performance is slightly degraded. It is a worthwhile trade-off to make given the available degrees of freedom.

You can determine how flat the field is by clicking in the graphics window and looking at the astigmatism plot. You will most likely see something like this plot:



This plot essentially tells you that along the sagittal (S) and tangential (T) image planes of the optical system *(see Appendix for a definition of sagittal and tangential rays)* the optimal focus shifts approximately 10-20 mm when going from the center of the field to the very edge of the field! It is no wonder the off-axis performance is quite poor. *As an aside, if there is no astigmatism and only field curvature, you would expect both the sagittal and tangential curves to* *lie on top of each other.* The goal of this exercise is try to flatten both of these curves. You will not succeed, but you will certainly make it a lot better. One way of doing this is trying out different curvatures for the front surface and solving for the curvature of the second surface to maintain the right focal length. Be sure to autofocus after each step and re-optimize for the optimal stop position to cancel coma. To clarify, you will need to follow these steps:

A. Change the radius of curvature of the front surface a small amount. *(Hint: you can start with a large negative number, which means it has a shallow curvature)*

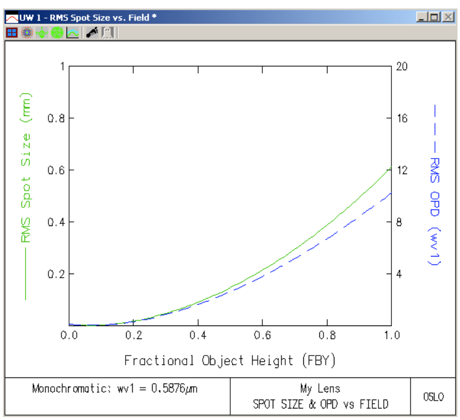
B. Optimize the system to obtain a focal length of 100 mm by allowing the radius of the rear surface to vary. *(Note: you no longer need to optimize for spherical aberration, so you can set its weight to 0. Always check to make sure you reach the correct EFL; otherwise, increase the number of your iterations)*

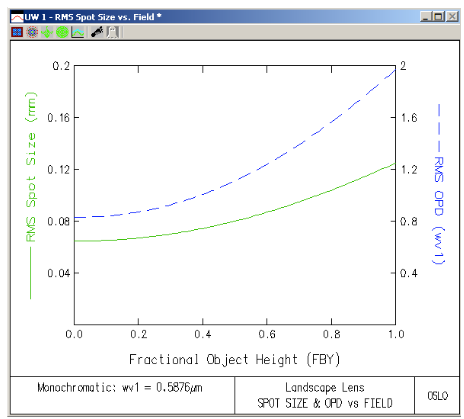
C. Turn off the variability of the radius of curvature of the rear lens surface, and optimize to reduce coma by allowing the stop to shift.

D. Refocus the system using the autofocus function and evaluate its performance to see how its on-axis and off-axis performance has changed.

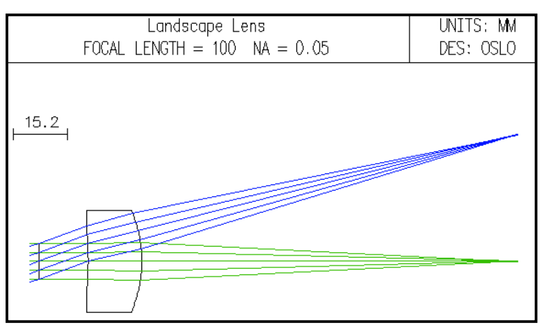
E. Continue steps A through D until you are satisfied. Always remember to check the right parameters are variable at each optimization step.

Once you have more or less flattened the field, you will notice that the spot size at the center of the field has worsened somewhat, but the off-axis performance will be much better. Below are two spot size versus field position plots for the unflattened *(left)* and flattened lenses *(right)* respectively. There has been almost a factor of 10 reduction in the off-axis spot size!





Your final lens should look something like this:



Of course, you may have noticed in the spot diagram that different wavelengths of light have different spot sizes. This is due to axial colour. Moreover, you will notice in the off-axis positions, the different wavelength spots are offset from each other. This is known as lateral colour. To construct a production quality lens, one will need to correct for this chromatic aberration by converting the single landscape lens into an achromatic doublet. This lens is called the Chevalier lens and is outside the scope of our current activity. If you have spare time after having completed this summer school, you can model a cemented achromatic doublet and replace the single element lens.

Save your lens file!

3.5 Design Challenge

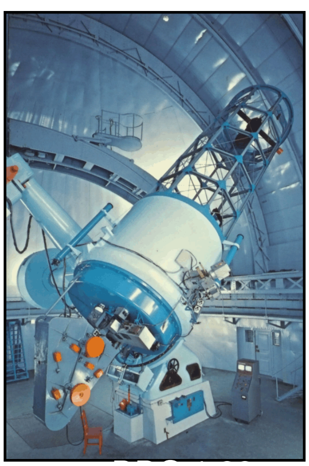
Now that you have created a working design, see if you can improve the performance for a single wavelength of light, λ = 0.5876 μm, further. By this I mean that your RMS spot size at fractional object heights of 0, 0.7, 1.0 are better than your previous design. You can use the following metric to compute the effective spot radius $r_{eff} = 0.15*r_0 + 0.5*r_{0.7} + 0.35*r_{1.0}$, where r_0, $r_{0.7}$ and $r_{1.0}$ are the spot radii measured at fractional object heights of 0, 0.7, and 1, respectively.

You can also explore changing the following while keeping all other operating parameters the same:

1. Glass material (Try materials with different indices of refraction)
2. Thickness of lens (Limit yourself to between 2 and 20 mm)
3. Geometry of system (e.g. the stop can also be placed behind the lens)

After having completed this exercise, please email me (sivanandam@dunlap.utoronto.ca) your OSLO .len file along with the value of r_{eff} you obtain. Be sure to include your name along with any observations you have of your design, i.e. if you made anything else better or worse in the process of your optimization. I will announce the best design before the end of the summer school. **If you have run out of time, just send me your lens from Section 3.4.**

4.Modelling the DDO 1.88-meter telescope *(Bonus Activity)* *(30 minutes)*



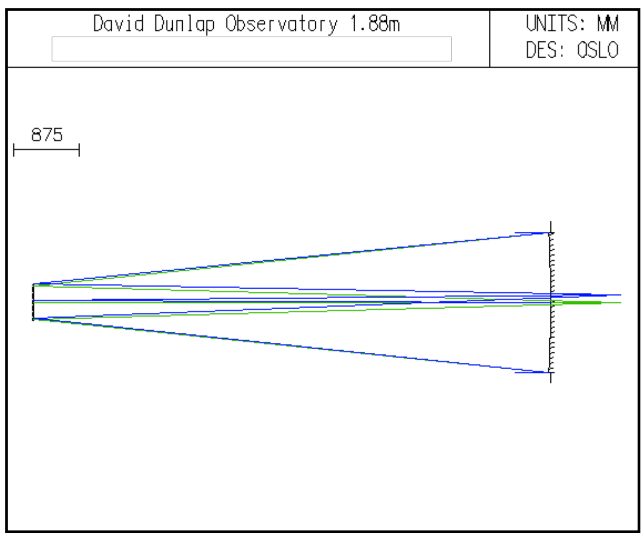
For your final activity, you will model the 1.88-meter reflective telescope at the David Dunlap Observatory. This observatory has considerable historical significance, which was a gift to the University of Toronto by Jessie Donalda Dunlap as a memorial to her husband David Alexander Dunlap, a wealthy lawyer, mining executive, and philanthropist. The telescope was a workhorse for astronomical research for the Department of Astronomy for many decades since its construction in 1935 until the Observatory grounds were sold off in 2008. The funds of this sale were used to create the Dunlap Institute for Astronomy and Astrophysics. At the time of its commissioning, this telescope was the second largest in the world.

Reflective telescopes remain the predominant workhorses in astronomical research because we are able to construct very large systems with considerable collecting area, which is essential in observing very faint signals of astronomical objects. Lens-based telescopes (refractors) have a fundamental weakness in that they cannot be scaled up to very large apertures due to weight and fabrication constraints. In fact, the largest refracting telescope in the world right now is the

40 inch (102 cm) at the Yerkes Observatory, while the largest optical reflective telescope is the Grand Telescopio Canarias that is 10.4-meters in diameter. The world's largest fully steerable telescope is actually the Green Bank radio telescope, which is a whopping 100-meters in diameter and is also a reflecting design. One very important quality of reflecting telescopes is that they are achromatic, i.e. the rays within the telescope travel the same path irrespective of wavelength. They do not suffer from chromatic aberration. A side effect of this is that the optical design principles of a reflecting optical telescope also applies to reflectors that operate at other wavelength. However, this does not necessarily scale up to very high energies such as X-rays and gamma rays were photons are notoriously difficult to collect.

4.1 Constructing a classical cassegrain reflector

The DDO 1.88-meter is a classical cassegrain telescope. This form of telescope uses two mirrors: one large (primary) and one small (secondary). The mirrors have specific shapes where the primary mirror is parabolic, while the secondary is hyperbolic. The two mirrors are separated such that the focii of the two mirrors are coincident. The details of how to choose the radii of curvature of the two mirrors and the conic constant of the secondary are outside the scope of this lab, but any text describing the design of telescopes will contain the necessary relations. The layout of the 1.88-meter is shown below.



Use the following telescope design parameters to create a realistic model in OSLO:
Primary Mirror - Radius of Curvature: 18288.2 mm, Conic Constant: -1 (Parabola)
Secondary Mirror - Radius of Curvature: 6157.2 mm, Conic Constant: -3.1765 (Hyperbola)
Distance from Primary to Secondary: 6931.1 mm
Entrance Aperture - Radius: 940 mm, System Stop: Primary Mirror
Field Angle: 0.1667 degrees

Hints:

1. To specify a mirror, click on the box in the "Glass" section and choose "Reflect". You can also draw the mirror as a hatched surface by choosing "Reflect (Hatch)".
2. To specify a conic constant for your surface, select the box under the "Special" section for a given surface and choose "Polynomial Asphere". A new parameter page will appear, and you can input the conic constant value there.

3. The signs of the radii of curvature and the thicknesses matter. After a mirror reflection, the thickness flips its sign. Choose the sign of the radii of curvature such that the focus of the telescope falls behind the primary. If you get everything right, the design should look like the figure above. In this version, the primary appears to block the light coming to a focus, but in reality, the primary mirror is fabricated with a hole in the centre to let light through.

Investigate the following questions:
1. What is the focal length of the telescope?
2. What is the f/# of the telescope?
3. How far behind the primary is the telescope focus located?
4. What are the dominant aberrations? What has happened to spherical aberration?
5. How significant are chromatic aberrations?

4.1 Evaluating the performance of the 1.88-meter

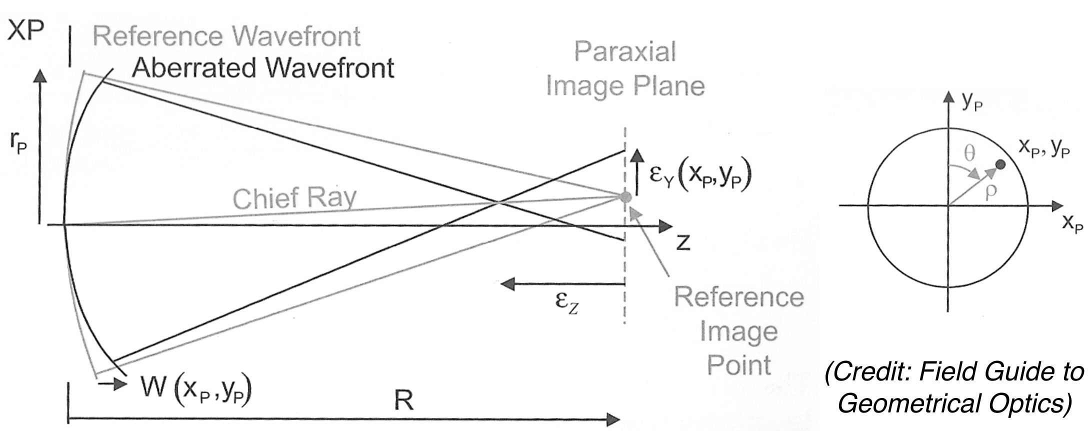
Typical seeing (atmospheric blurring) values at excellent astronomical sites are often 0.5-1 arcsecond (1/3600th of a degree). Suppose that the DDO site has seeing values that are typically 1".

Investigate the following question:
Within what field angle is the telescope's imaging performance as good as or better than the seeing of the site? *(Hint: Calculate the plate scale of the telescope, i.e. how many millimeters an arcsecond subtends in the telescope's image plane (a.k.a. focal plane). Use the spot size diagnostic to calculate the field angle within which the optical performance is satisfactory.)*

5.Conclusions

In this lab, you will have learnt how to use optical design software to model a relatively simple optical system, evaluate its performance, and control its aberrations. This is the first step in the design of an optical system. The next step after you have met your design requirements is to carry out a tolerance analysis. A tolerance analysis will let you know how sensitive the optical design is to alignment and manufacturing tolerances, which are an unavoidable part of constructing optical systems. After completing a careful analysis of the effects of tolerances and coming up with an alignment plan, one would contract companies to manufacture the optics. If you have not managed to complete the design or are interested in exploring more, feel free to download the OSLO software and try things out. Email me with if you have any questions.

Appendix - Crash course on aberration theory



(Credit: Field Guide to Geometrical Optics)

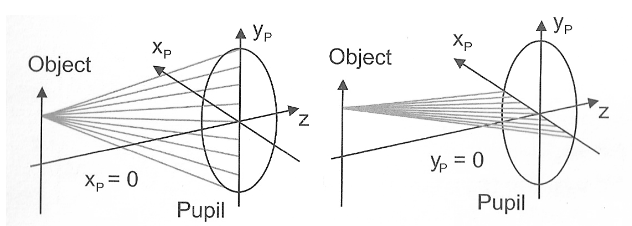
Over the years, multiple methods have been devised to determine the aberrations of an optical design, the most common of which has been computing the third order (Seidel) aberrations of a system. A schematic of an optical system is shown in the figure above. In this picture, you will see the exit pupil (XP) of the system with a radius r_p and the ideal unaberrated wavefront called the reference wavefront. The reference wavefront is a spherical wavefront which comes to a focus on the paraxial image plane located at a distance R away from the XP. Aberrations will cause the wavefront to deviate from this spherical wavefront, which is shown by the aberrated wavefront in the above figure. There are two ways to quantify these aberrations. One way is to measure the optical path difference (OPD) between the aberrated and reference wavefronts, $W(x_p,y_p)$, at the XP where x_p and y_p are normalized pupil co-ordinates (i.e. $-1 < x_p < 1$ and $-1 < y_p < 1$). Another way is to measure the transverse ray aberration which is the offset between the aberrated ray and the reference ray on the paraxial image plane, $\varepsilon_x(x_p,y_p)$ and $\varepsilon_y(x_p,y_p)$. For a rotationally symmetric system, one can carry out a polynomial expansion of the OPD as a function of pupil co-ordinates and image plane position (field position) to obtain the dominant third order (Seidel) monochromatic geometric aberrations:

$$OPD = W(\rho,\theta,H) = W_{040}\rho^4 + W_{131}H\rho^3\cos\theta + W_{222}H^2\rho^2\cos^2\theta + W_{220}H^2\rho^2 + W_{311}H^3\rho\cos\theta$$

where ρ and θ are normalized polar co-ordinates in the pupil plane (i.e. $0 < \rho < 1$, $0 < \theta < 2\pi$) and H is the normalized radial field position (i.e. $0 < H < 1$), which is also known as normalized image height. In fact, the coefficients of these aberrations can be determined by only tracing a few rays through the optical system, which is what makes this method very powerful. See the cheat sheet in the introduction to obtain a description of each coefficient. The Seidel transverse ray aberration can then be derived by differentiating the OPD:

$$\varepsilon_x(x_p,y_p) = -\frac{R}{r_p}\frac{\partial W(x_p,y_p)}{\partial x_p}$$
$$\varepsilon_y(x_p,y_p) = -\frac{R}{r_p}\frac{\partial W(x_p,y_p)}{\partial y_p}$$

Two special sets of rays are also used for aberration analysis called tangential rays ($x_p = 0$) and sagittal rays ($y_p = 0$). These rays are used for transverse ray aberration or OPD plots to identify geometric aberrations are useful for differentiating between even (no θ dependence) and odd (θ dependent) aberrations and in determining the extent of astigmatism as discussed in Section 3.4.



Tangential rays Sagittal rays
(Credit: Field Guide to Geometrical Optics)