DESIGN OF OPTICAL SYSTEMS

A (very) short[1] course in optics design:

Optical systems are designed using ray tracing software like OSLO, Zemax, CodeV (to name the best known). We already used Oslo to illustrate some geometrical aberrations and thus learned the basics that are summarized here:

1) Describing an optical system using the surface data spreadsheet (Figure 1):

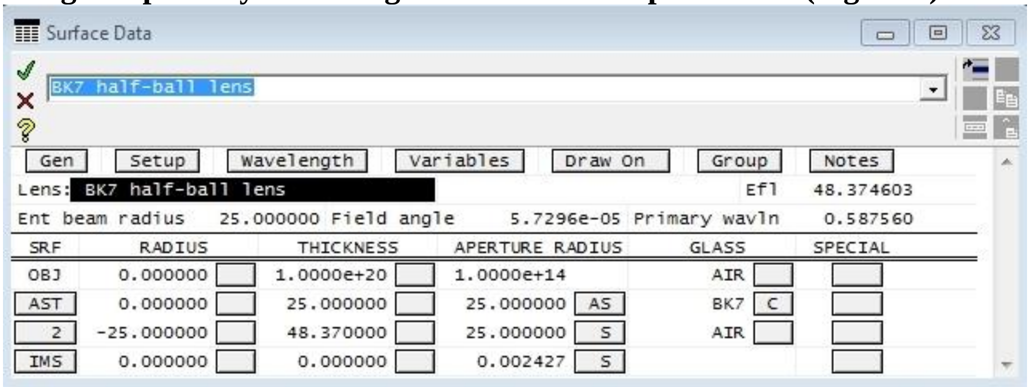

Figure 1: Example of a surface data spreadsheet describing an optical system.

Except the first line and the last line, each line of the spreadsheet describes an optical interface:

- “Radius” is the radius of curvature on the interface. RD > 0 means that the center of the sphere is to the right of the interface position. (In Figure 2, RD[1] is positive). RD = 0 is a flat surface.
- “Thickness” is the distance to the next interface (measured on the optical axis of the system as described in Figure 2). Negative values are needed if a mirror is used.

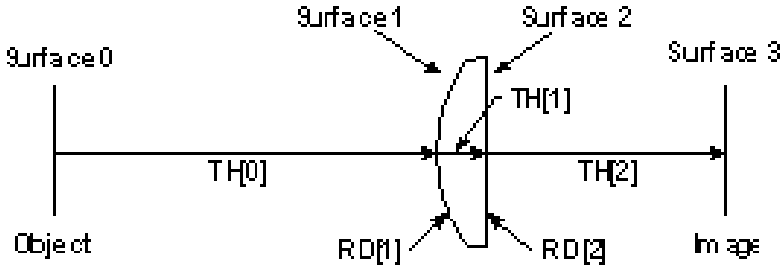

Figure 2: Meaning of some column values in the surface data spreadsheet.

- “Glass” describes the material in which the light propagates after the interface (over a distance “thickness”).
- “Aperture radius” is the diameter of the open aperture of the lens divided by 2. This value is usually calculated by the software as visible by the letter S on the corresponding button. In order to act on the width of the light-beam, modify the value of the “Ent(trance) beam radius” above the spreadsheet. The “aperture radius” can however also be set manually to implement an iris diaphragm.

The first line describes the object and its distance to the first interface (value in the thickness column).

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[1] Please consider this lab work just as a glance into the world of optics design. Typically an assistant optics designer should have at least 5 000 h of experience in ray-tracing. At more than 10 000 h one may be able to make a full complex design independently. (For comparison: An employee usually works 1 600 h per year.)

The last line describes the screen and contains the (manual) autofocus-function in the thickness column. The position where an observer would place the screen in order to obtain the sharpest image of a homogeneously illuminated object, is best described by the "best RMS OPD" (RMS = root mean square, OPD = optical path difference).

2) Some definitions in geometrical optics

For an off-axis object point (for example (0, PY, 0)) one defines two planes: The *tangential plane* (or meridional plane) that comprises the optical axis and the object point (abbreviated T in some plots) and the *sagittal plane* that is perpendicular to the tangential plane and comprises the object point and the center of the aperture stop.

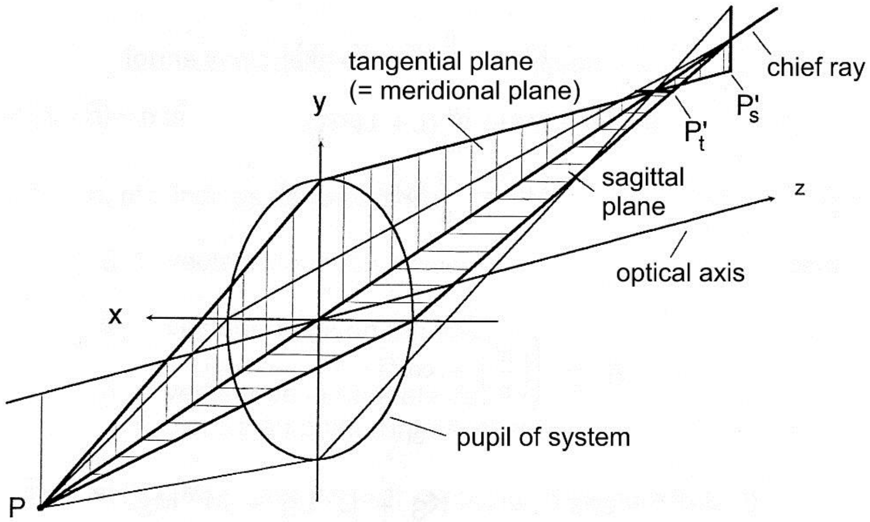


Figure 3: Some definitions in ray optics. P is vertically displaced from the optical axis ($y_P \neq 0$). Thus the tangential plane is the vertical plane (y-z-plane) and the sagittal plane contains the x-axis. P'_s is the image formed by sagittal rays and P'_t is the image formed by tangential rays.

The ray from the object point through the center of the aperture stop is called the *chief ray*. The distance between the chief ray and the optical axis at an image location defines the size of the image.

Another important ray is the *marginal ray*. It is the tangential (or meridional) ray that starts at the point where the object crosses the optical axis, and touches the edge of the aperture stop of the system. This ray is useful, because it crosses the optical axis again at the locations where an image will be formed.

3) Configuring the surface data spread sheet for design tasks

Designing an optical system involves variations of some of its parameters in order to obtain the wished performances. However many parameters exist which may be dependent on one another. In order to avoid manual adjustment of the whole chain of dependent parameters after each variation of an independent parameter, these dependencies can be implemented in the spreadsheet. These functions are accessed by clicking on the buttons to the right of the parameters. The most frequent dependencies are:

- *"Make the lens as small as possible, but large enough to let pass all rays":* Aperture radius / solved (switched on by default).
- *"Make the lens as thin as possible, but thick enough to hold it without risking breakage":* Thickness / solves / edge thickness. Remark: It is not possible to use both features simultaneously as the edge thickness solve will ask for a fixed aperture radius.
- *"Move the screen always to the paraxial focus":* This can be achieved automatically by using the thickness of the last material (the before-last line) and making it dependent on a 'solve' of a ray similar to the marginal ray, but staying close to the optical axis, which is called "axial ray" in OSLO.

- *“Move an element between two other elements that keep their position”:* Go to the second distance (the one that should be adjusted automatically) and choose: Thickness / Pickups / minus thickness / constant (sum of both thicknesses) / multiplier (1.0).

The influence of the remaining parameters or at least some of them can then be observed using sliders under Optimize / Slider-Wheel design. The defined parameters can then conveniently be modified using the sliders and the dependent parameters can be observed in the surface data spread-sheet, the autodraw window and another graphics window, the content of which is chosen at slider-wheel design time.

4) Evaluating an optical system

Load the following sample from the Lens database / public / demo triplet (f50mm f/4 20deg).
Oslo will display the “report graphics” plot which summarizes the performances of the optical system. The implemented ‘nearly symmetrical’ design is one way to minimize several types of aberrations in an optical system.

Ray intercept curves

To the left you find the ‘ray intercept curves’ that represent the image space displacements as a function of object-space fractional coordinates. Two examples are given in Figure 4.

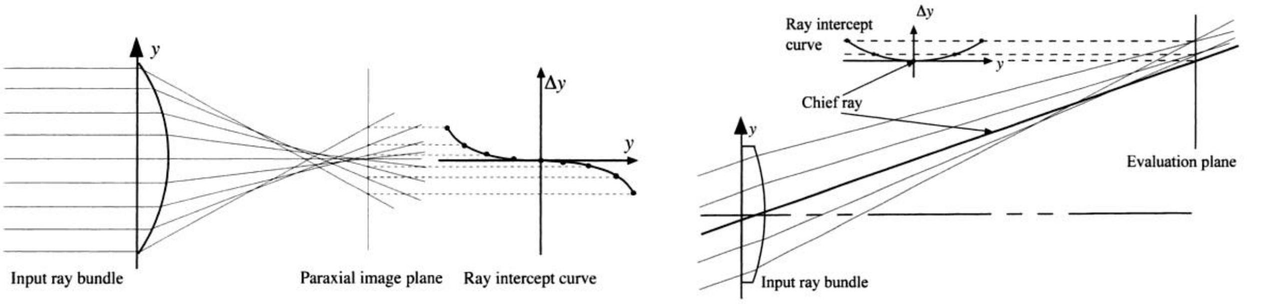


Figure 4.11 Ray intercept curve (right) of a lens with spherical aberration. The errors in the rays in the paraxial image plane are plotted as a function of the location of the input ray on the lens.

Figure 4.12 Lens with coma and ray intercept curve (top). The errors in the rays in the paraxial image plane are plotted as a function of the location of the input ray on the lens.

Figure 4: Examples for ray intercept curves.

For a more detailed explanation of these curves, read the attached chapter of the ‘handbook of optics’. In order to see the axis labels you may generate intercept curves for one field point by using Evaluate / Ray fans / Single field point.

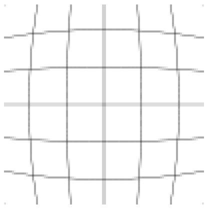
- ➔ What is the optimum curve in this graph? (displayed by an ideal system)
- ➔ How to estimate the diameter of the blur circle from these plots?

Spherical aberration

Typically the longitudinal spherical aberration is displayed (distance in mm between the point where the beam crosses the optical axis and the paraxial focus) as a function of object point position (or angle). Lateral spherical aberration can be calculated by multiplying with tan(direction of chief ray in image space).

- ➔ What is the optimum curve in this graph? (displayed by an ideal system)
- ➔ Describe the changes occurring when you put the screen at different locations by using the manual autofocus function.
- ➔ When looking at the aberration curve, can you tell if the paraxial focus was chosen as reference? Explain.

Distortion
The distortion value is negative for barrel type distortion and positive for pincushion type distortion (Figure 5).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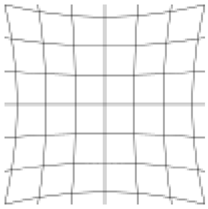
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Figure 5 Image of a regular grid made by a system with barrel type distortion (left) and a system with pincushion type distortion (right).

Point spread function and encircled energy
If an optical system is diffraction limited, geometrical ray-tracing no longer provides realistic values. The size of an image point is then determined by the point spread function (PSF). OSLO can also calculate point spread functions and plots them as well as the part of energy of the incoming beam that goes through a circular diaphragm placed at the screen location.

5) Using automatic optimization

Ray-tracing programs include optimization algorithms that can help you to find the best solution to your design-problems. Mathematically speaking optimization is a minimization problem and the critical questions are which are the parameters to modify and which function should be minimized.
The parameters that should be modified are simply indicated in the ‘surface data spreadsheet’ by defining them as ‘variable’.
The function to minimize is usually called ‘merit function’ or in OSLO ‘error function’ and is defined in Optimize / Generate Error Function. A complex black-box error function that is available and that may work for a large range of applications is the GENII Ray aberration error function. However you may define simpler error functions that you can fully understand by choosing the Aberration Operands you want. A description of the available options is given on page 346 of the OSLOProgramRef6X file and an example how to use it is given in the OSLOOpticsReference file (page 40). In short you choose the operands to keep (for example PY, SA3 and EFL) and the weight (importance) each of these operands should have in your optimization. By default, OSLO optimizes all values to zero but this is not reasonable for all operands. If an operand should be optimized to a value different from zero (for example the effective focal length) you need to modify the entry in the ‘definition’ column. For example, in order to optimize a system to an effective focal length of 200 mm change ‘OCM21’ (which is the internal reference of the variable containing the effective focal length) to ‘OCM21 - 200’.
Once variables and error function are defined, the optimization can be started by Optimize / Iterate and the resulting (optimum) values will replace the initial values in the surface data spreadsheet. Pay attention to the fact that different starting values may lead to different results after optimization, even if the problem is always the same. This may occur because the merit function may have several local minima.

Exercises:

1) Simple optimization test

Make a single BK7 lens that has the same effective focal length and the same NA as the triplet from the lens data base. In order to achieve this, start with a plano-convex shape (in the right orientation) having a radius of the curved shape of 25 mm and use automatic optimization using the operands PY, SA3 and EFL.

- ➔ What are the significations of the operands PY and SA3? To which optimum values should they be optimized and why?

- ➔ Briefly compare the performances of the triplet and the singlet lens.

2) Achromatic doublet

Design a cemented achromatic doublet similar to the one in Figure 6 with the same effective focal length and the same NA as the triplet from the lens data base. The glass map in the appendix will help you to choose the glass types. Compare its chromaticity with the singlet lens and the triplet lens.

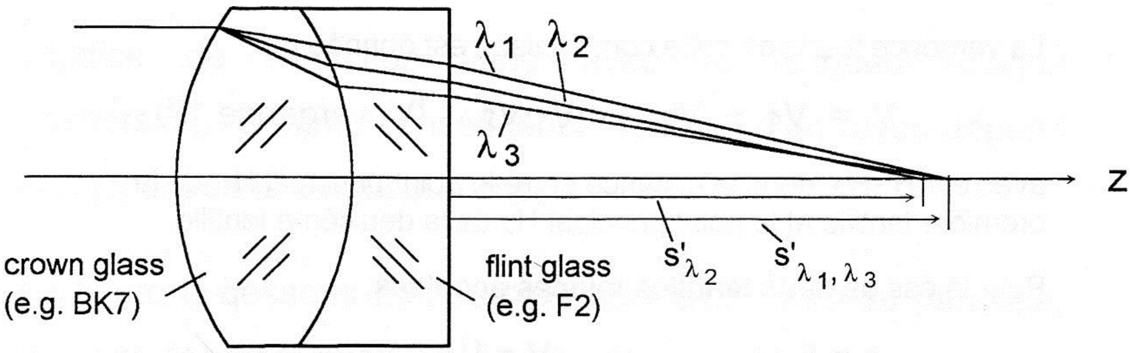

Figure 6 Sketch of a positive cemented doublet lens.

- ➔ Optimize this doublet to reach a spot size lower than the diffraction limit.
- ➔ If you want to use this lens to do a fiber coupling, how much light will you be able to couple to a fiber with a core diameter of 20 µm? (Calculate the Point Spread Function).

3) Zoom lens

Understand and design a very simple zoom lens according to the schematics in Figure 7.

- ➔ Using a geometrical construction, show that the effective focal length of the zoom system in Figure 7 is varying when the two positive lenses are moved.

- ➔ Why does a (far away) object appear larger on the photograph if the lens has a longer focal length? How to quantify the image size in a ray-tracing software?

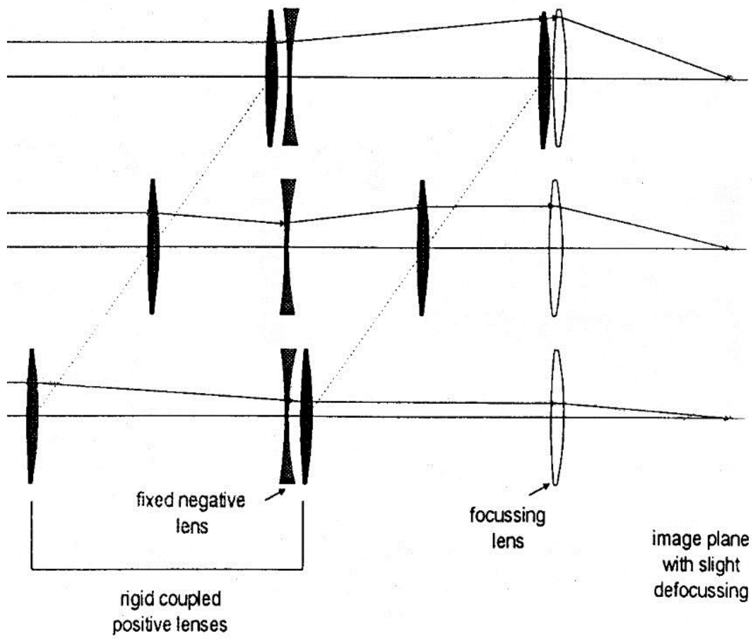

Figure 7 Sketch of a simple zoom lens. The two moving lenses are made out of glass with a high refractive index. The refractive index of the fixed negative lens is lower than this. The image plane of this kind of system is not exactly fixed.

Start with a configuration using symmetric lenses and monochromatic light (to simplify things). Prepare your spreadsheet such that by changing only one thickness parameter the rigidly coupled lenses 'slide' as in reality and the screen is always automatically positioned at the location of the paraxial image.

➔ For your starting configuration:
- Print three system drawings like the ones in Figure 7.
- Print the surface data spreadsheet for one of the positions
- Characterize the relative variation of the image plane location when moving the mobile lenses.

Now minimize the relative variation of the image plane location.
I propose to do this using the Optimize / Slider-wheel design feature of Oslo. Define two slider wheels, one for zooming and one for changing the first radius of curvature of the system. You may also change other parameters but the optimization of the first radius of curvature is essential to achieve a nearly stable image plane location. The asymmetry of the lenses may be observed in Figure 7.

➔ For your final configuration:
- Print the surface data spreadsheet for one of the positions
- Characterize the relative variation of the image plane location when moving the mobile lenses.
- Plot the image size as function of the zoom position
- Plot the spot diagram size (sharpness) as function of the zoom position
- If your system is diffraction limited in any zoom position, print the encircled energy plot.

Appendix I: Abbé diagram