MICRO-517 Lecture 5-6 Homework

1. Design of a Landscape Lens

1.1 Theory

We now consider the design of a single lens, the landscape lens. Clearly, we cannot correct chromatic aberrations in this case; the only thing that is possible is to select a glass with low dispersion (high V value).

Assume we wish to have a focal length of 100 mm ($K = 0.01$ mm^{-1}), an aperture of $h = 4.00$ mm, and a field angle of $w = 20°$ (see Figure 1). This left us two degrees of freedom: stop position and bending.

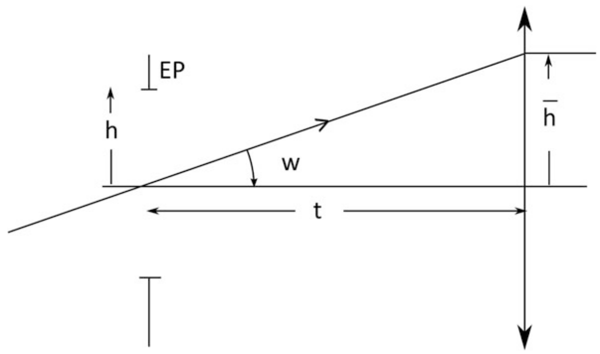

Figure 1. Layout of the landscape lens.

The first four Seidel coefficients of a thin lens *at the stop* are

$$S_1 = \frac{h^4 K^3}{4}\left\{\mu_1 B^2 + \mu_2 BG + \mu_3 G^2 + \mu_4\right\}$$

$$S_2 = -\frac{h^2 K^2 H}{2}\left(\mu_5 B + \mu_6 G\right)$$

$$S_3 = H^2 K$$

$$S_4 = \frac{H^2 K}{n}$$

$$S_5 = 0$$

where $\mu_1 = \frac{n+2}{n(n-1)^2}$, $\mu_2 = \frac{4(n+1)}{n(n-1)}$, $\mu_3 = \frac{3n+2}{n}$, $\mu_4 = \frac{n^2}{(n-1)^2}$, $\mu_5 = \frac{n+1}{n(n-1)}$, and $\mu_6 = \frac{2n+1}{n}$ are coefficients, $H = hw$ is the Lagrange invariant, $B = (c_1 + c_2)/(c_1 - c_2)$ the shape factor, c_1, c_2 the surface curvature, $G = (s' + s)/(s' - s)$ the position factor, s, s' the object and image distance.

The low refractive index, low dispersion glass N-BK7 ($n=1.515$, $V=64$) is a good choice for this lens. This leads to the coefficients of $\mu_1=8.78$, $\mu_2=12.89$, $\mu_3=4.32$, $\mu_4=8.65$, $\mu_5=3.22$, and $\mu_6=2.66$. For object located at infinity, we have a position factor of $G=-1$.

In the case of a landscape lens, the stop is located at a remote location. Applying the stop shift equation to find the aberration with a stop away from the lens, we have

$$S_1^*=S_1,\ S_2^*=S_2+\left(\frac{\bar{h}}{h}\right)S_1,\ S_3^*=S_3+2\left(\frac{\bar{h}}{h}\right)S_2+\left(\frac{\bar{h}}{h}\right)^2 S_1$$

where $\bar{h}=wt$ is the height of the chief ray, $w=20°$ is the field angle, t is the distance from the entrance pupil to the lens, and $h=4.00$ mm is the height of the marginal ray (determined by the size of the entrance pupil).

By judiciously locating the stop (entrance pupil) by finding the right t, we can make $\frac{\bar{h}}{h}=-\frac{S_2}{S_1}$ so that the coma is $S_2^*=0$, leaving $S_3^*=S_3-\frac{S_2^2}{S_1}$. Correction of this astigmatism, then, requires $S_3=\frac{S_2^2}{S_1}$. From the thin-lens aberration formulas, we have

$$\left(\mu_1B^2+\mu_2BG+\mu_3G^2+\mu_4\right)=\left(\mu_5B+\mu_6G\right)^2$$

Given that $G=-1$ (object at infinity), this becomes

$$\left(\mu_1B^2-\mu_2B+\mu_3+\mu_4\right)=\left(\mu_5B-\mu_6\right)^2$$

This quadratic equation can be solved by plugging in the coefficients we found before.

Here we note that the solution we found is under thin lens assumption (zero thickness). A non-zero thickness must be added with necessary adjustments in the surface curvature to maintain the optical power in a surface model for real lens.

1.2 Design Task

Let's complete the design of a single lens as a landscape lens based on the above specifications and parameters by solving the quadratic equation of the shape factor B. There are two solutions, which represent two different configurations of the system: one with stop in front of the lens and the other with the stop behind the lens (Figure 2). For each case you should calculate S_1 and S_2 in order to find $\frac{\bar{h}}{h}$ through the relationship $\frac{\bar{h}}{h}=-\frac{S_2}{S_1}$. Given known h and w, $\bar{h}$ and t can be found.

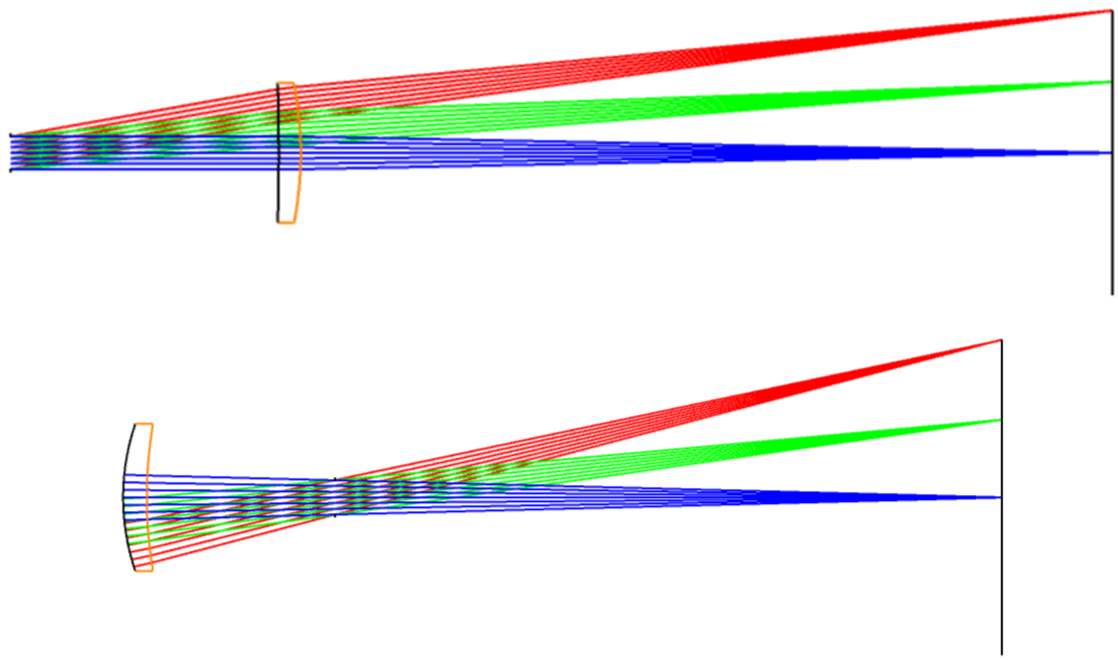

Figure 2. Two configurations of the landscape lens.

Although may not be necessary at this point, you may find using spreadsheet software such as Microsoft Excel more convenient and efficient than using a calculator. With a thoughtful design, such a sheet can be used in the predesign of many lenses. Programming in MATLAB can also provide the same convenience.

1.3 ZEMAX Optimization

Given the simple structure and the effectiveness of the ZEMAX global optimization, the two solutions described above can be found through a direct global search starting with a flat glass plate. Follow the procedure below:

1. Create a new lens design in ZEMAX OpticStudio. Use the default wavelength of 0.55 nm, Use “Float by Stop Size” as the aperture type with object at infinity. Define field points at angles of 0°, 10°, and 20°.
2. Insert one stop surface (surface 1) and two flat surfaces (surface 2 and 3). The semi-diameter of the stop and its distance to the next surface should be set according to the first solution above. Use N-BK7 as the glass type with a thickness of 3 mm. Place the image plane 100 mm away from surface 3.
3. Set the radius of surface 2 and 3 and the thickness of surface 2 to be variable. Open the Optimization Wizard and set the following: Image Quality “Spot”, Glass Min 2, Max 5, Edge Thickness 2.
4. Run Global Search and wait until the merit function on the right does not change. It should not take long.
5. Save the results and repeat steps 1-4 to find the second solution.

In this design, the results from the global search should be very good. This is serendipity in ZEMAX due to the low degree of freedom in the system. Study the Seidel diagram and see how the coefficients from each surface balance each other. Also compare the ZEMAX results with the analytical solutions in surface structures and Seidel coefficients. Discuss the origin of the difference in the Seidel coefficients if there are discrepancies.

1.4 Submission

Submit the calculations and the relevant ZEMAX file. The calculations can be either scanned from scratch paper or in Excel or MARLAB file.

2. Design of an Achromatic Doublet

2.1 Theory

The design of doublets is relatively straightforward with a clear procedure. Doublets are used as telescope objectives, aplanatic, achromatic or apochromatic. They are also indispensable as achromatic modules in two-component and four-component systems, and in micro-objectives. Although the original Cooke triplet consisted of single lenses, later members of the triplet family comprised doublets. Designing a simple achromatic doublet encompasses many of the tricks and pitfalls of optical design. Once you have finalized a design of an achromatic doublet lens, you are safe to drive on the highway of optical design.

A doublet lens is composed of two lens components, one of “crown” glass, a low refractive index, low dispersion glass, and the other of “flint” glass, a high refractive index, high dispersion glass. Compared with singlets, doublets introduce more degrees of freedom for better correction of aberrations. A doublet can simultaneously correct axial chromatic aberration (at two wavelengths) and spherical aberration. When coma is also corrected, we have an aplanatic doublet.

2.1.1 Thin Lens Predesign

With a thin doublet, the correction of axial chromatic aberration (LCA) requires

$$C_1 = h^2\left(\frac{K_1}{V_1} + \frac{K_2}{V_2}\right) = 0$$

where K_1 and K_2 are the power of the two constituent lenses, V_1 and V_2 are the Abbe number of the two glasses, and h is the height of the marginal ray determined by the size of the entrance pupil. The combined power of the doublet is $K = K_1 + K_2$. This leads to the distribution of the optical power between the two component lens as

$$K_1 = \frac{V_1}{\Delta V}K \text{ , } K_2 = -\frac{V_2}{\Delta V}K$$

in a crown-in-front configuration, and vice versa in a flint-in-front configuration, where $\Delta V = V_1 - V_2$ is the difference in the Abbe number.

An achromatic doublet lens is corrected for LCA at two wavelengths. A typical chromatic focal shift is shown in Figure 3, which is the signature of achromatic doublets and should be used to verify the success of a design. The non-zero focal shift at the wavelength in between the two corrected wavelengths is termed secondary spectrum, which can be evaluated as

$$\Delta f = \frac{\Delta P_d}{\Delta V} f$$

where $\Delta P_d = P_{d1} - P_{d2}$, and P_d is partial dispersion defined by

$$P_d \frac{n_F - n_d}{n_F - n_C}$$

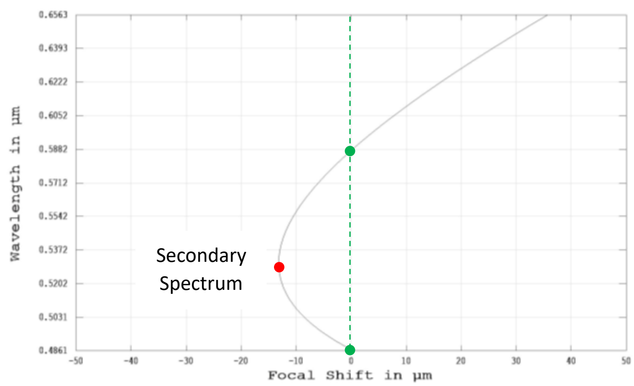

Figure 3. Example chromatic focal shift of an achromatic doublet with secondary spectrum.

Now that we have determined the optical powers K_1 and K_2, we need to correct the aberrations, which are functions of the shape factors B_1, B_2 and position factors G_1, G_2. Since the position of the object is fixed, let's determine G_1, G_2 first. With the object located at the infinity, at the first lens we have $s_1 = -\infty$ and $s_1' = f_1 = 1/K_1$, and thus $G_1 = (s_1' + s_1)/(s_1' - s_1) = -1$. At the second lens, the object is at the focal point of the first lens, thus $s_2 = f_1 = 1/K_1$ and by the lens equation we have $s_2' = 1/(K_1 + K_2) = 1/K$, which leads to $G_2 = (K_1 + K)/(K_1 - K)$. With the position factors determined, we can now correct the aberrations using the shape factors B_1, B_2.

To correct the aberrations, we write

$$S_1 = S_{11} + S_{12}$$

where

$$S_{11} = \frac{1}{4} h^4 K_1^3 \left(\mu_{11} B_1^2 + \mu_{21} B_1 G_1 + \mu_{31} G_1^2 + \mu_{41} \right)$$

$$S_{12} = \frac{1}{4} h^4 K_2^3 \left(\mu_{12} B_2^2 + \mu_{22} B_2 G_2 + \mu_{32} G_2^2 + \mu_{42} \right)$$

are the spherical coefficients for the front and rare lens component, respectively, and

$$S_2 = S_{21} + S_{22}$$

where

$$S_{21} = -\frac{1}{2} h^2 K_1^2 H \left(\mu_{51} B_1 + \mu_{61} G_1 \right)$$

$$S_{22} = -\frac{1}{2} h^2 K_2^2 H \left(\mu_{52} B_2 + \mu_{62} G_2 \right)$$

are the coma coefficients for the front and rare lens component, respectively.

An aplanatic doublet must have $S_1 = S_2 = 0$. From $S_2 = 0$ we can find a linear relation between B_1 and B_2, with which we can eliminate one of the form factors from the equation $S_1 = 0$ and reach a quadratic equation for B_1 or B_2. The unknown can then be solved. Once B_1 (or B_2) is known, B_2 (or B_1) can be calculated from $S_2 = 0$. For each component lens, the curvatures of the doublet can be calculated with

$$c_{i1} = \frac{1}{2}\left(B_i + 1\right)\frac{K_i}{n-1}$$

$$c_{i2} = \frac{1}{2}\left(B_i - 1\right)\frac{K_i}{n-1}$$

where $i = 1, 2$.

2.1.2 Cemented Doublet

Although air-spaced doublets enjoy a superior aberration correction and a higher optical damage threshold, very often the two component lenses in a doublet are cemented for a “solid” lens with lower production cost. In an air-spaced doublet, we have in principle two degrees of freedom available for the correction of coma and spherical, namely the bending factors B_1 and B_2. With a cemented doublet, B_1 and B_2 are linked together as

$$\frac{B_1 - 1}{n_1 - 1} V_1 = -\frac{B_2 + 1}{n_2 - 1} V_2$$

which follows directly from the requirement of equal curvature at the two surfaces of the cementing side, i.e. $c_2 = c_3$ (the cementing condition) and the curvature formula above. We will therefore suffer one less degree of freedom by obeying the cementing condition, which results in a compromise in the aberration correction. Note, however, with an air-spaced doublet this relation will be approximately fulfilled when the airspace is small.

We therefore have two ways of correcting the doublet:

- Obeying the cementing condition and choosing the glasses in such way that spherical and coma are both small enough, or
- Neglecting the cementing condition and correcting spherical and coma.

With the first method we find the classical Fraunhofer and Steinheil doublets. With the second method we also find the Gauss doublet (Figure 4).

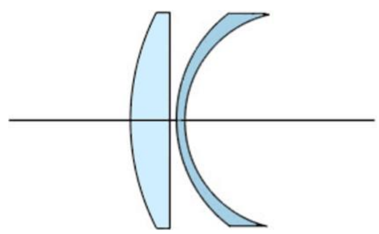

Figure 4. An example Gauss doublet.

2.1.3 Surface Model

Once the thin lens model has been corrected, we need to give thickness to the lenses to obtain a physically sound surface model for real lenses. The addition of thickness, however, will change the optical power. We thus need to adjust the surface curvature to maintain the original power. To give thickness, we insert a thickness between the first and second surface of each lens. For a positive lens, the thickness should be 10–15 % of its diameter, while the edge thickness should be larger than 1.5 mm (sharp edges are difficult to make and to mount). For a negative lens, the central thickness should be no less than 6 % of the diameter.

When thickness is added to a lens element, the optical power will change from its designed value. To correct the change in optical power (within a single lens element), we calculate the new power after thickness insertion as

$$K_i^{(new)} = K_{i1}^{(thin)} + K_{i2}^{(thin)} - \frac{dK_{i1}^{(thin)} K_{i2}^{(thin)}}{n}$$

where $i = 1, 2$, and rescale r_1, r_2, and d by the factor

$$\frac{K_i^{(new)}}{K_{i1}^{(thin)} + K_{i2}^{(thin)}}$$

after which the lens with thickness has the same power as the thin lens before the thickness insertion, i.e., $K^{(thick)} = K^{(thin)} = K_1^{(thin)} + K_2^{(thin)}$.

When the surface model is established with a reasonable starting point, we are set to optimize the system.

2.2 Design Task

Let's design an aplanatic doublet lens of an effective focal length $f = 100$ mm ($K = 0.01$ mm^{-1}) using the glass pair of N-BK7 and N-SF10. The technical data of these glasses can be found online from SCHOTT. We assume in this design that the lens is at the stop with the first surface as the pupil, and the aperture semi-diameter is $h = 10$ mm. The object is located at infinity. Use field points of 0°, 1°, and 2° and F.d.C. wavelengths.

Follow the steps below in your design:

1. Calculate K_1, K_2, G_1, and G_2.
2. Calculate the μ coefficients for each glass type. You can use the previous values of N-BK7.
3. Write out the equations $S_1 = 0$ and $S_2 = 0$. Solve the quadratic equations for the shape factors B_1 and B_2. Usually a pair of solutions exists.
4. For each lens, calculate the surface curvature c_1 and c_2. A curvature that is greater than $5K$ is deemed optically unhealthy and should be discarded.
5. Add a proper thickness to each lens and rescale the parameters to maintain the optical power unchanged.
6. Set up the merit function using the optimization wizard in ZEMAX OpticStudio using spot RMS as the criterion and optimize the design. The glass thickness should be constrained within 2 – 8 mm with edge thickness no less than 1.5 mm. The air thickness should be constrained within 0.1 – 1 mm. Try both air-gapped and cemented cases. You can use the pickup solve in the radius field and zero thickness to implement the cemented case.

2.3 ZEMAX Optimization

Build the surface model obtained above in ZEMAX and run local optimization to improve the performance. Compare the Seidel coefficients with the thin lens model solution.

Doublet is about the most complex system that can still find a solution through ZEMAX global search. Use a pair of parallel plates of 3 mm thick with an air gap of 0.5 mm for a starting point and try the global search in ZEMAX OpticStudio for your luck. Compare the results from above.

In both designs, the operand of "AXCL" (axial color) should be added on top of the default merit functions generated through Optimization Wizard. Use "1" and "3" in the two wave fields, 0 for the target, and "1.0" for the weight. This place axial color shift in the merit function for optimization. The achromatic performance should be verified using the plot of chromatic focus shift. In addition, the operand of “EFFL” (effective focal length) should be added on top of “AXCL” with “2” in the wave field and “1.0” in the weight field. You should use 100 mm as the initial guess for the image distance, which may not be accurate with the effective focal length specified in the optimization. So the “Quick Focus” feature should be used during the first few rounds of optimization.

2.4 Submission

Submit the calculations and the relevant ZEMAX file. The calculations can be either scanned from scratch paper or in Excel or MARLAB file.