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This is a take-home exam emphasizing conceptual understanding of optical design principles and practical implementation in Zemax. You may only ask questions of me, but you are free to use your books and class notes.

Timing: This exam will be available via D2L from Wednesday afternoon (March 8, 2017) until 11 pm on Friday night (March 10, 2017). You should expect to complete the exam in several hours. It must be turned in via D2L no later than midnight on Friday, March 10, 2017.

What to turn in:

Option a) Turn in your hand-written exam to Deb in the ECE Department office (610 Cobleigh Hall) by 5 pm on Friday, March 10, and upload a zipped collection of your Zemax files, with each one named so that it is very clear who they belong to and which part of which problem they relate to.

Option b) Upload to D2L a neatly scanned copy (easily readable – not distorted, poorly lit phone pictures) of your hand-written calculations and notes describing your design approach and results. Also upload a zipped collection of your Zemax files, with each one named so that it is very clear who they belong to and which part of which problem they relate to.

1. (10) Geometric optics fundamentals

A lens with center thickness t = 6 mm and refractive index n = 1.5 has the following radius of curvature values for its front and rear surfaces, respectively:

R_1 = 60 mm

R_2 = 120 mm

a) Calculate the effective focal length of this lens.

EFL = 232.258 mm

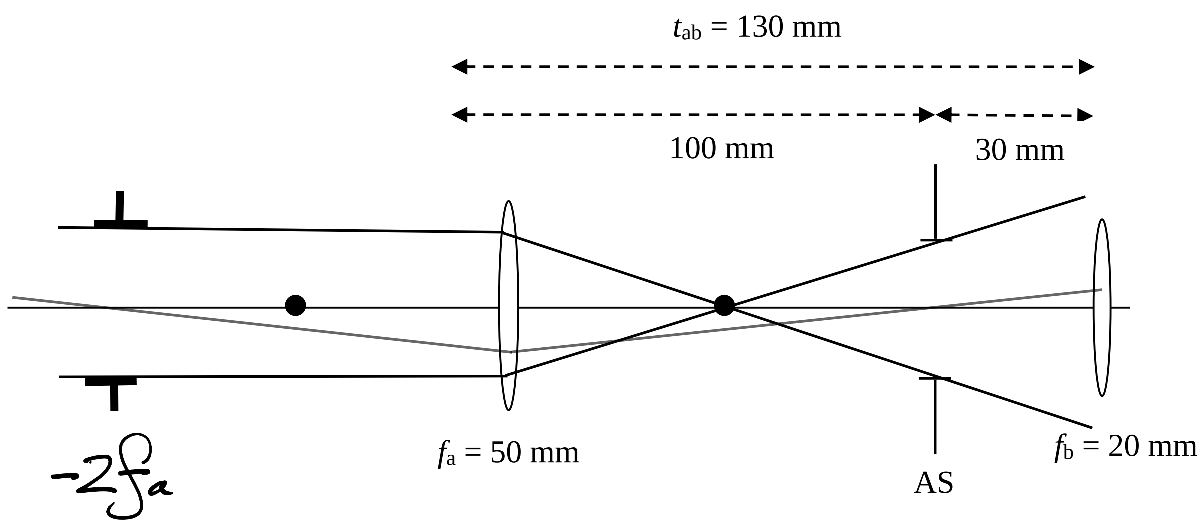
b) Use paraxial ray trace equations to calculate the back focal length and δ', the distance from the back surface to the second principal plane.

BFL = 224.516 mm

$\delta' = -7.742$ mm

2. (10) Entrance pupil

Sketch three rays to find the location of the entrance pupil for the two-lens system below with aperture stop “AS” as indicated below. Each dot marks a focal point of lens *a*.



3. (10) Aberrations

These questions explore your conceptual understanding of Seidel 4th-order wave-front aberrations. Answer quantitatively (i.e., tell me that it increases 3×, not just that it increases) and justify each answer as simply as possible.

a. How does spherical aberration change if the f/# of a lens is reduced from f/4 to f/2 while holding the effective focal length constant? Why?

$\frac{SPHA(f/2)}{SPHA(f/4)} = 16$, quartic in pupil radius.

b. How does spherical aberration change if the field is increased from 1° to 3°? Why?

$\frac{SPHA(3^\circ)}{SPHA(1^\circ)} = 1$, no dependence on field angle

c. How does coma change if the field is increased from 1° to 3°? Why?

$\frac{COMA(3^\circ)}{COMA(1^\circ)} = 3$, linear in field angle.

d. How does astigmatism change if the field is increased from 1° to 3°? Why?

$\frac{ASTI(3^\circ)}{ASTI(1^\circ)} = 9$, quadratic in field angle.

4. Reverse-Telephoto Design

Design a simple **reverse-telephoto** (wide-angle) lens with the following properties:

- Effective focal length = EFL = f_e = 20 mm
- Back focal length (or distance) = BFL = 30 mm
- Lens separation = $t_{a,b}$ = 15 mm
- Image space $f/\#$ = 8
- Field angles = 0°, 14.14°, 20°
- Wavelength = 0.55 μm (yellow-green)

Design goal: maintain all first-order properties (except when noted) and achieve **rms spot sizes ≤ 10 μm** (use 'dithered' spot diagram setting).

a. (10)

i. Calculate the optical power of two thin lenses to achieve the stated EFL, BFL, and t_{ab}. Show your work and explain any assumptions.

$\phi_1 = -0.033\ mm^{-1}$

$\phi_2 = 0.056\ mm^{-1}$

ii. Calculate the radii of curvature for your two thin lenses, assuming equi-convex or equi-concave elements, with the first lens made of BK7 and the second lens made of SF2 glass.

$R_{1a} = -R_{1b} = -31.111\ mm$

$R_{2a} = -R_{2b} = 23.463\ mm$

iii. Enter your thin-lens design into Zemax with an aperture stop located just before the front surface of the 2nd lens. Save your file as *Exam1_S17_name_1o1b.zmx* ('name' is your last name).

EFL = 20.000 mm

BFL = 30.000 mm

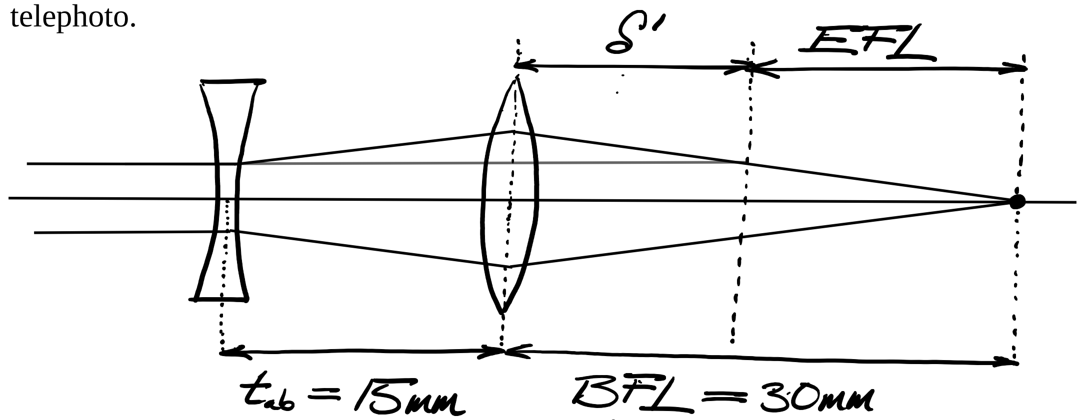
f/# = 8.000

b. (10) Calculate principal plane locations (ok to use equations).

d’ = 10.0mm (distance from last thin lens to p’)

d = 16.667mm (distance from first thin lens to p)

Sketch your lens, showing locations of the lenses, focal points, and principal planes. Given what you know about a telephoto design, explain why it is called a reverse-telephoto.



principal planes behind lens ⇒ reverse telephoto.

c. (10 points) Insert 1-mm thickness for your two lenses. Place a variable on the last lens surface curvature and optimize to restore your EFL and BFL while also maintaining t_{ab}. Verify that the “total track” (length) is longer than the EFL.

Exam1_S17_name_2o1b.zmx → *Exam1_S17_name_2o1a.zmx*

Brief explanation of how you did this in Zemax:

- Used M-Solve to find location of paraxial image plane
- Used EFFL operand to optimize EFL.
- Used OPTH and diff as in HW to optimize BFL.

Write down the values for the following first-order properties (from Zemax):

EFL = 19.921mm

BFL = 30.052mm

t_{ab} = 15.000mm (distance between lens *a* and lens *b*)

Total track = 47.052mm

From Zemax, write down the following:

rms spot sizes: 15.2, 72.6, 136 µm (use "dithered," "centroid,")

Do these spot sizes meet your design goal? No

Which Seidel aberration is dominant? Distortion (give its name)

List the values for the following Seidel aberration coefficients:

W_{040} = 0.729 units = waves
W_{131} = -1.165
W_{222} = 6.836
W_{311} = 51.609

Is this solution practical? yes Explain:
It could be built, lenses are thick enough.

What do the ray fans and spot diagrams tell you? (briefly describe shape of ray fans and spots, and tell what the shapes indicate … including the presence of higher-order aberrations if appropriate):

The ray fans have a very linear shape, indicative of the large amount of distortion.
Astigmatism is also observable by comparing fans in x and y directions.

Additional comments:

d. (10 points) Place variables on the four lens surface curvatures, load the default merit function, and optimize to maintain the transverse ray aberration with respect to the centroid (TRAC) while maintaining first-order properties.

Exam1_S17_name_3o1b.zmx → *Exam1_S17_name_3o1a.zmx*

Briefly describe what occurred in this optimization cycle.

- The first order optical properties were able to be satisfied.
- The RMS spot size is now the correct order of magnitude.

EFL = 20.000mm
BFL = 30.000mm
t_{ab} = 15.000mm
rms spot sizes: 14.6, 14.5, 14.7 µm

Do these spot sizes meet your design goal? No

Which Seidel aberration is dominant? Distortion (give its name)
Is this different from before? No.
Why? (explain briefly the main reason):

- TRAC does not optimize for distortion.
- The spot size could be zero and the distortion could be nonzero.

List the values for the following Seidel aberration coefficients (ok to read from Zemax):

W_{040} = 0.697
W_{131} = 1.002
W_{222} = -1.042
W_{311} = 87.29

Is this solution practical? yes. Explain:

The lens is still a reasonable size and probably could be manufactured.

What do the ray fans and spot diagrams tell you? (briefly describe shape of ray fans and spots, and tell what the shapes indicate):

Large astigmatism off axis.
Cubic shapes suggest spherical.

Additional comments:

e. (10 points) Place variables on the distance from the first lens to the stop and the distance from the stop to the second lens. Constrain the stop to remain between lenses and constrain the total distance between lenses to be no more than 30 mm. With variables also on the curvatures, optimize with TRAC while maintaining first-order properties.

Exam1_S17_name_4o1b.zmx → *Exam1_S17_name_4o1a.zmx*

Explain what you did and what happened (did this help? Why or why not?):

- Used the ABLT operand in conjunction with OPTH and DIFF to restrict the sum of the thickness of the back of the lens and the stop to < 30mm.
- This improved the RMS spot size by about 30%

EFL = 20.000 mm
BFL = 30.000 mm
t_{ab} = 30.000 mm
Distance from 1st lens to stop 23.287 mm
Distance from stop to 2nd lens 6.713 mm

rms spot sizes: 8.23, 11.1, 11.2 μm

Do these spot sizes meet your design goal? No

Which Seidel aberration is dominant? Distortion (name)

List the values for the following Seidel aberration coefficients (ok to read from Zemax):

W_{040} = 0.396
W_{131} = 1.127
W_{222} = -0.572
W_{311} = 116.112

Is this solution practical? Yes Explain:
althougth the lens is starting to look thin.

What do the ray fans and spot diagrams tell you? (briefly describe shape of ray fans and spots, and tell what the shapes indicate):

- Coma is most prevalent on the intermediate field angle, seen from the quadratic structure.
- Astigmatism dominates the maximal field angle, seen by comparing plots in x and y.
- All field angles display spherical.

Additional comments:

f. (10 points) Now let the BFL vary. Reoptimize with variables on the curvatures, inter-lens separation (constrained to be no more than 30 mm), and BFL, while maintaining EFL = 20 mm.

Exam1_S17_name_5o1b.zmx → *Exam1_S17_name_5o1a.zmx*

Explain what you did and what happened. If you must have BFL > 25 mm (a mechanical requirement based on camera dimensions), will this design work?

- Took the weight of the DIFF operand constraining the BFL to ~~zero~~.
- Further decreased spot size by adding dummy image surface.

EFL = 20.000 mm
BFL = 28.192 mm
t_{ab} = 25.118 mm
Track length 55.310 mm

rms spot sizes: 4.08, 5.19, 6.91 μm

Do these spot sizes meet your design goal? Yes

Which Seidel aberration is dominant? Distortion (name)

List the values for the following Seidel aberration coefficients (ok to read from Zemax):

W_{040} = 0.387
W_{131} = 0.727
W_{222} = −0.172
W_{311} = 100.805

Is this solution practical? Yes
Explain:
I don't know how thin you can make lenses

What do the ray fans and spot diagrams tell you? (briefly describe shape of ray fans and spots, and tell what the shapes indicate):

- Coma still most dominant in the intermediate field.
- Astigmatism still visible in maximal field. May be coupled to distortion.

Additional comments:

g. (10 points) Explore! See how small you can allow the f/# to become while still meeting the 10 μm rms spot size requirement ... what if we can allow 15 μm spots? Everything but the EFL can change as long as the resulting system is practical.

Show me what you try and explain how you got your best result and how good it is:

We were holding the f/# using the aperture value. To minimize the f/#, we will decrease the f/# by a small amount, reoptimize and repeat, until we can no longer get the spot size below the target value.

f/6.73 (10μm spot),
f/5.54 (15μm spot)

How low could you go for the f/#? ___________

Remember: customers generally want "fast" optics, meaning small f/#.

Based on your experience with this design, what is the consistently biggest problem (i.e. the largest aberration) and how will that affect the images?

Distortion is the biggest problem, and it will result in a "fish-eye" effect, where the image

Additional comments: appears as if it is projected onto a sphere.