Engineering Design Study: A Lens Athermalized over a Wide Range of Temperatures

Journée thématique Calcul Optique

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Synopsys

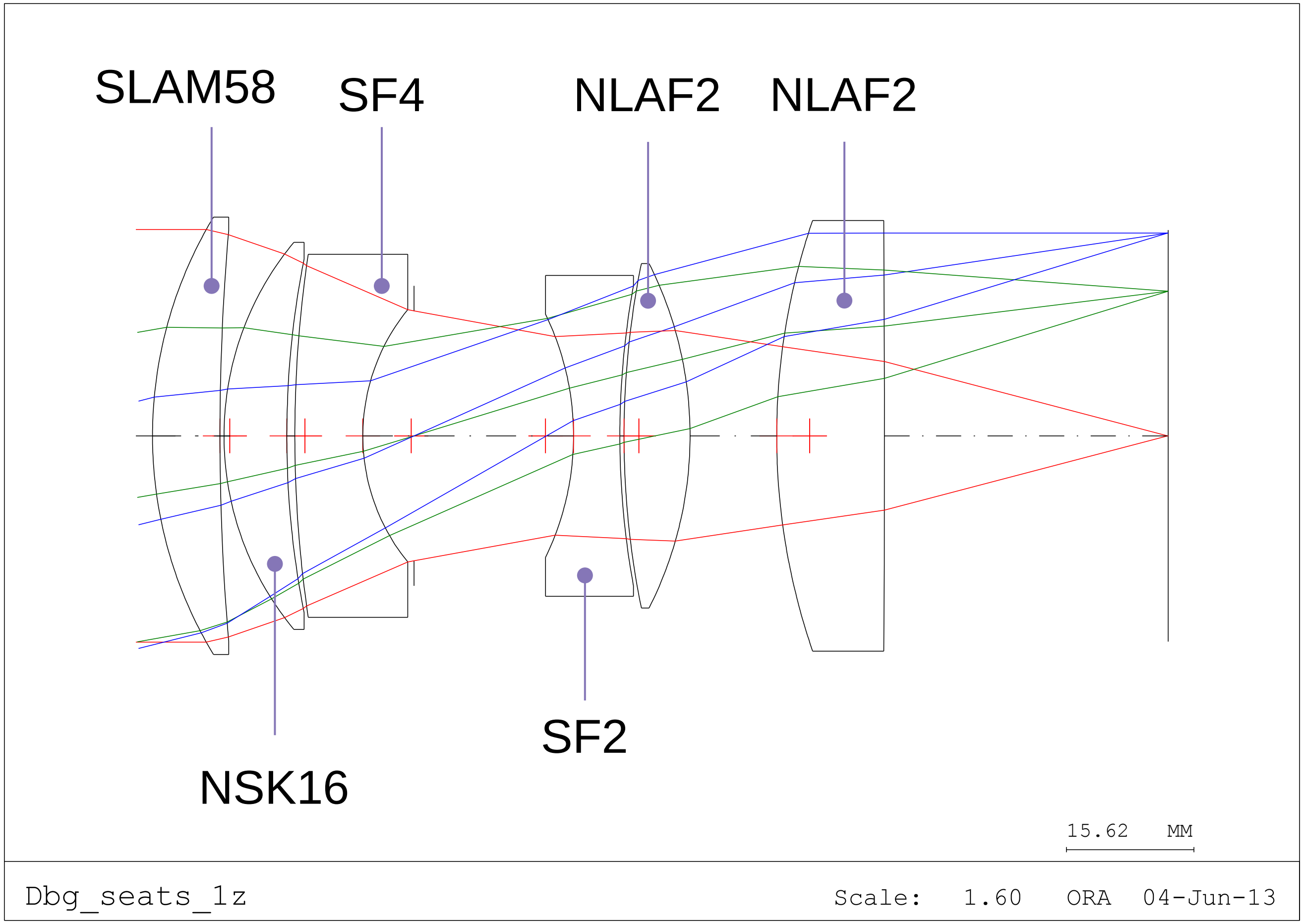
Overview

- Synopsys Engineering recently completed the design of a lens athermalized over a 200°C temperature range.
- This presentation explains the design procedure using a Double-Gauss as a non-proprietary design example.
- For this exercise, we will assume a temperature range from -100°C to +100°C
- Factors considered:
  - Mounting technique
  - Variation of dn/dT over temperature
  - Method of selecting glasses

The Starting Point Lens

F/2
Field Diameter: 28°

Wavelengths:
d, F, C, equally weighted



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Thermal Effects, Analysis & Design Tools

- Before discussing the procedure for athermalization, we first estimate the size of the problem

On the following slides:
CTE = Coefficient of Thermal Expansion (α)
dn/dT = Change of refractive index with temperature

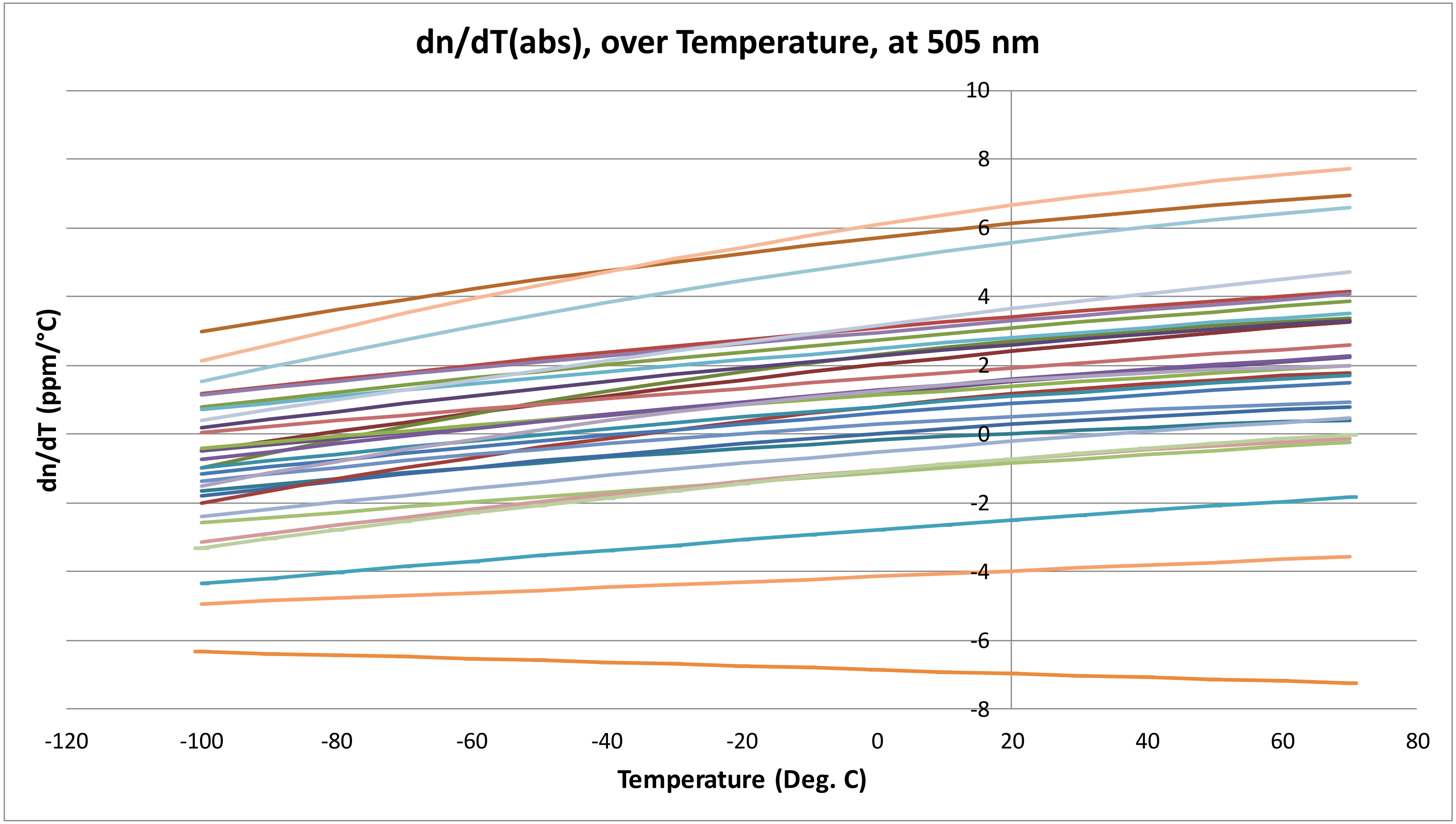
Thermal Effects Example: NBK7 Singlet

- Lens radii scale up as CTEglass (≈7 ppm/°C for NBK7)
  - This tends to increase the focal length
- Index increases as dn/dT (≈3 ppm/°C , relative to air, for NBK7)
  - It may seem counterintuitive that the index increases with temperature, but this is indeed the trend for almost all optical glasses
  - This tends to shorten the focal length
- From the above, the focal length of an NBK7 singlet increases as 7-3 = 4 ppm/°C
- The housing expands as CTEh (≈24 ppm/°C for Aluminum)
  - (Steel is better, but the customer wanted AL)
- The housing pushes the detector away more rapidly than the focal length is increasing (24-4=20 ppm /°C)
- For 100 mm EFL, we expect:
  - A focal error of +240 µm at -100°C
  - A focal error of -160 µm at +100°C
- At F/2, these represent blur diameters of 120 µm and 80 µm, respectively

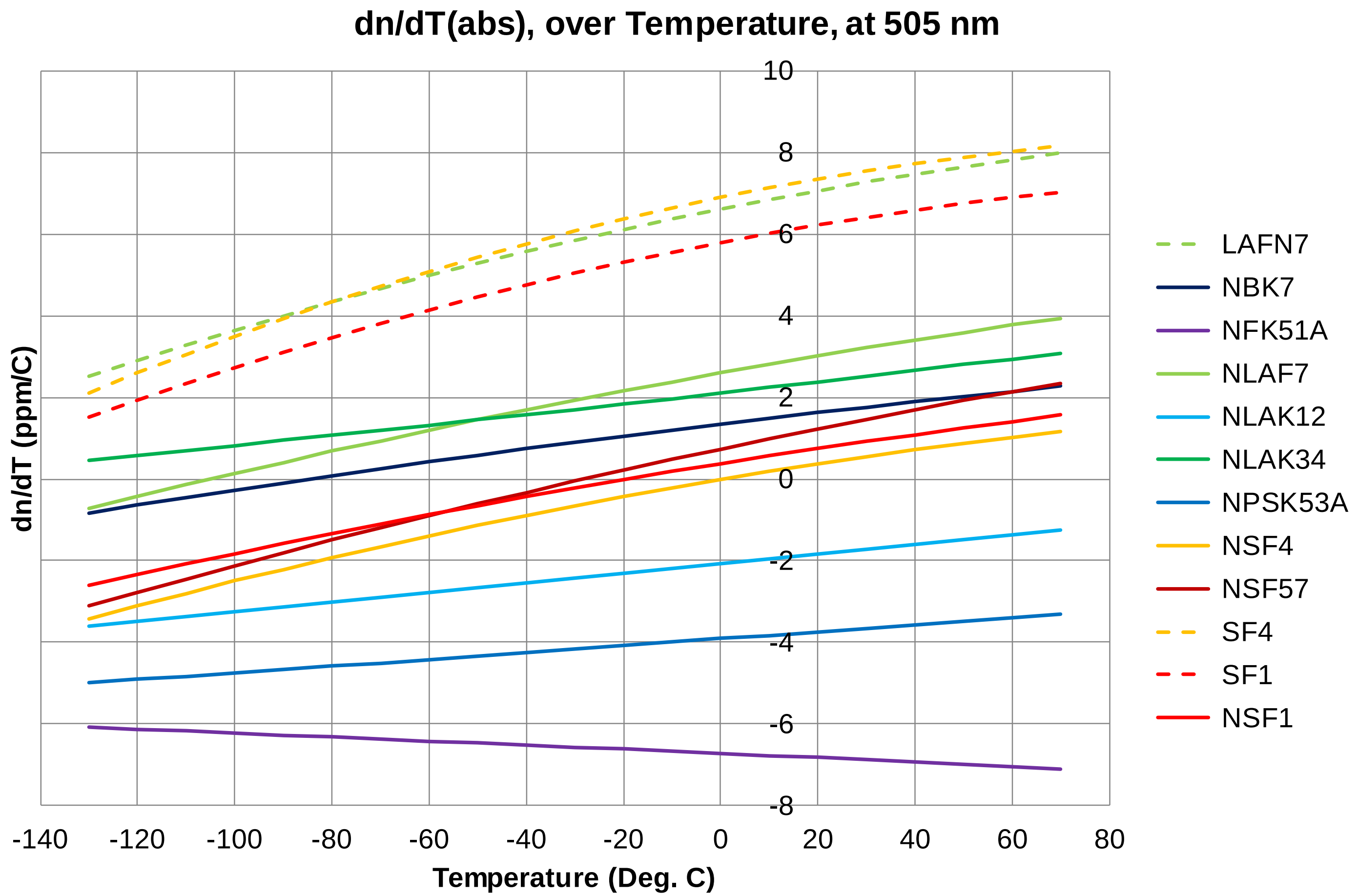
Passive Athermalization

- For a singlet, we want the focal length to expand more rapidly with temperature
  - Choosing a housing material (such as stainless steel) with a smaller CTE would also help, but the customer selected aluminum as the housing material
- In a real system, it is a little more complex than this singlet example because of spacer changes, but roughly speaking:
  - We would like a NEGATIVE dn/dT for positive (crown) elements… to weaken the + elements
  - We would like a POSITIVE dn/dT for negative (flint) elements… to strengthen the - elements
- What dn/dTs are available?
  - The next slide shows the ABSOLUTE dn/dT values of some glasses
  - These need to be divided by the index of air to get relative index, but the trend is the same…

dn/dT (absolute)
…for many glasses



dn/dT (absolute)
…for a selected set of glasses



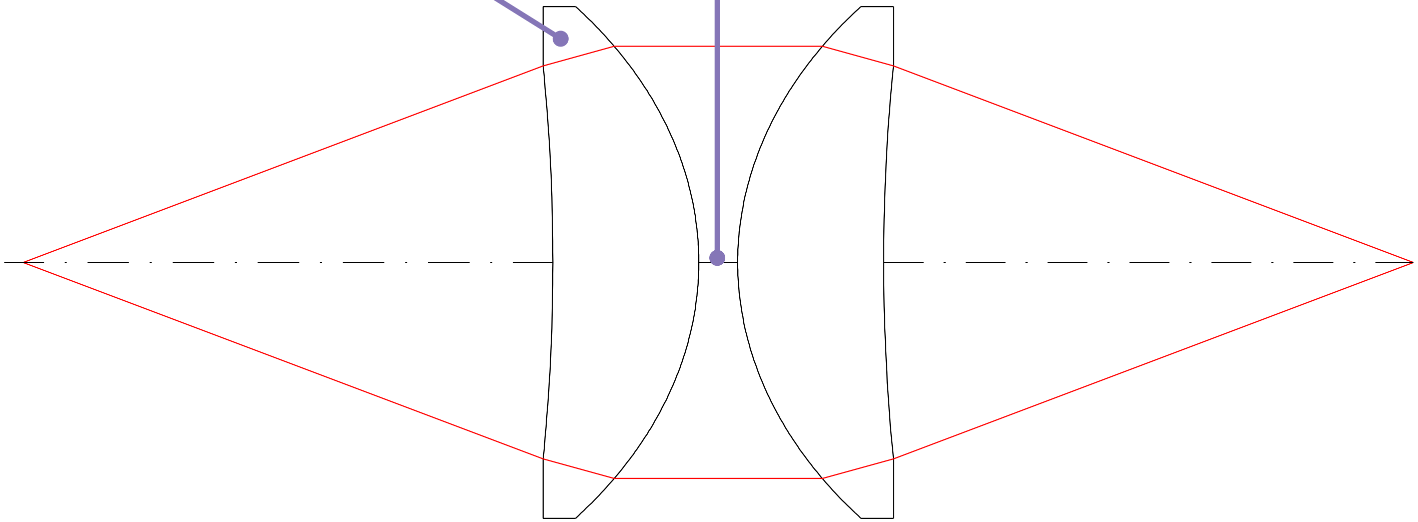
Real Systems are More Complex!

- At F/2, we need to consider not only the thermal change of focal length, but also the thermal change of aberrations
- In addition, a multi-element lens has spacers between the elements that change with temperature, so the singlet example, though instructive, is not accurate.
- **We need a multi-temperature model of the system that model of the system that is accurate and remains accurate as the radii, thicknesses and spacings change**
- The next few slides describe the analysis and design tools currently available.

Thermal Pickups

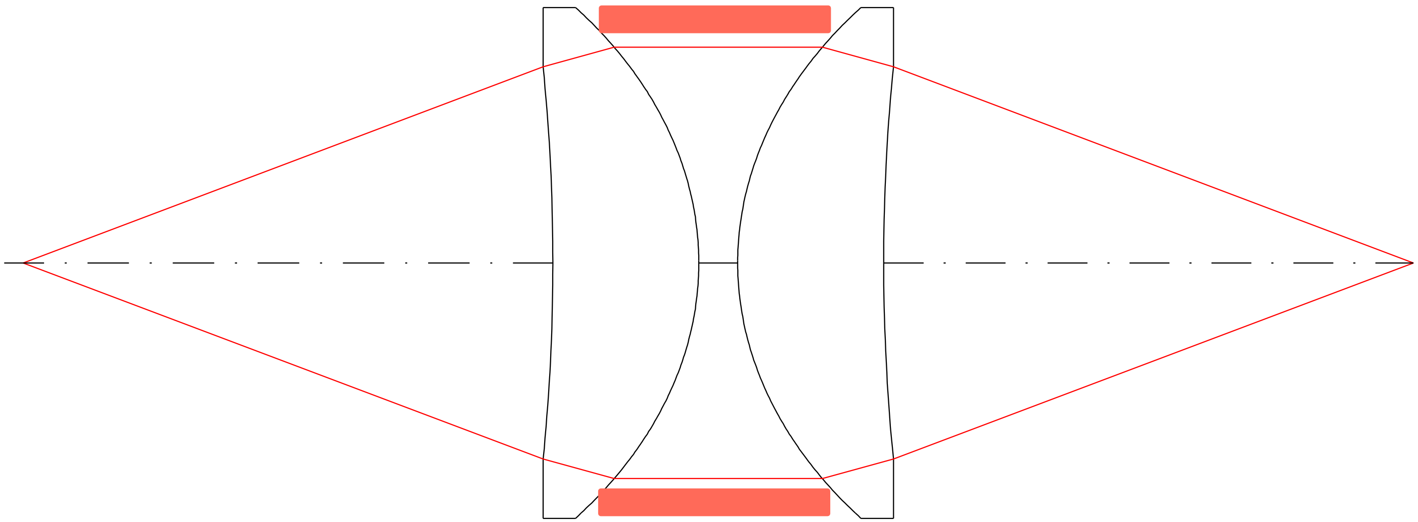
Lens thicknesses and radii vary according to the CTE of the glass

Lens separations vary according to the CTE of the housing (e.g., aluminum)



Thermal Pickups: A Problem

The mechanical structure that separates the lenses contacts the lenses at their edges.



The distance over which the CTE of Aluminum is applied is much longer than the vertex-to-vertex separation of the lenses!

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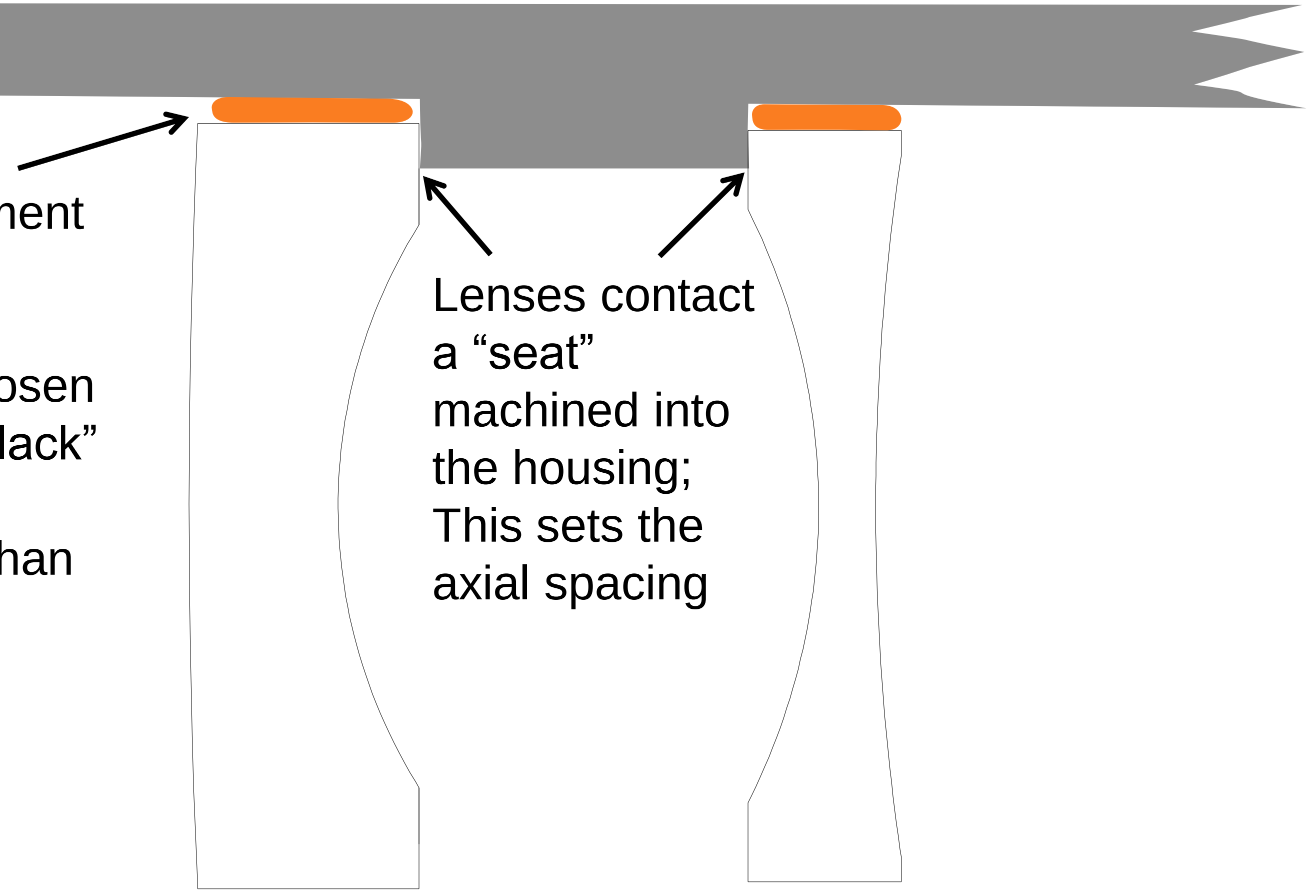
Mounting Details

Elastomeric Cement

Thickness of the cement layer chosen to “take up the slack” as the housing expands faster than the lenses



The expansion of the air gap depends on the CTE of the housing and the distance between the *seats*, not the distance between the lens vertices

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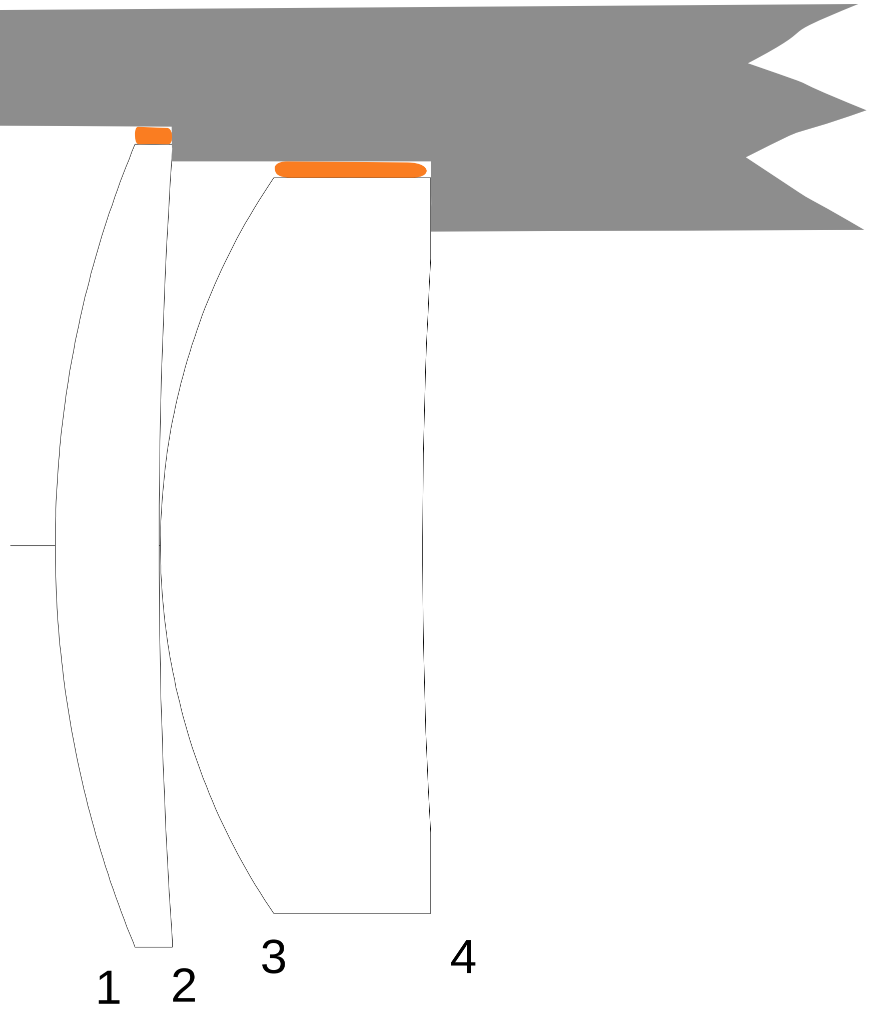
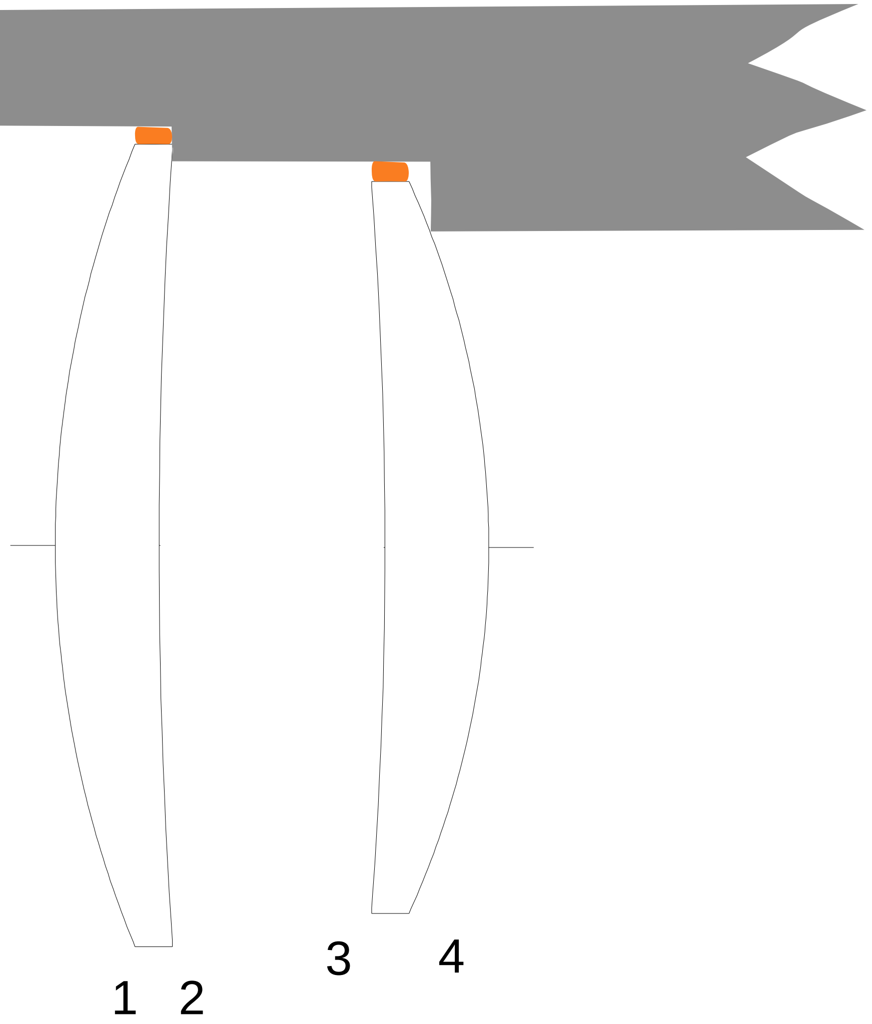
A More Complex Case…

It is a little more complex when the seats are not on neighboring surfaces:

- The distance between the seats for Surfaces 2 and 4 is set by the CTE of the housing and the distance between the seats
- The vertices for Surfaces 2 and 4 move according to the CTEs of the glasses and the sag distances
- The axial thicknesses of the elements changes according to the CTEs of the glasses
- The positions of Surfaces 1 and 3 (vertices) change according to the above



More Complex Still…



If a seat contacts a convex surface, then the motion of the surface vertex (and therefore the **PIK** scale factor) is even more complex because the contact point of the seat moves away from the axis.

If we assume that the lens stays in contact with the seat, then the equation on the next slide holds…

Seats on Convex Surfaces

- If a seat contacts a convex surface then the motion of the surface vertex (and therefore the **PIK** scale factor) is even more complex!
- The housing expands in both the longitudinal direction and the radial direction
- The contact point of the lens with the seat moves away from the axis
- If we assume that the lens stays in contact with the seat, then the scale factor that governs the expansion of the lens sagitta is approximately*:

$$ScaleFactor = (Sag_{(at\ \Delta T)}/Sag_{(at\ 20)})$$

where

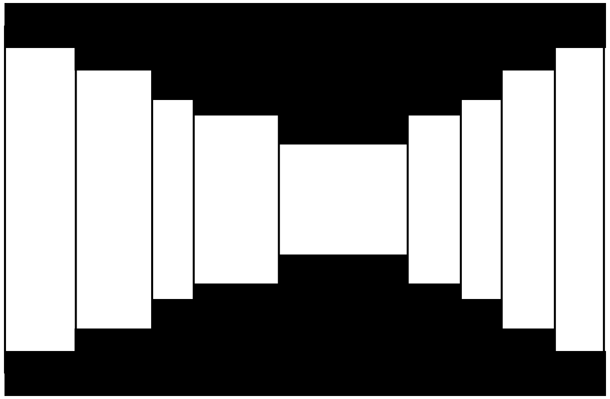
$$Sag_{(at\ 20)} = R\left[1 - \sqrt{1 - (h/R)^2}\right]$$
$$Sag_{(at\ \Delta T)} = R'\left[1 - \sqrt{1 - (h'/R')^2}\right]$$
$$R' = R\left(1 + \Delta T * CTE_{glass}\right)$$
$$h' = h\left(1 + \Delta T * CTE_{housing}\right)$$

*Calculated as above, this formula is exactly correct to the initial radius value R, and is approximately correct for modest changes in R. For large changes in R, the relationship between R and R' cannot be represented perfectly with a Pickup. (We will later see that this small error is negligible.)

Improved System Model (ENV_PIK)

- The macros assume an “hourglass” shaped housing, with a single “waist”.
  - The lenses before the waist are loaded from the front and have seats that contact the surface 0.5 mm* outside the clear aperture in each case
  - The lenses after the waist are loaded into the rear, and have seats that contacts the surface 0.5 mm* outside the clear aperture

*(this value is user-selectable)



Modeling Lens Seats

- For this assignment, we created a new suite of macros (**ENV_PIK.seq**) that models the lens seats correctly, using a set of dummy surfaces to represent the lens seat locations.
- Macro **ADD_SEATS** inserts the dummy surfaces
- Macro **ENV_PIK** sets up multiple “zoom” positions, each representing a different temperature and/or pressure.
  - The user can optimize the variables of Zoom Position 1; ENV_PIK uses pickups with appropriate scale factors to adjust the variables of the other zoom positions appropriately.
- Macro **PULL_SEATS** removes the dummy surfaces from the system

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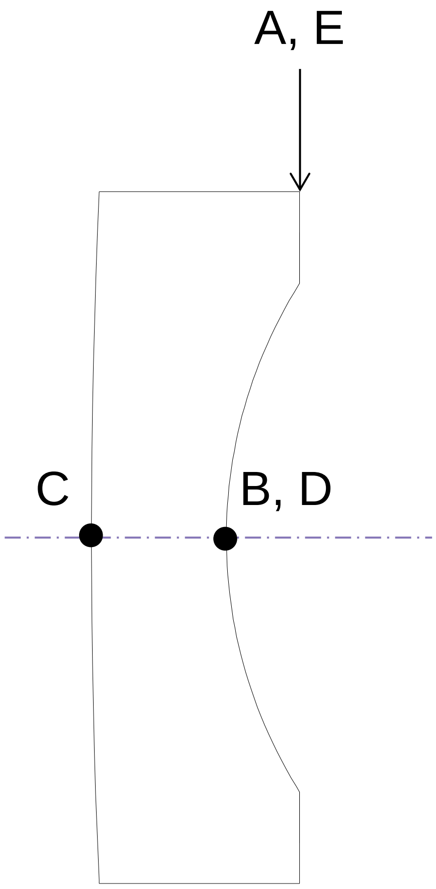
Dummy Surfaces Added to the Lens Model

(Elements before the Waist)

- To model a system accurately, we use 5 surfaces per element (3 of which are dummies)
- For surfaces before the waist, The surfaces are
  - A: a dummy at the seat location, 0.5 mm outside of the clear aperture of the rear surface
  - B: a dummy at the location of the rear surface vertex
  - C: a real surface at the location of the front surface vertex
  - D: a real surface at the location of the rear surface vertex
  - E: a dummy at the seat location (Same as A, but “after” the surface)



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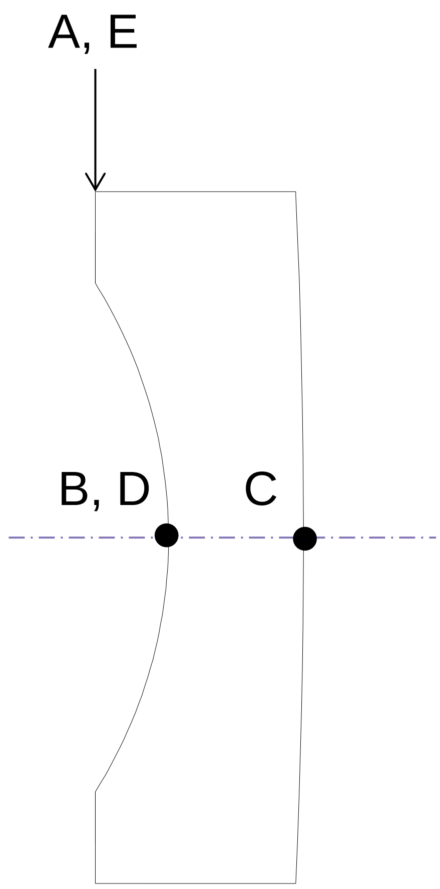
Dummy Surfaces added to the Lens Model

(Elements after the Waist)

- For surfaces after the waist, the surfaces are
  - A: a dummy at the seat location, 0.5 mm outside of the clear aperture of the front surface
  - B: a real surface at the location of the front surface vertex
  - C: a real surface at the location of the rear surface vertex
  - D: a dummy surface at the location of the front surface vertex (same as B)
  - E: a dummy at the seat location (Same as A, but "after" the surface)



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Expansion Details (Why we used 5 surfaces per element)

- Regardless of whether the surface is before or after the waist:
  - The distance AB is a sag distance
    - If Concave, Scales with CTE_{glass}
    - If Convex, scales with the equation on Slide 22
  - The distances BC and CD are the axial thickness of the lens (equal, but opposite in sign)
  - The distance DE is a sag distance
    - Same rules apply as for AB

Revisiting dn/dT

For a 200° temperature range, it is important to get it right!

- dn/dT varies with temperature, given by the formula

$$\frac{dn}{dT} = \left(\frac{n(\lambda, T_0)^2 - 1}{2n(\lambda, T_0)}\right)\left[D_0 + 2D_1\Delta T + 3D_2(\Delta T)^2 + \frac{E_0 + 2E_1\Delta T}{\lambda^2 - (\lambda_{tk})^2}\right]$$

Where

D_0, D_1, D_2, E_0, E_1 and λ_{tk} are constants provided by the glass manufacturer, and $\Delta T = T - T_0$

- The next slide is a reminder of what the dn/dT curves look like…

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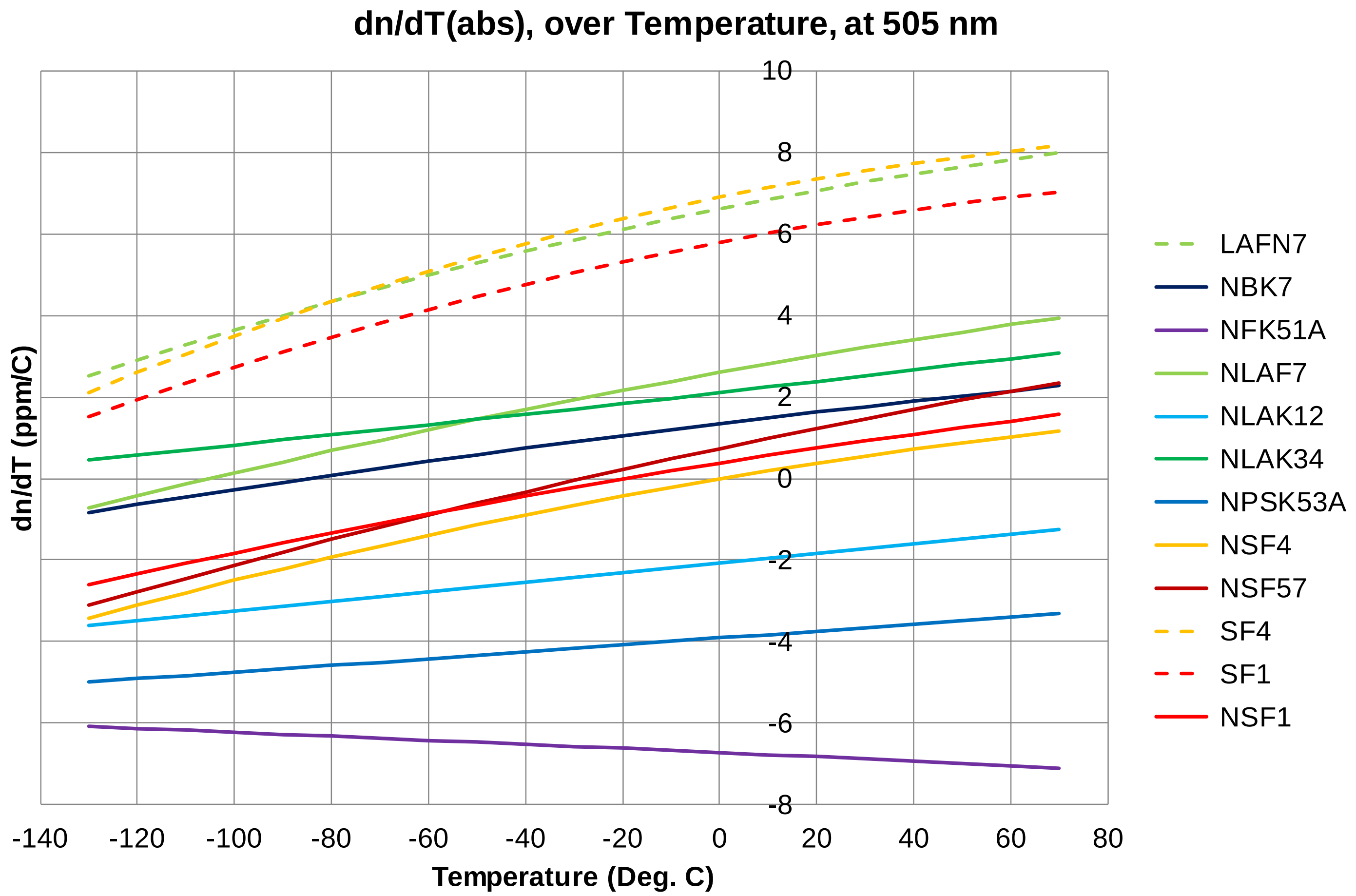
dn/dT (absolute)
…for a selected set of glasses



dn/dT

What value to use?

- The values vary strongly over temperature:
  - The dn/dT values for many glasses even change signs between 20°C and -100°C!
- It is not appropriate to use the value at 20°C for this wide a temperature band!
- Therefore: Integrate the dn/dT curve to obtain the index at any desired temperature:

$$\Delta n = \int_{T_0}^{T} dn = \int_{T_0}^{T} \left(\frac{dn}{dT} \right) dT$$

- Interestingly, the dn/dT curves for many of the glasses are positive near 20°C but become negative at negative temperatures. This means the integrated value (for those glasses) may be substantially lower than the value listed for -20°C… or even negative!

What about the CTE Value?

- Schott lists two values for each glass:
  - CTE -30/+70 is “valid” from -30°C to +70°C
  - CTE 20/300 is “valid” from +20°C to +300°C
- For NBK7 the two values are 7.1E-6/°C and 8.3E-6/°C
- The values differ significantly, so it is clear that the CTE value varies with temperature
  - Between +20°C to +70°C, both Schott values are “valid”
  - Which to use???
- Ideally, we would integrate the CTE curve as we did the dn/dT curve…but we don’t have the data!
- The best we can do is use the CTE -30/+70 values (for Schott)
  - Schott gives CTE -30/+70 values
  - Ohara gives CTE -30/+100 values

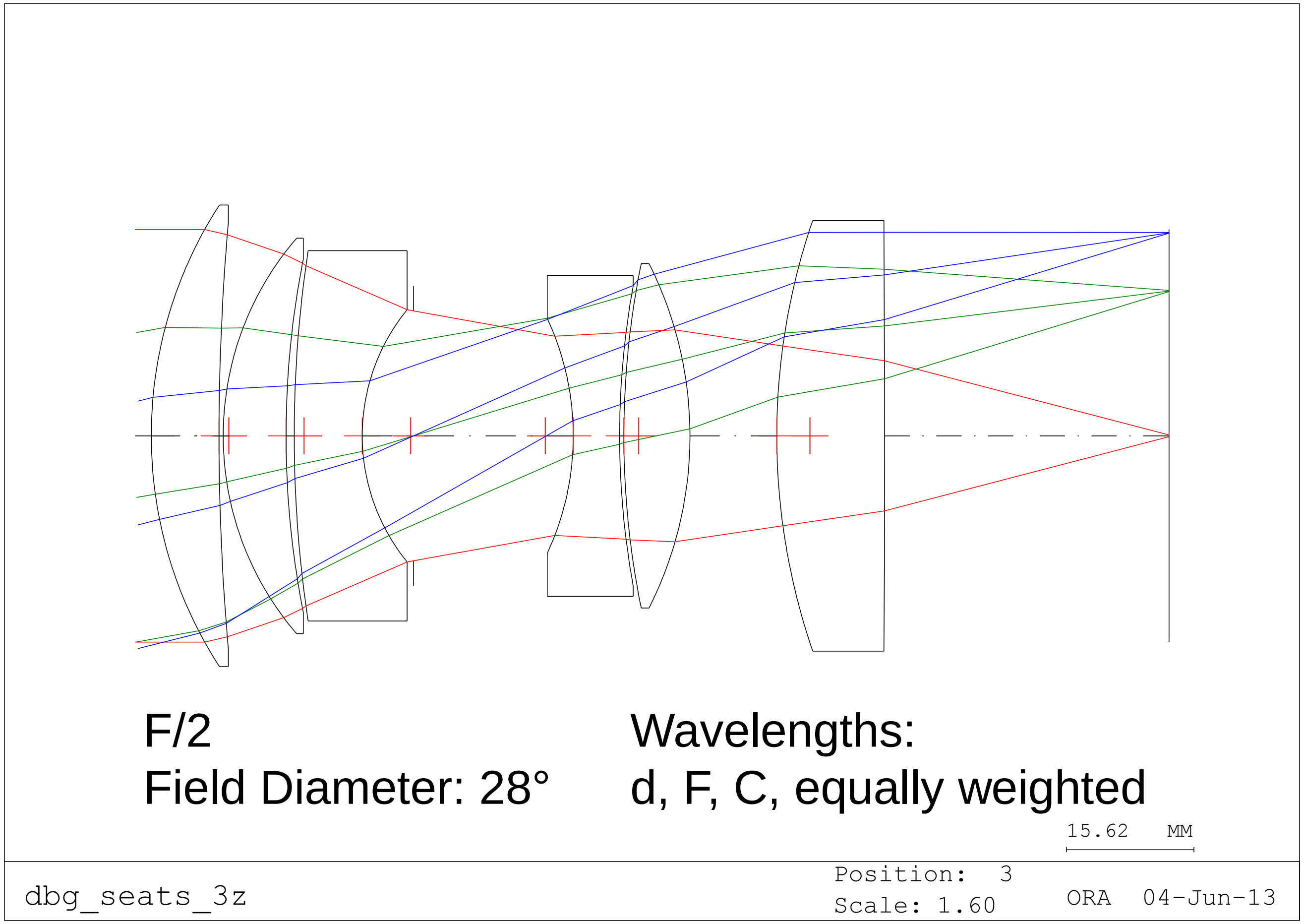
New Macro ENV_PIK

- Builds a zoomed (multiconfiguration) model of the system (up to 9 zooms)
  - Z1 is the nominal system, and uses relative indices for glass and air
  - Z2..N use absolute indices for both glass and air
- Uses 5 surfaces (3 dummies and 2 real surfaces) to represent each element
  - We have a macro (**Add_Seats**) to automatically insert these dummies
  - We have another macro (**Pull_Seats**) to pull out the dummies, leaving a lens defined by the surface vertex locations
- Integrates the dn/dT curve from 20° to obtain the index at the temperature in question
- Uses the -30/+70 value for the CTE
- *Note that when a glass is changed it is necessary to re-run **ENV_PIK**: the pickups handle changes in radii, and thicknesses, but not changes in glass type.*

Creating a Temperature-Zoomed Model using ENV_PIK

- Starting with the Starting Point Lens shown on Slide 5, we used **ENV_PIK** to create a lens model zoomed over temperature (nominal, cold, hot)
- The results are shown on the next few slides

Thermally Zoomed Model, with dummy surfaces shown:

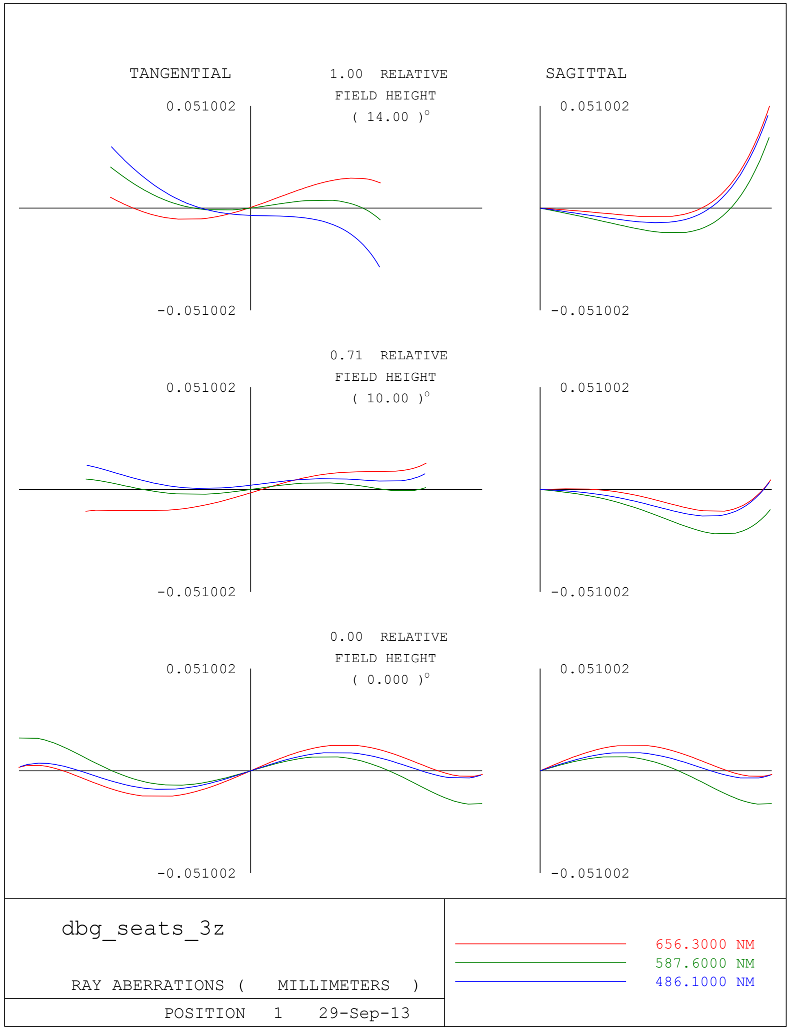


F/2
Field Diameter: 28°

Wavelengths:
d, F, C, equally weighted

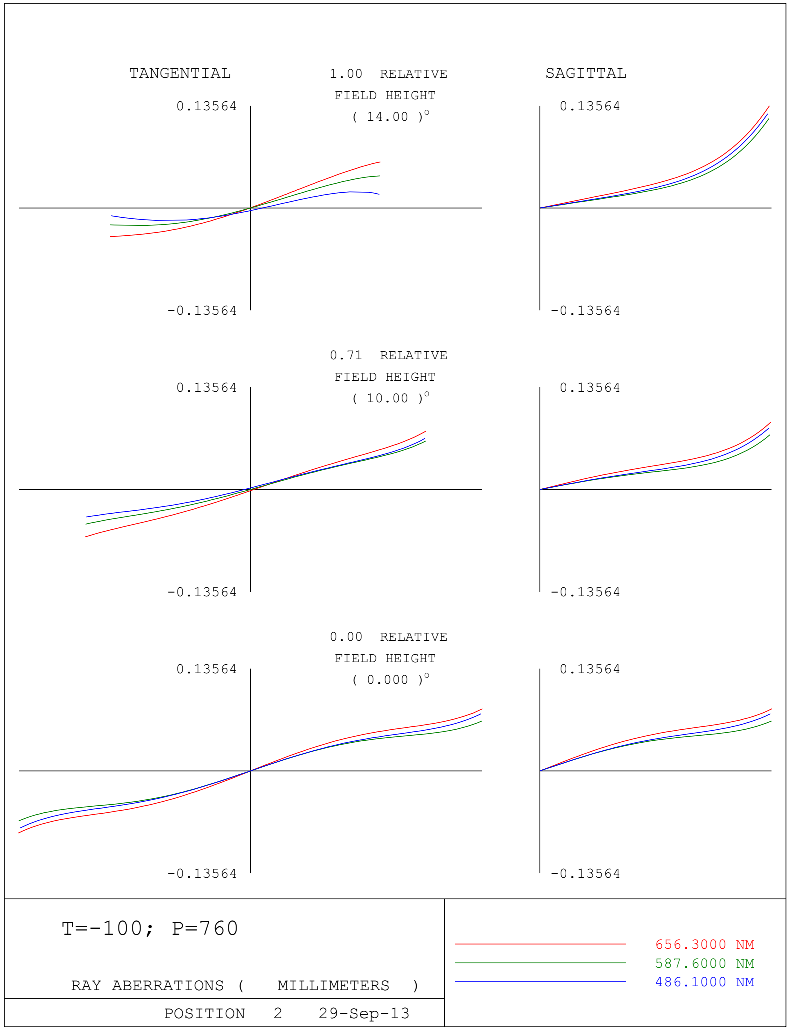
Initial Aberrations at 20°C (Z1)

Vertical Scale = ±51 µm



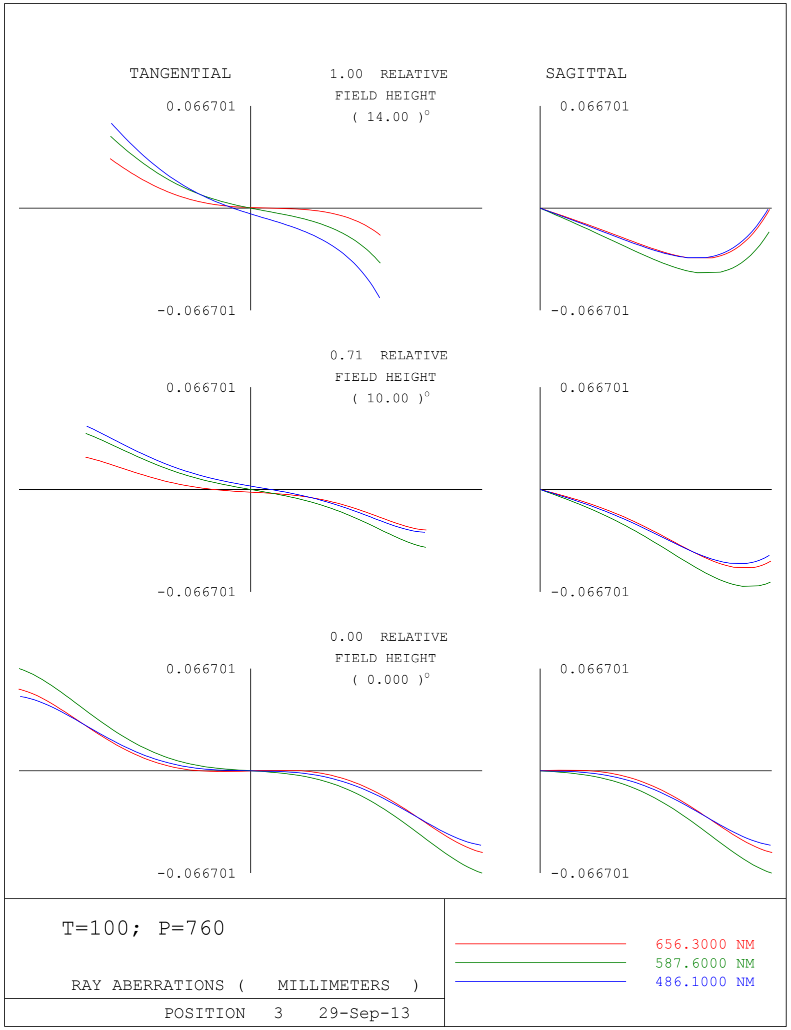
Initial Aberrations at -100°C (Z2)

Vertical Scale = ±136 µm



Initial Aberrations at +100°C (Z3)

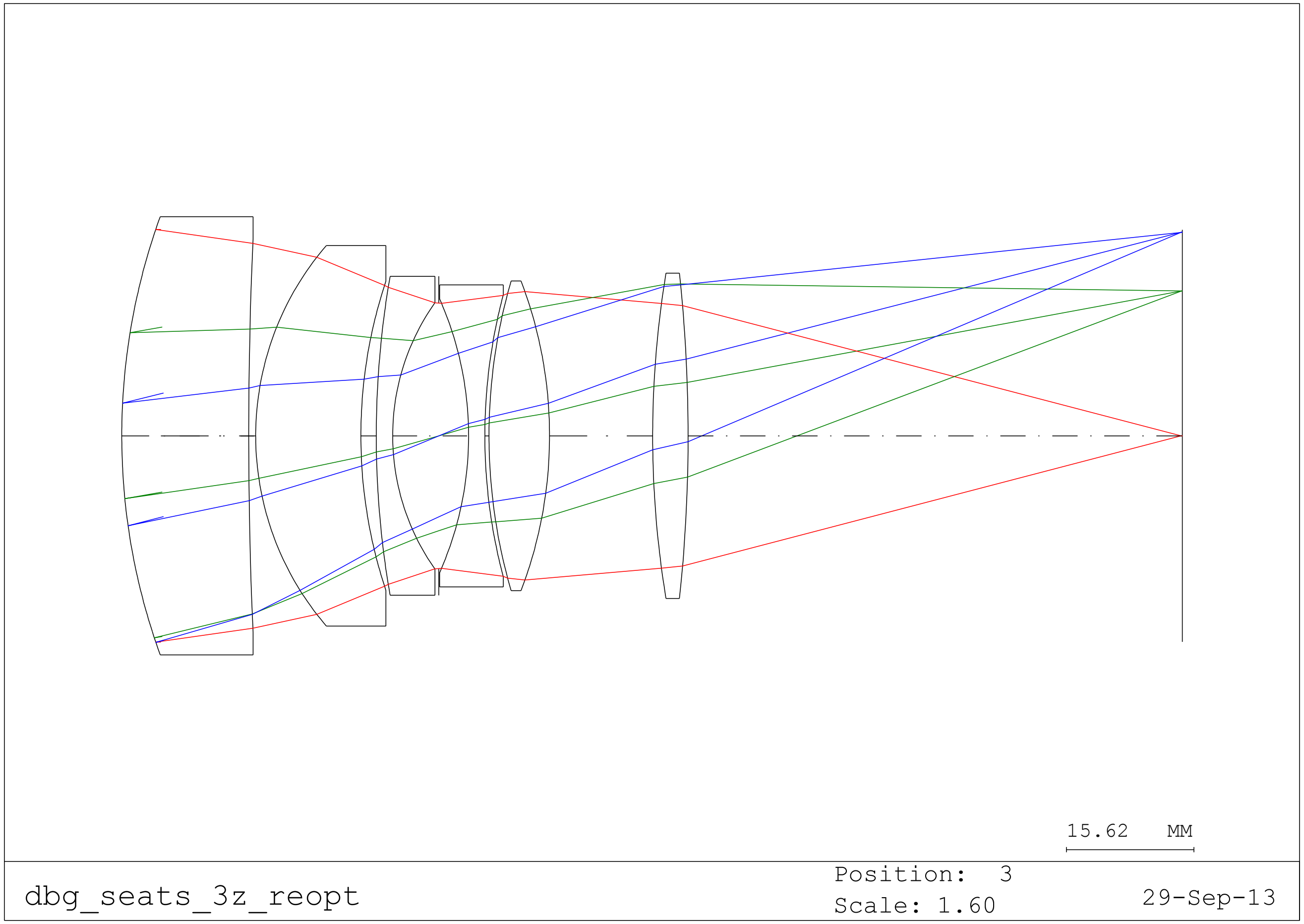
Vertical Scale = ±67 µm



RMS Spot Size Over Temperature
(Original System)

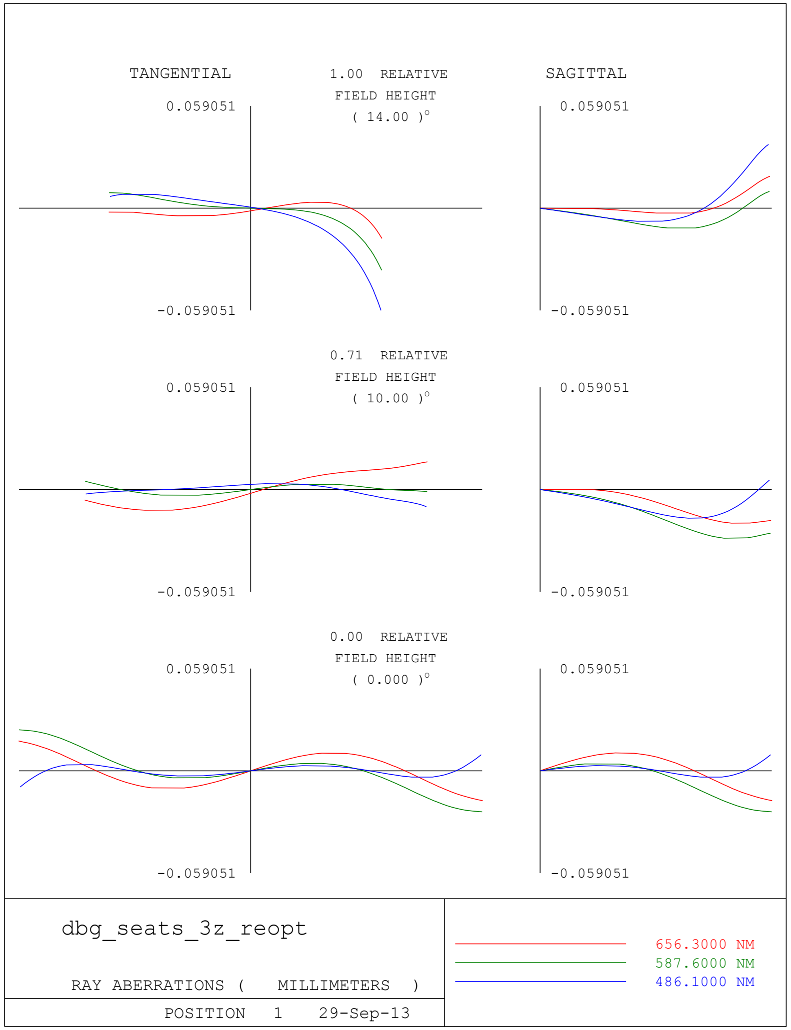
Temperature (°C)	Field	RMS Spot Size (μm) Original System (Dbg_seats 3Z)
20	Axis	15.9
20	10°	22.4
20	14°	23.7
-100	Axis	105.9
-100	10°	86.8
-100	14°	85.1
+100	Axis	71.0
+100	10°	69.6
+100	14°	61.9

Next: Reoptimize with Current Glasses



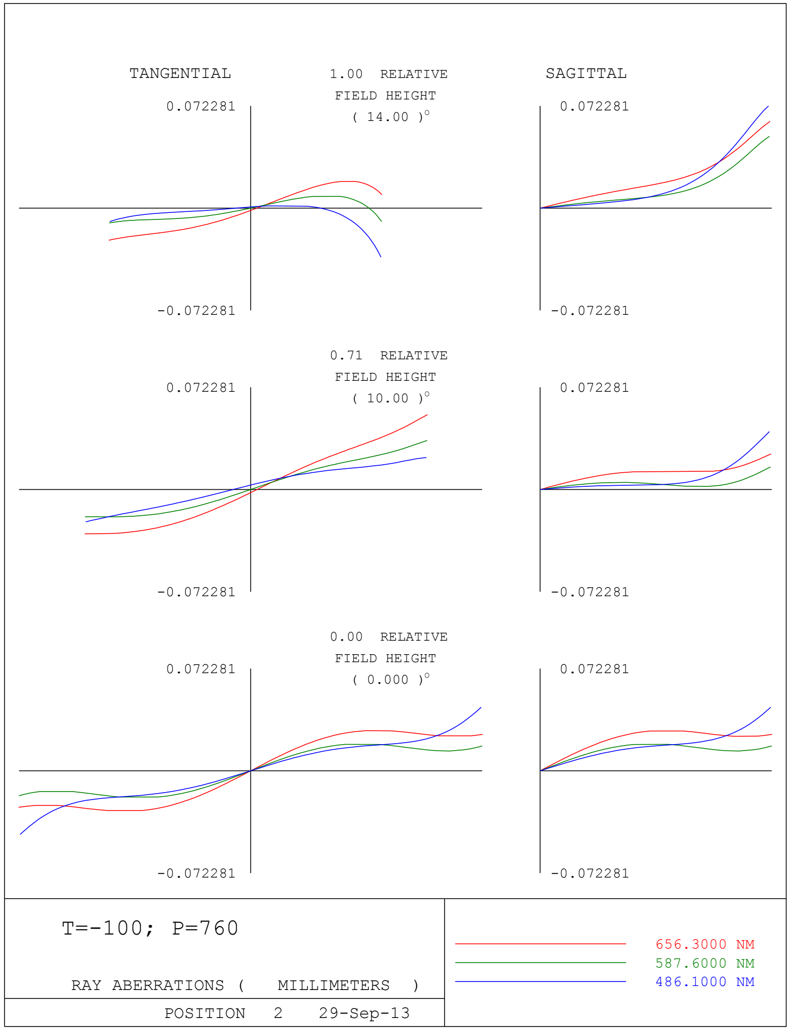
Aberrations at +20°C (Z1)

Vertical Scale = ±59 µm



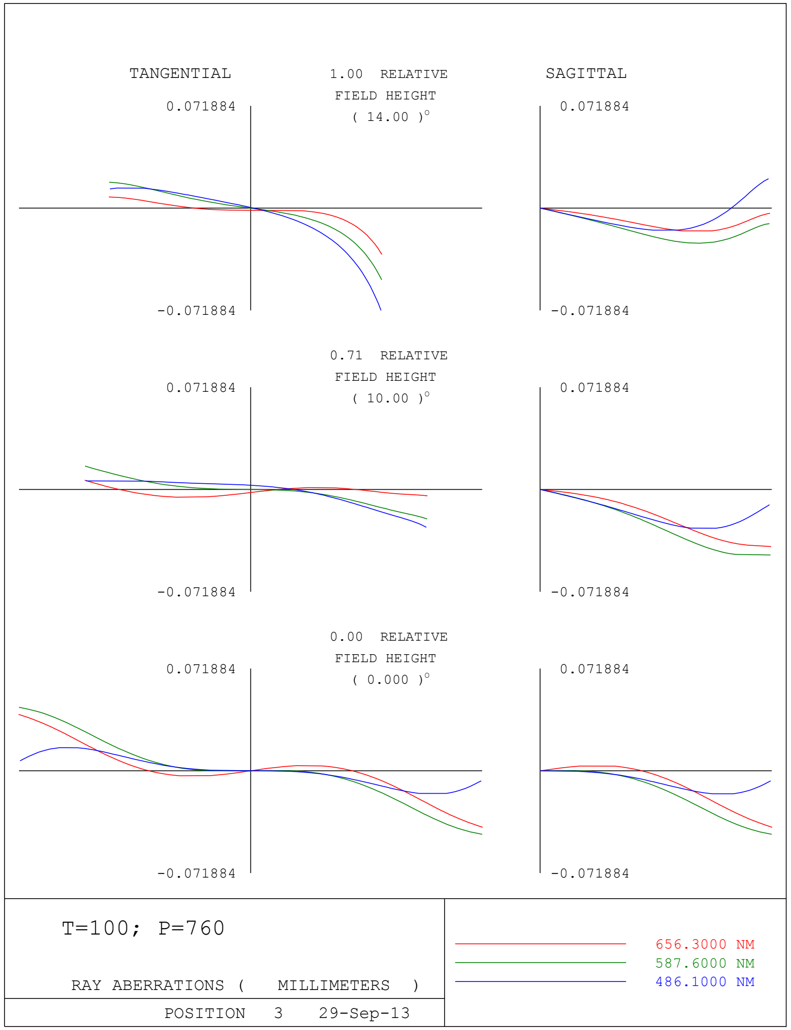
Aberrations at -100°C (Z2)

Vertical Scale = ±72 µm



Aberrations at +100°C (Z3)

Vertical Scale = ±72 µm



RMS Spot Size Over Temperature

(Re-Optimized System)

Temperature (°C)	Field	RMS Spot Size (µm) Original System (Dbg_seats 3Z)	RMS Spot Size (µm) Optimized Radii (Dbg_seats 3Z Reopt)
20	Axis	15.9	20.6
20	10°	22.4	27.6
20	14°	23.7	22.0
-100	Axis	105.9	45.6
-100	10°	86.8	41.7
-100	14°	85.1	39.7
+100	Axis	71.0	44.1
+100	10°	69.6	45.3
+100	14°	61.9	36.4

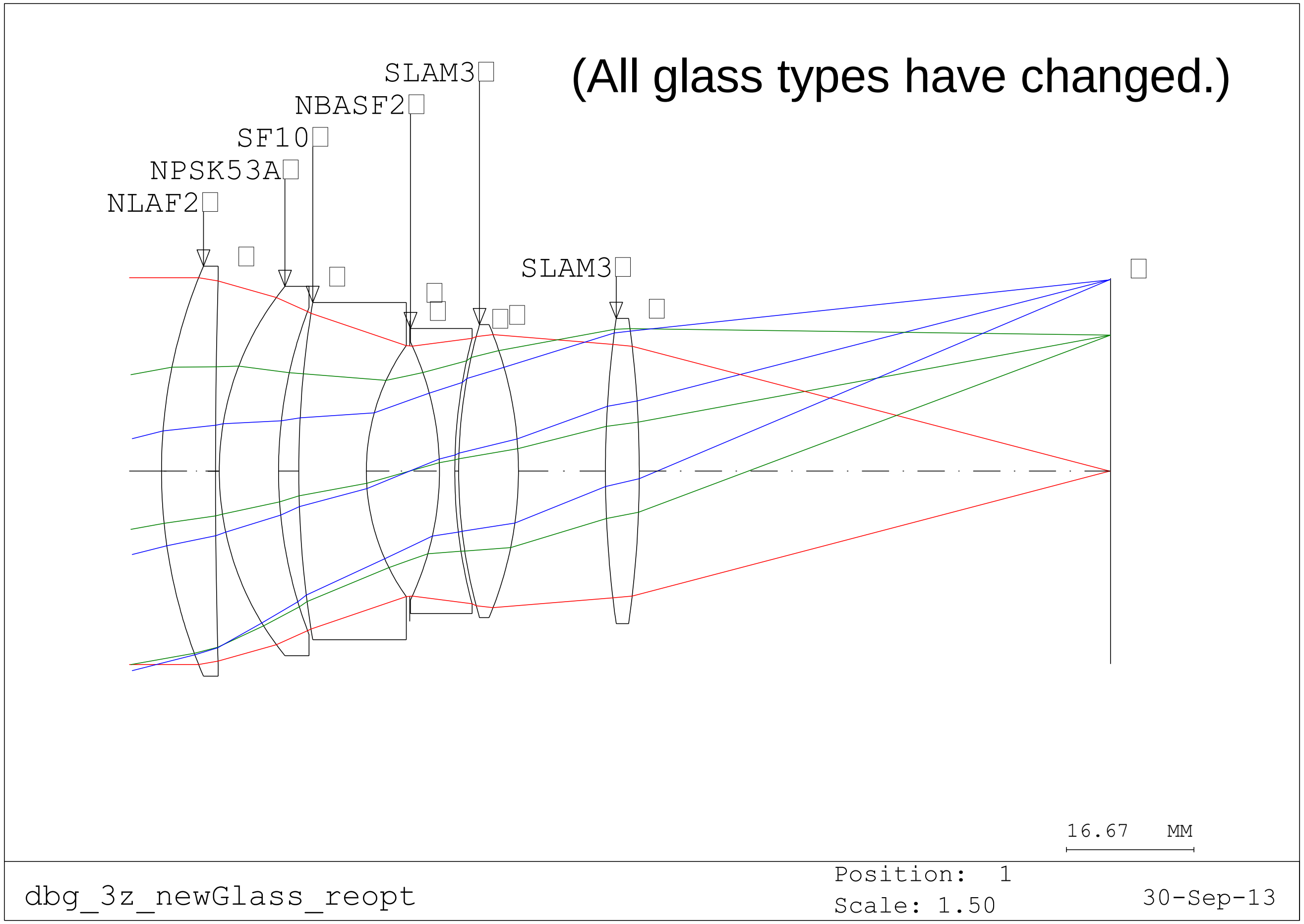
Reselecting Glass Types

- Optimizing in the zoomed state, with the current glasses, improved the performance
- But: there is every reason to believe that the system would perform better with a different set of glasses
  - After all, when we selected these glasses, we were ignoring the thermal properties!
- Therefore, use **Optimization > Glass Expert …** to explore the possibilities
  - **ENV_PIK** has already been run on the system, so the global variables regarding number of zooms, temperatures, and pressures, are already in memory
  - The **AUT** sequence that Glass Expert calls must do the following:
    - Call **ENVP_Rezoom** (inside the sequence but before calling **AUT**) to re-zoom the lens with the current glass types. (**ENVP_Rezoom** is identical to **ENV_PIK**, but does not query the user for number of zooms, etc.)
    - De-zoom to the nominal zoom position (**DEZ 1**) after **AUT** but before returning
  - After Glass Expert finishes, run **ENVP_Rezoom** one last time to zoom the system over temperature

Glass Expert Progress

- We reoptimized the lens using **Glass Expert**
  - We allowed the use of NKZFS glasses and NPSK53A, but we excluded NFK51A from consideration
  - By changing glasses using **Glass Expert**, the merit function was reduced by a factor of 3.6 in 1.5 hours

After Glass Expert



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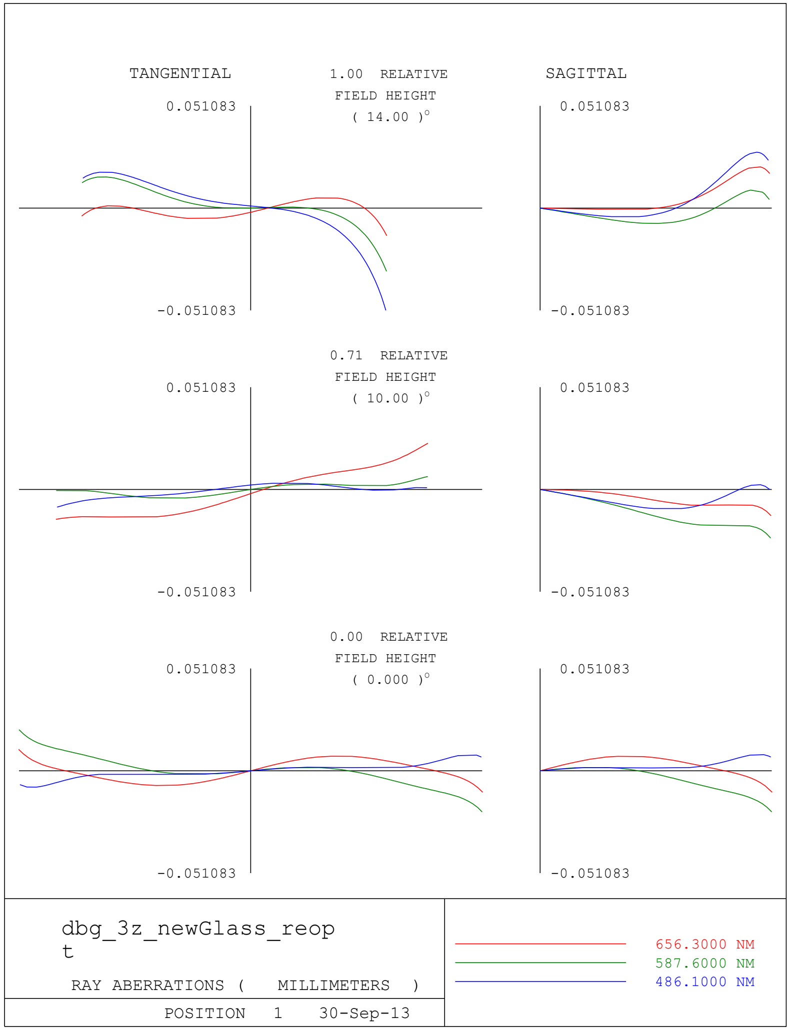
Aberrations at +20°C
(with new glasses)

Vertical Scale = ±51 µm



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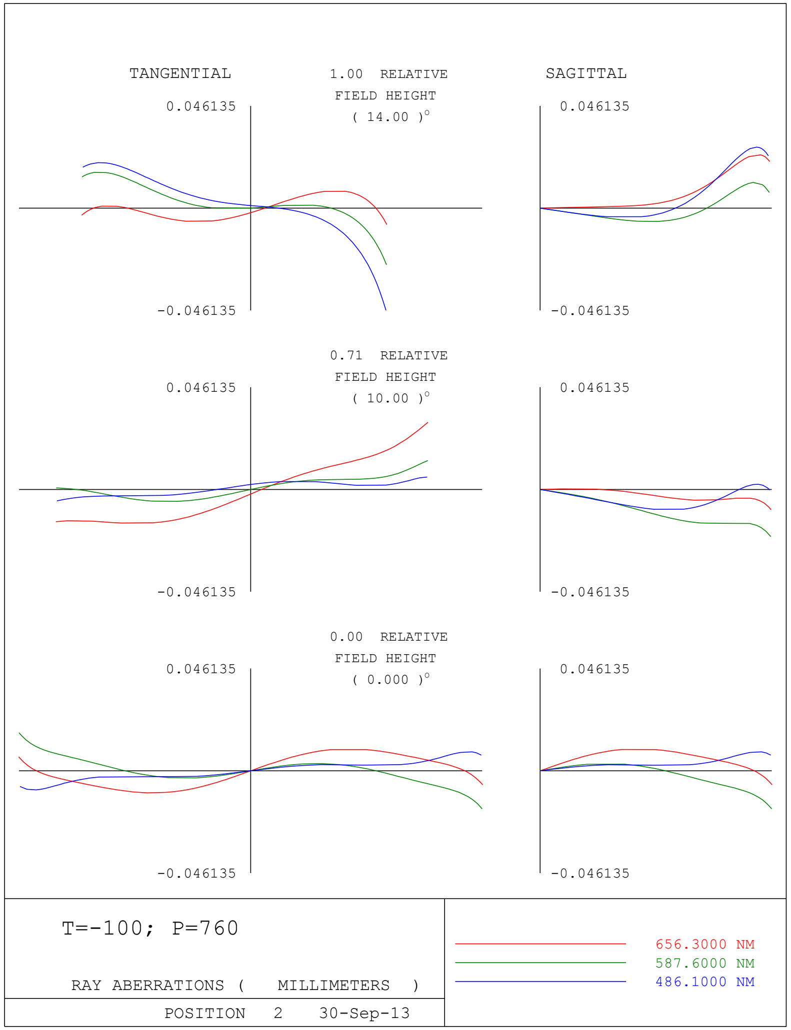
Aberrations at -100°C

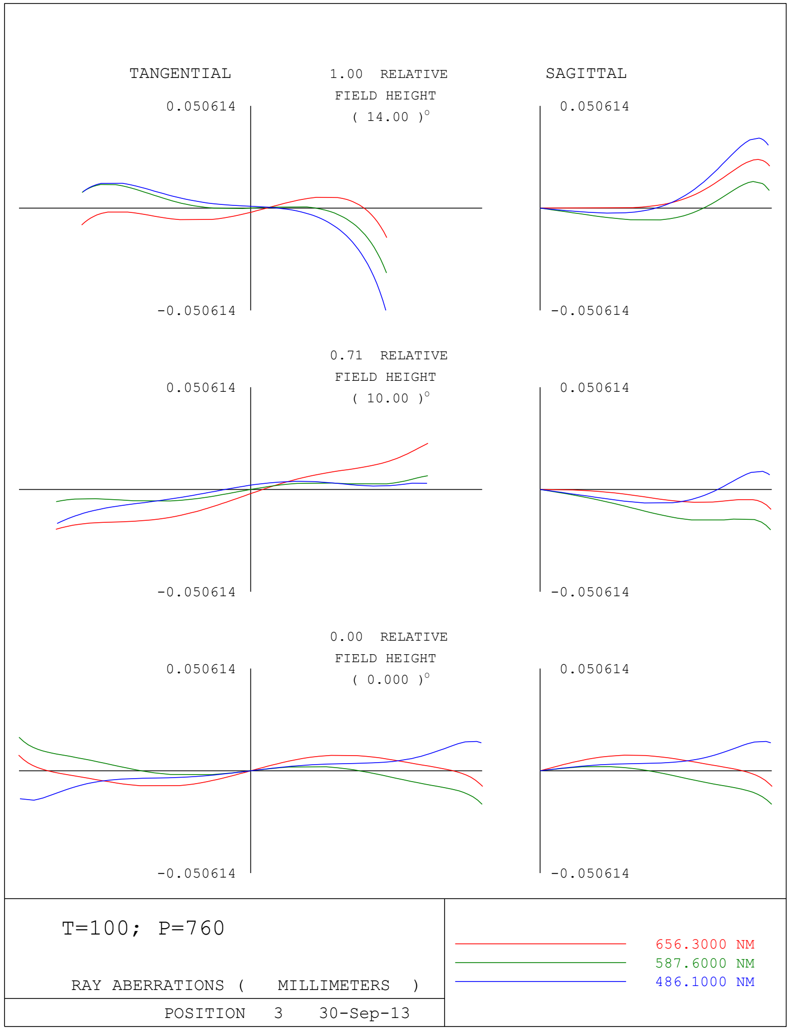
(with new glasses)

Vertical Scale = ±46 µm



Aberrations at +100°C
(with new glasses)

Vertical Scale = ±51 µm



Summary of Results

Temperature (°C)	Field	RMS Spot Size (µm) Original System (Dbg_seats 3Z)	RMS Spot Size (µm) Optimized Radii (Dbg_seats 3Z Reopt)	RMS Spot Size (µm) After Glass Expert (Dbg_3z_ newglass_ reopt)
20	Axis	15.9	20.6	13.5
20	10°	22.4	27.6	21.7
20	14°	23.7	22.0	21.7
-100	Axis	105.9	45.6	12.5
-100	10°	86.8	41.7	22.3
-100	14°	85.1	39.7	21.1
+100	Axis	71.0	44.1	14.3
+100	10°	69.6	45.3	21.4
+100	14°	61.9	36.4	21.9

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Summary

- Synopsys has created a new tool, **ENV_PIK,** for the design and analysis of designs covering wide temperature bands
  - Allows modeling of different pressures as well as different temperatures
  - Handles the seating of lenses in a realistic manner
  - Facilitates zoomed optimization and the use of Glass Expert in selecting optical glasses
  - Integrates the dn/dT curve over the temperature range to obtain the correct indices at the temperatures of interest
  - In principle, the tool should integrate the CTE values (for both glass and housing materials) over the temperature band, but the necessary data are not available, so it uses the "-30/70" values supplied by the manufacturer
- The combination of **ENV_PIK** and **Glass Expert** is a very powerful tool for the athermalization of optical systems

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