Lens Design Tips

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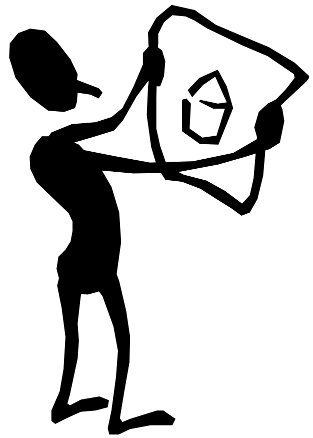
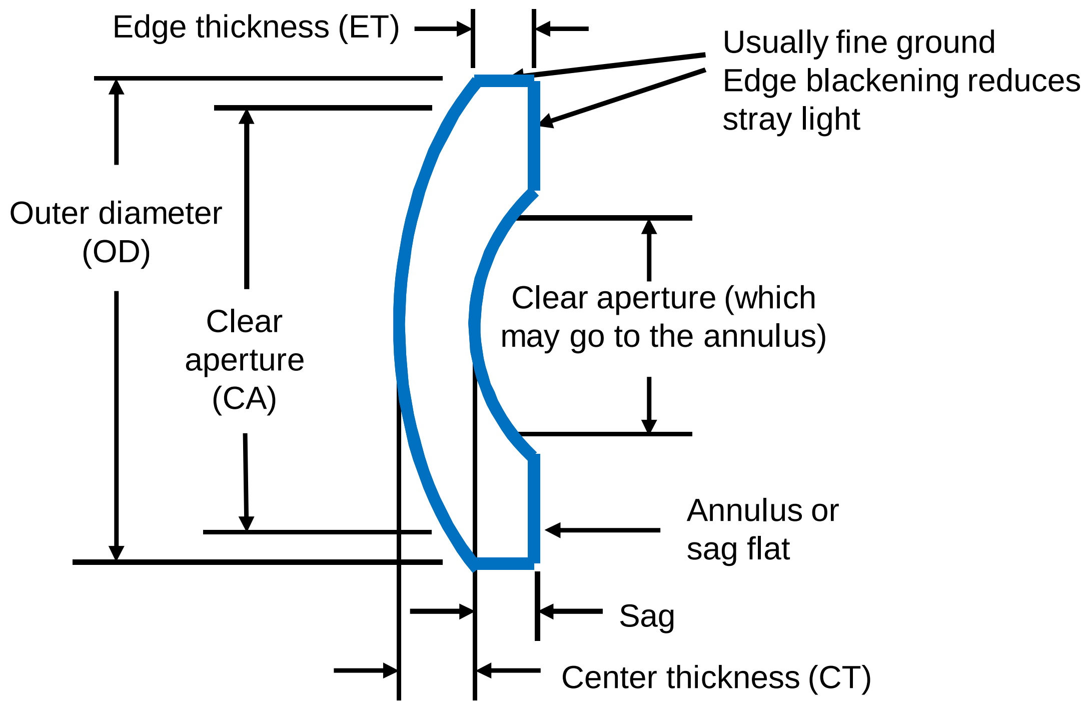
Opti 517

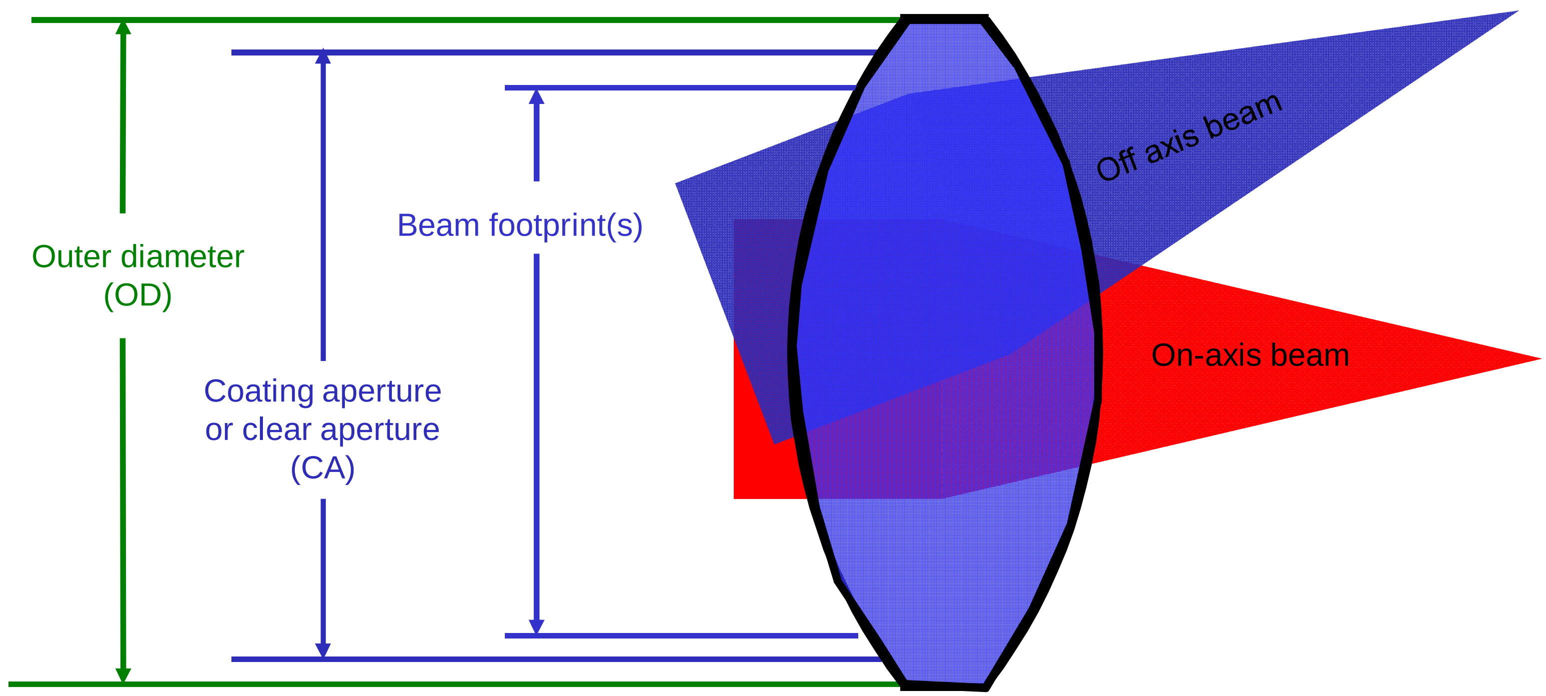


Anatomy of a Lens



Sharp corners (≤ 90°) usually chamfered to 0.5 mm face width

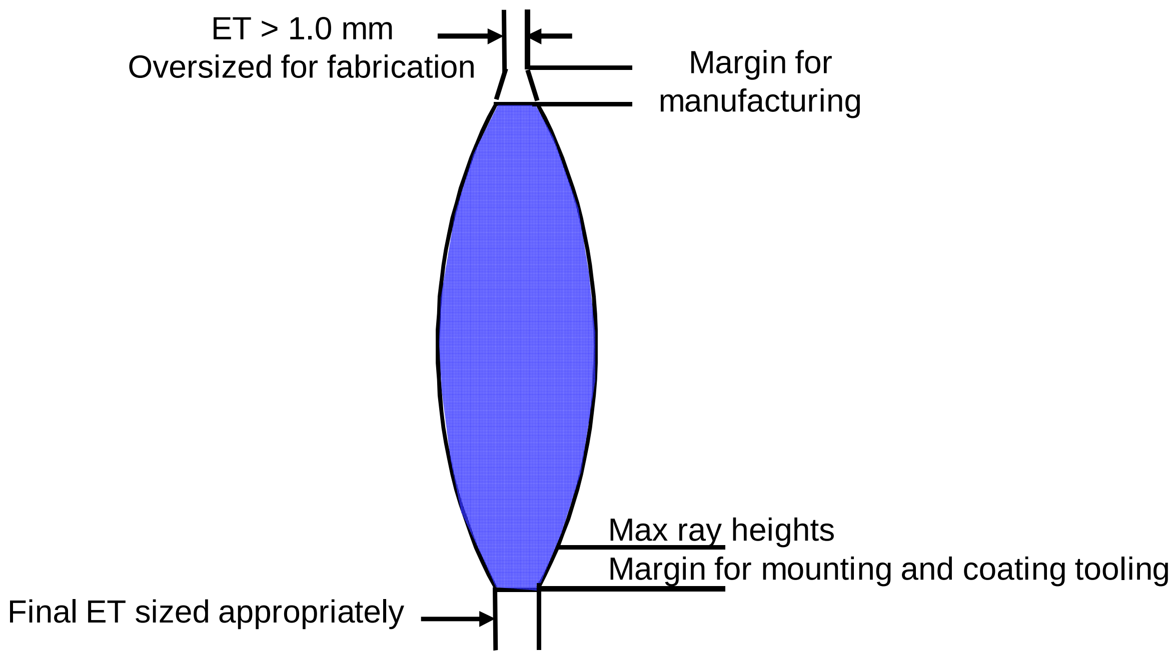
Used Optical Beams and Footprints



Lens diameter does not necessarily define the used footprint for a given field

Lens Geometry: Edge Thickness

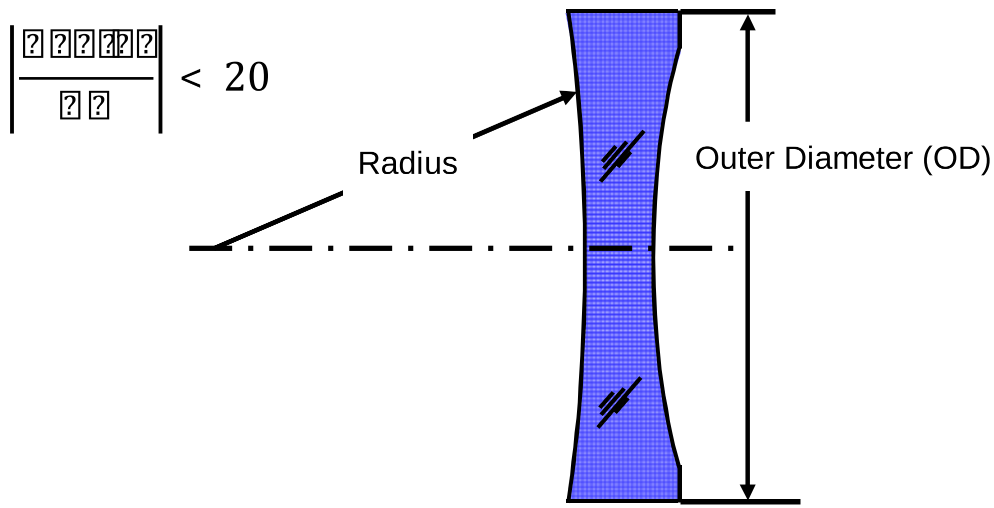
- Lenses are usually oversized 1-2 mm during fabrication
  - Chipping may occur at the edges, prompting the oversize margin
  - If too little margin, scratch/dig specifications may be compromised
- On steep radii surfaces, allow for more oversize margin
- In CODE V, the MNE general constraint (minimum edge thickness) in AUTO only constrains the ET over the clear apertures
  - To constrain ET over a larger physical diameter during AUTO, use
    `ET Sk MEC [overage_factor [overage_constant]] > target`



Lens Geometry: Long Radius

- Long radii are hard to test
  - During use of test plates in production
  - On a radius slide or on an interferometer
- If a radius approaches 20x the outer diameter, make the surface flat
- To constrain this in CODEV, use a user-defined constraint in AUTO

```
@ratio_sj == 0.5*absf((rdy sj)/(sd sj))
DSP ratio_sj
@ratio_sj < 20
```

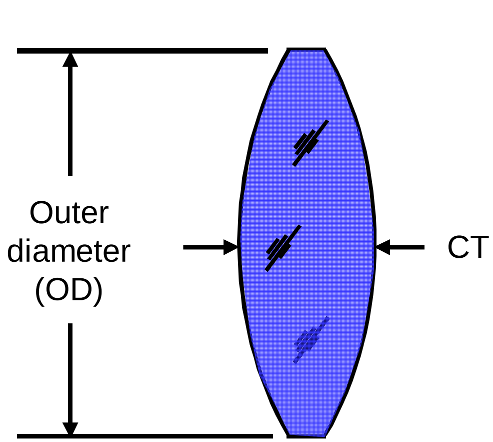


Lens Geometry: Aspect Ratio

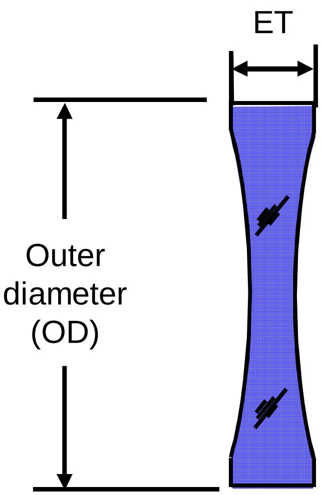
- High aspect ratios risk surface irregularities due to springing after deblocking
- In CODE V, the aspect ratio can be constrained during AUTO with

```
ATC Sk [MEC [overage_factor [overage_constant]]] >=< target
ATE SK [MEC [overage_factor [overage_constant]]] >=< target
```

For example, `ATC S3 MEC 1.0 1.0 > 3 < 12.5`



3 < [illegible] < 12.5



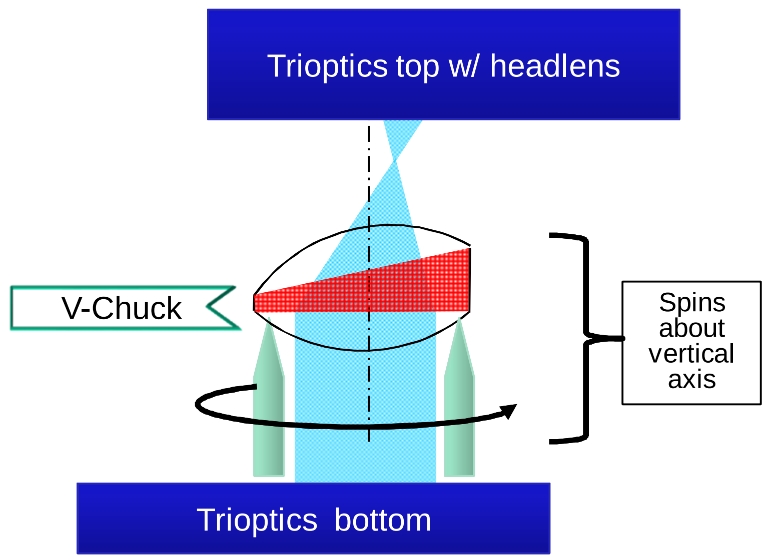
[illegible] = [illegible] / [illegible]

[illegible] = [illegible] / [illegible]

Lens Geometry: Focal Length

- Lens centering machines (e.g., from Trioptics) work off beam deviations
- Long focal length singlets and doublets can lead to measurement errors
- Simple optimization constraint can save fabrication difficulties with centering
  - $|EFL_{component}| < 500$ mm to avoid problems
  - In CODE V, use the constraint in AUTO
    `EFY Sj..k < pos_target` or `EFY Sj..k > neg_target`
  - You can also use

```
@EFLjk == absf((efy sj..k))
DSP @EFLjk
@EFLjk < target
```



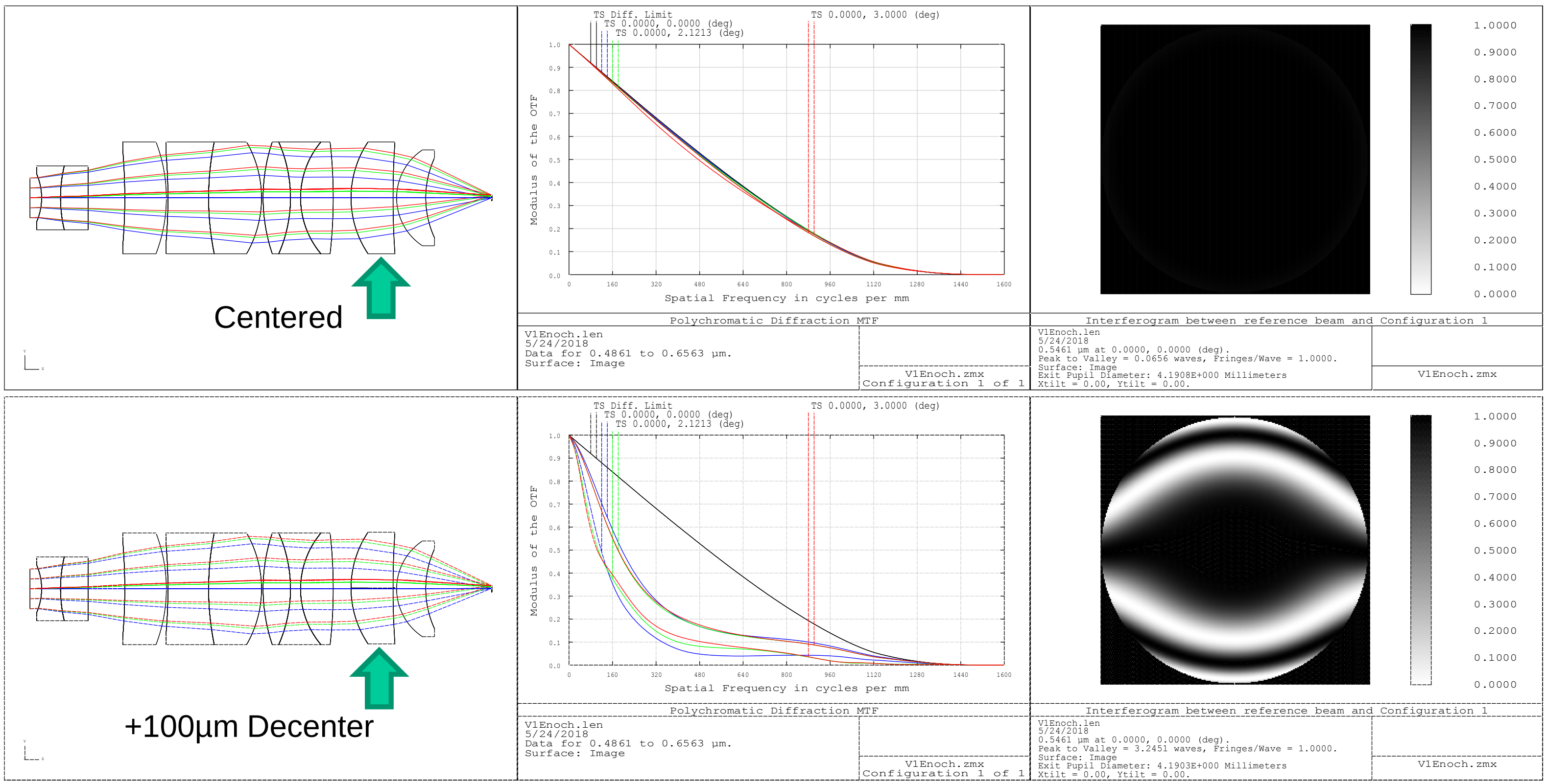
Spherical Aberration as an Assembly Metric

Å A well-designed optical system balances every surfaceȏs spherical aberration to minimize the sum of the spherical aberration content at the image plane

Å Lateral shear of spherical wavefronts produces coma

Å Coma produces the largest MTF drop to MTF compared to other aberrations

Å Constraining the maximum surface spherical aberration reduces the sensitivity of the surface to decenter and reduces the costs of tolerances and assembly



Wavefront
ə/15 PTV
ə/50 RMS

Wavefront
3ə PTV
ə/2 RMS

Surface Spherical Aberration Theory

Spherical wavefront hits a surface with W_{040} SA

$$W(\rho) = 2W_{040}\rho^4$$
$$W(x,y) = 2W_{040}(x^2 + y^2)^2$$

Lateral shear: differentiate wrt x

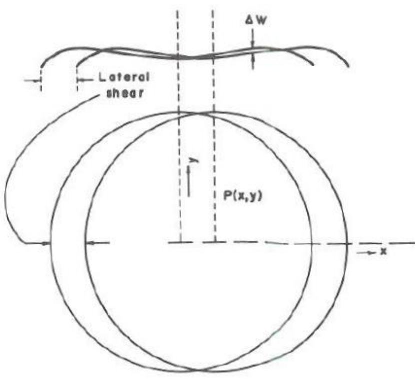
$$\frac{\partial W(x,y)}{\partial x} = 2W_{040}(4x^3 + 4xy^2 + y^4) \approx 8W_{040}x^3$$
$$\frac{\Delta W}{\Delta x} = 8W_{040}\rho^3\cos^3\theta$$
$$\Delta x = Decenter\ Tolerance$$
$$\Delta W = Wavefront\ with\ tolerance\ \Delta x$$

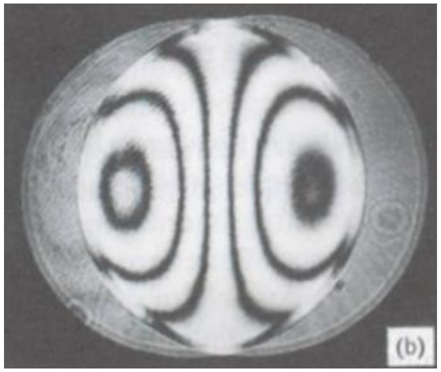
$$\Delta W = \Delta x \cdot 8 \cdot W_{040} \cdot Coma$$

Reduce Tolerance?

Reduce surface SA!

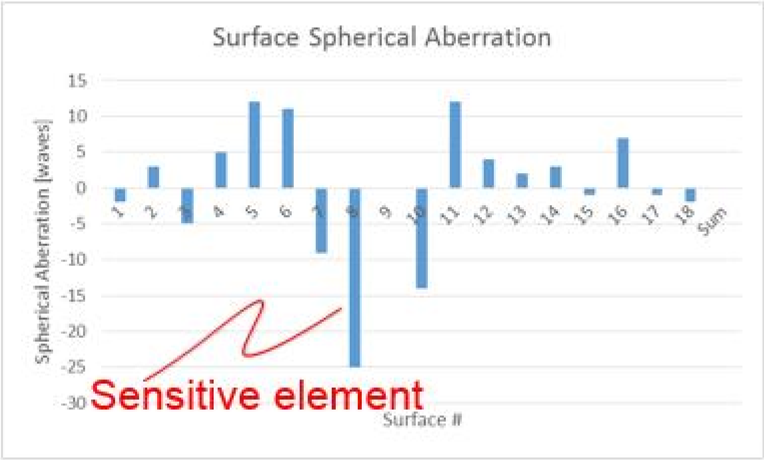
Figures from “Optical Shop Testing”, Malacara



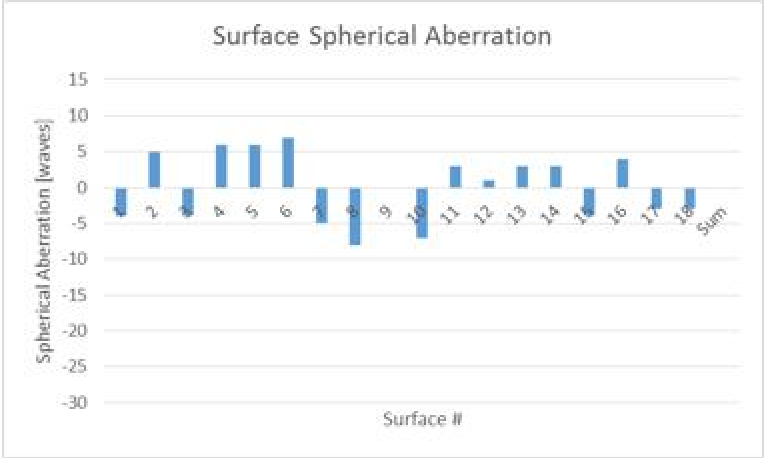


Reduced surface SA reduces axial coma induced by tilted and decentered elements

SA Desensitization in Optical Design



Optical Design iteration #1
without Surface SA constraints

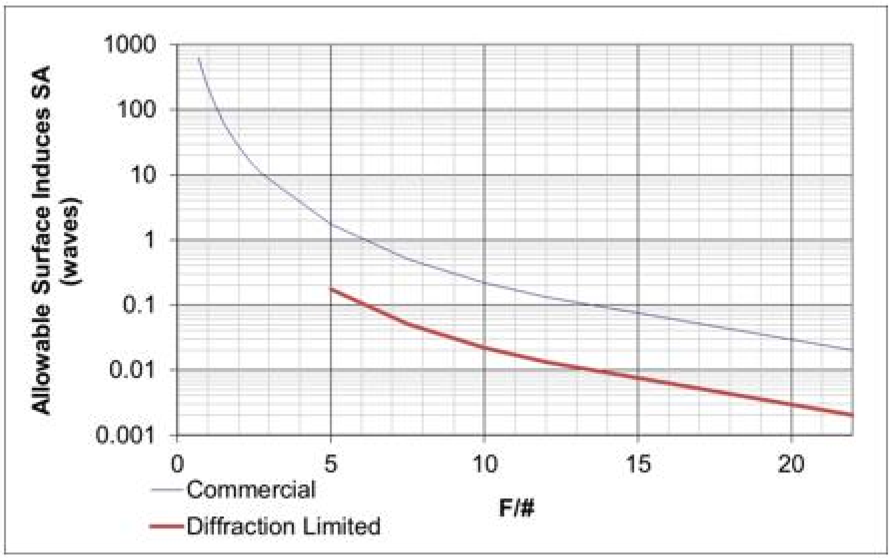


Optical Design iteration #2
With Surface SA constraints

Minimizing the maximum surface SA "spreads the pain" among all the elements

Surface SA Goal Based on F/# and MTF Drop

	Commercial	Diffraction Limited
Maximum Surface SA (λ)	$< \frac{215}{F/\#^3}$	$< \frac{22}{F/\#^3}$
Allowed MTF drop due to tolerances (spatial frequency 0.5 of optical cutoff)	-20%	-2%



These are empirically based on measured data for many lens assemblies fabricated at Edmund Optics

Target the maximum surface SA based on the allowable MTF drop and the system f/number

Constraining the Maximum Surface SA

Å To constrain the surface spherical aberration in waves for surface Sk in AUTO, use the following (for dimensions in mm)

```
AUTO
...
^sa_target == 2
^ref == (ref)
^sa_sk == absf((sa sk)/8/((wl w^ref)/1e6)/2)
dsp ^sa_sk
^sa_sk < ^sa_target
...
```

Optical System Color Correction Regimes

Å Refractive optical systems have to color correct for the defocus due to glass dispersion

Å There are many solutions available, primary, achromatic, apochromatic, etc.

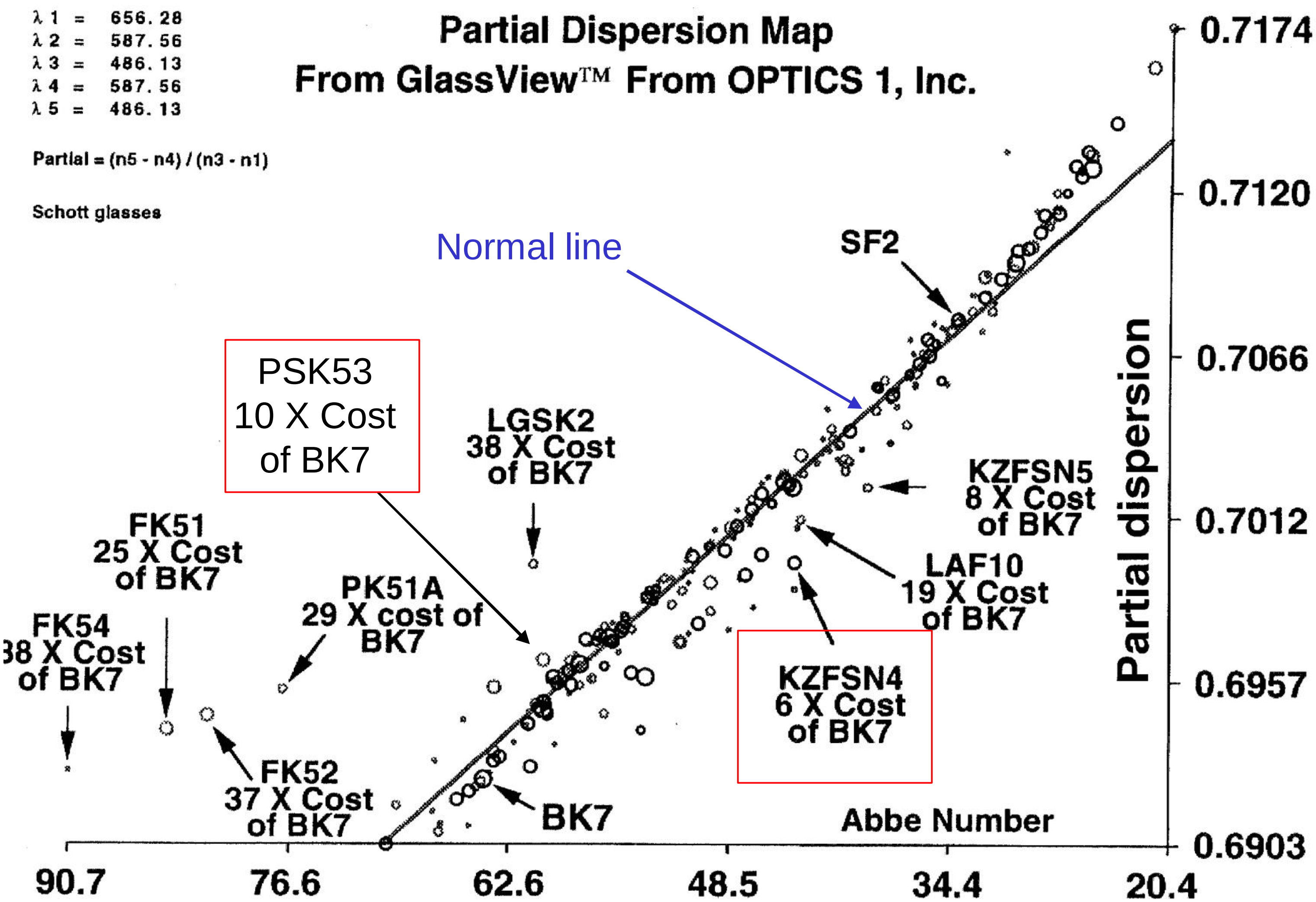
Å The level of correction and first order optical properties can impose heavy requirements on glass tolerances

	Primary Color	Achromatic	Apochromatic
# wavelengths for common focus	1	2	3
Defocus	$\frac{EFL}{V}$	$EFL\frac{\Delta P}{\Delta V}$	Complex
Relative Defocus	100·Diffraction DoF	8·Diffraction DoF	<0.25·Diffraction DoF
Component Relative EFL	100	~50	~25
Relative Surface SA	1	4	17

Achromatic Lens Design

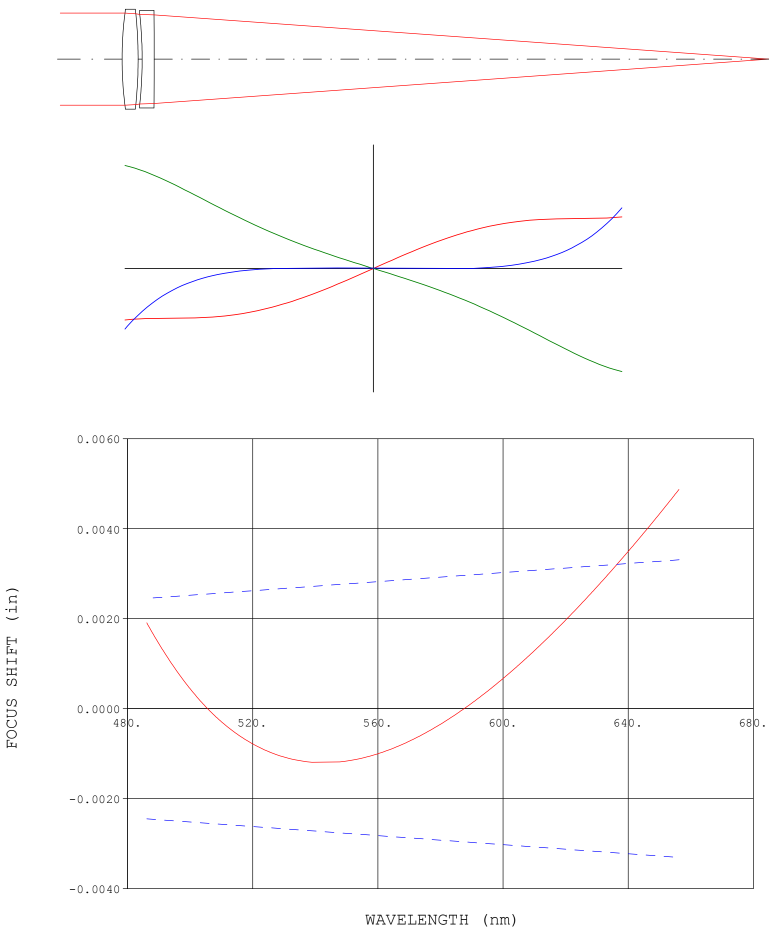
- Correcting secondary color requires consideration of a parameter called the partial dispersion
  - Partial dispersion is defined for four wavelengths across the spectral band $P = (n_{\lambda 1} - n_{\lambda 2}) / (n_{\lambda 3} - n_{\lambda 4})$
- Correcting secondary color takes special glasses whose partial dispersions are different from "normal" glasses
  - These glasses cost significantly more than "normal" glasses
  - Most glasses follow a "normal" line
- The technique is to find two glasses that have reasonably similar partial dispersions, but have different V values
  - Use these glasses with the standard achromatic equations to solve for the lens powers
- If the V values are too close together, the lens powers will be strong, and the lenses will be "fat"
  - This will introduce significant spherochromatism (change in spherical aberration with wavelength) due to the higher angles of incidence

Partial Dispersion Map

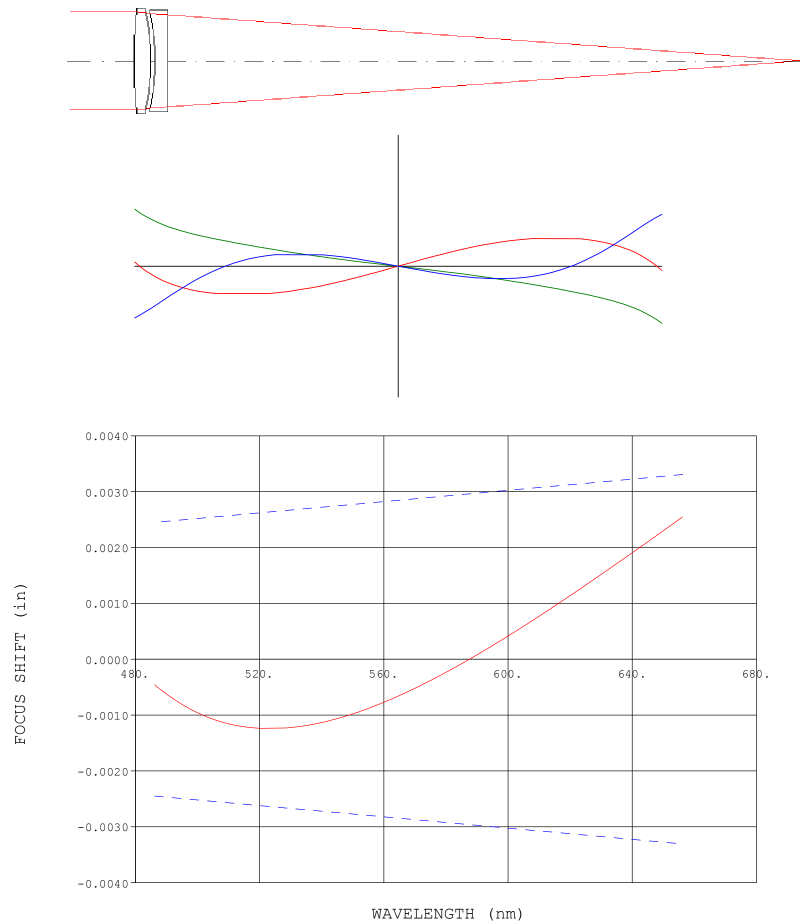


Reduction of Secondary Color

BK7 ï SF2
SF2 is 1x cost of BK7



PSK53 ï KZFSN4
PSK53 is10x cost of BK7
KZFSN4 is 6x cost of BK7



Apochromatic Design

Å Apochromatic lenses (significantly reduced secondary color) can be designed using three different glasses

Power

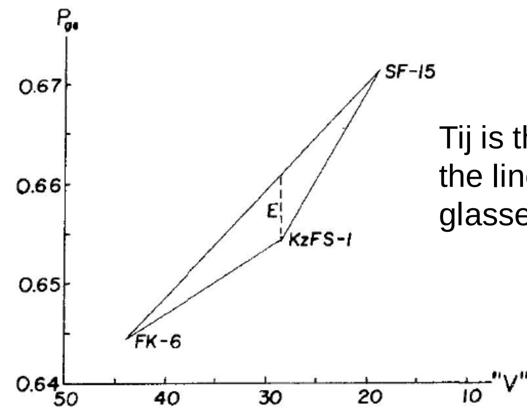
$$\Phi_{total} = \Phi_1 + \Phi_2 + \Phi_3$$

Axial Color

$$\delta\Phi = \frac{\Phi_1}{V_1} + \frac{\Phi_2}{V_2} + \frac{\Phi_3}{V_3} = 0$$

Secondary Color

$$\delta\Phi_{dc} = \frac{\Phi_1 P_1}{V_1} + \frac{\Phi_2 P_2}{V_2} + \frac{\Phi_3 P_3}{V_3} = 0$$



Tij is the slope of the line between glasses i and j

All three lenses will be as weak as possible if glasses are selected with large E1, E2, E3

Solve For Power

$$\Phi_1 = -\frac{T_{23}}{E_1} V_1 \cdot \Phi_{total}$$

$$\Phi_2 = -\frac{T_{31}}{E_2} V_2 \cdot \Phi_{total}$$

$$\Phi_3 = -\frac{T_{12}}{E_3} V_3 \cdot \Phi_{total}$$

$$T_{12} = \frac{P_1 - P_2}{V_1 - V_2}$$

$$T_{23} = \frac{P_2 - P_3}{V_2 - V_3}$$

$$T_{31} = \frac{P_3 - P_1}{V_3 - V_1}$$

$$E_1 = -\frac{\Gamma}{V_2 - V_3}$$

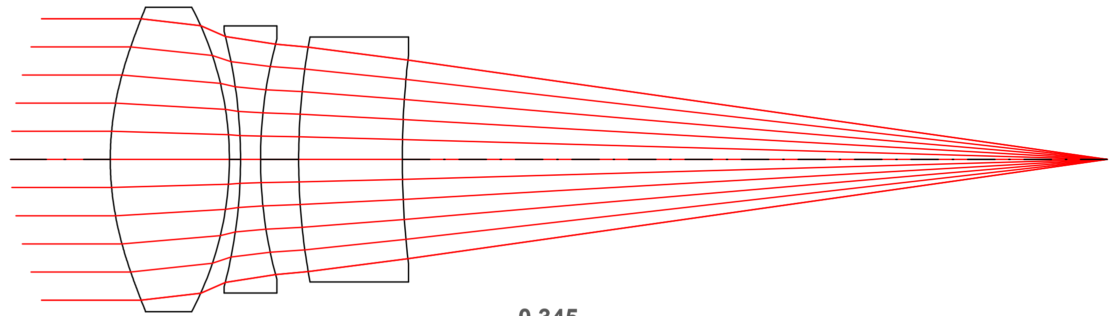
$$E_2 = -\frac{\Gamma}{V_3 - V_1}$$

$$E_3 = -\frac{\Gamma}{V_1 - V_2}$$

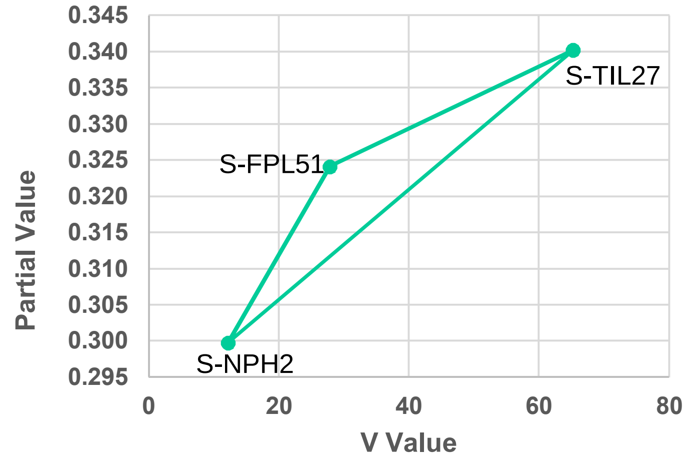
$$\Gamma = \left[V_1(P_2 - P_3) + V_2(P_3 - P_1) + V_3(P_1 - P_2)\right]$$

Apochromatic Design Example

Select:
S-FPL51
S-TIL27
S-NPH2



				EFL Total	100			
				Phi Total	0.01			
	650	550	440	V	P		Phi	Efl
S-FPL51	1.437446	1.439739	1.444186	65.24731	0.340276		0.024121257	41.45721
S-TIL27	1.571224	1.577946	1.591957	27.87649	0.324207		-0.01710718	-58.455
S-NP2	1.910208	1.933071	1.986452	12.23799	0.299858		0.002985922	334.9049
						W=	0.016279494	
				Gamma	0.658633			
				E1	-0.04212			
				E2	0.012425			
				E3	-0.01762			
				T12	0.00043			
				T23	0.001557			
				T31	0.000762			



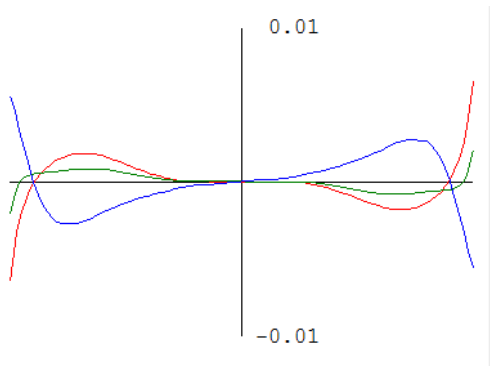
Lens Data Manager

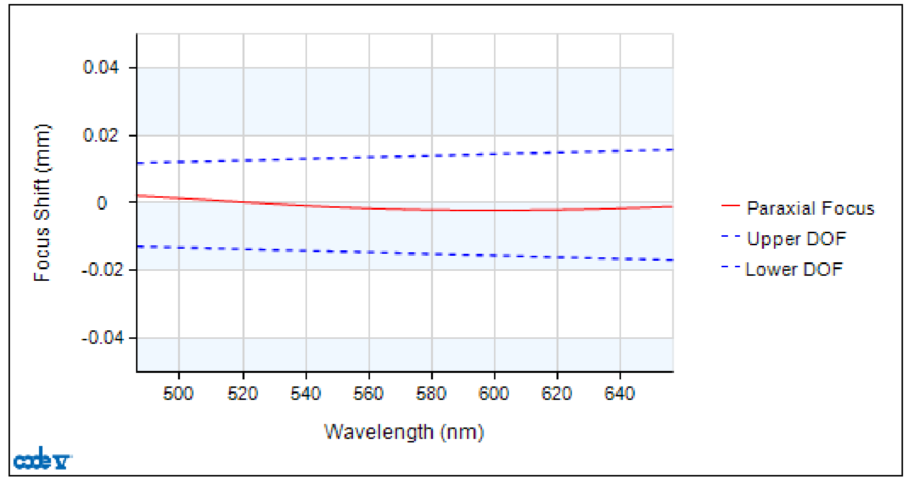
System Data... Surface Properties...

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object			Infinity	Infinity			
Stop		Asphere	29.631000	11.947000	SFPL53_OHARA		14.000000
2			-32.197000	1.123000			13.299696
3			-49.716000	2.000000	STIL27_OHARA		12.220758
4			44.198000	3.829000			11.452745
5			65.474000	10.394000	SNPH2_OHARA		11.166284
6			86.714000	70.694000			9.883172
Image			Infinity	0.000000			0.002045

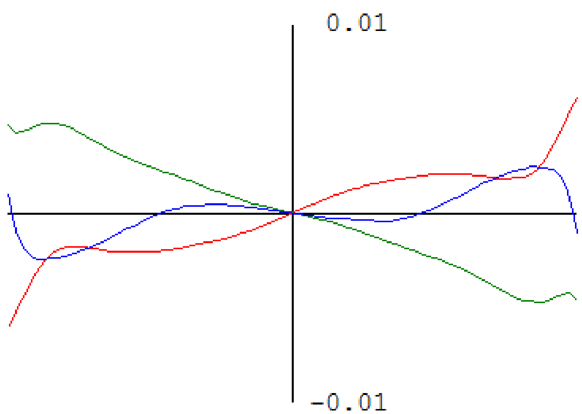
End Of Data

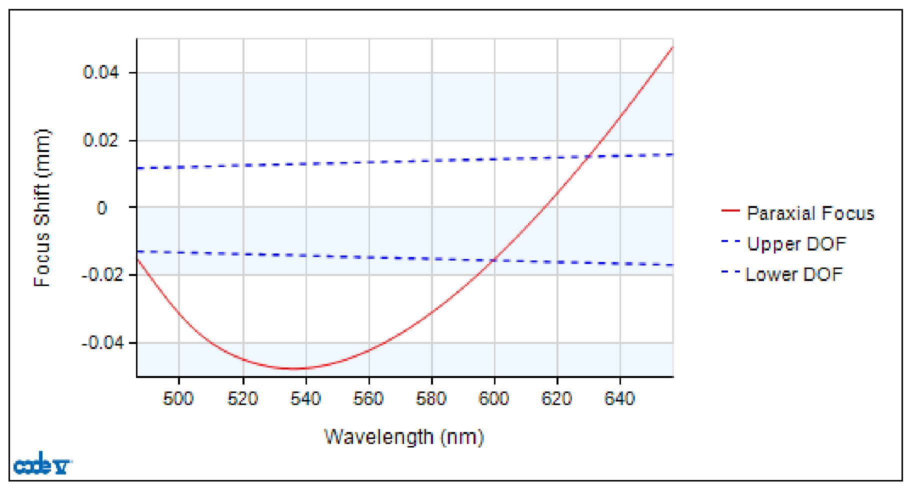
Apochromatic Example Performance





Compare with standard N-BK7 ï F2 doublet





Surface Axial Color

Å Optical design tools for material selection have become very adept at locating new solutions for color correction
  - ï Glass substitution and Hammer in Zemax
  - ï Glass Expert in Code V

Å Unfortunately, solutions can be found which are very sensitive to material dispersion tolerances
  - ï Commercial dispersion tolerances typically range between 0.8% and 0.5%

Schott[1]	
Grade	**ΔV**
Step 1	± 0.2%
Step 2	± 0.3%
Step 3	± 0.5%

Ohara[2]	
Grade	**ΔV**
Standard	± 0.8%
Request	± 0.3%

CDGM[3]	
Grade	**ΔV**
Grade 1	± 0.5%
Grade 2	± 0.8%
Grade 3	± 1.0%

1 Schott North America Inc., “Optical Glass Catalog”, Table 1.2, (2014)
2 Ohara Corporation, “Guarantee of Quality”, http://www.oharacorp.com/o7.html, (2014)
3 CDGM Glass, “Quality Definition”, Table 5, http://www.cdgmgd.com/attachments/soft/InstructionEN.pdf, (2014)

Å Surface axial color is proportional to glass tolerances

Sensitivity to Glass Dispersion

Seidel chromatic aberrations of an optical system, y = marginal ray height, V=dispersion

$$C_L = \sum_{n=1}^{\#\,of\,elements} \frac{y^2}{V \cdot Focal\_Length}$$

(Axial color or longitudinal chromatic aberration)

Sensitivity found by first derivative with respect to dispersion

$$\frac{\partial}{\partial V} C_L \cong \frac{\Delta C_L}{\Delta V} = \frac{-C_L}{V}$$

Tolerance sensitivity scales directly with aberrations

$$\overbrace{|\Delta C_L|}^{\text{Sensitivity}} = C_L \overbrace{\left(\frac{\Delta V}{V}\right)}^{\text{Abbe Number Tolerance}}$$

Reduce surface chromatic aberration !

Reduce Tolerance?

Controlling Surface Axial Color

- In CODE V, use a user-defined constraint for each sensitive lens
  - For example,

```
AUTO
...
^LCA_Target == 0.01
@LCA_E2 == absf((ax s3)+(ax s4))
@LCA_E2 < ^LCA_TARGET
...
```

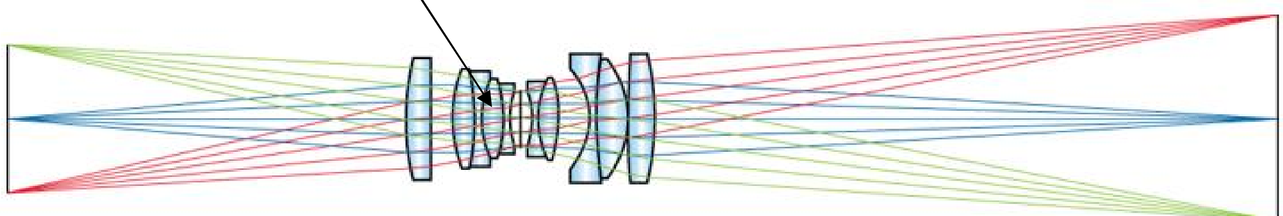
- Use third-order coefficients (THO output) to identify sensitive lenses

Sample Design

- Linescan lens requirement:
  - Polychromatic focus, high resolution
  - Red, green, or blue monochromatic high resolution without refocus
  - Apochromatic solution too costly (elements with short EFL and sensitive to mount)
- Solution: Achromat with secondary color ~1/2 diffraction-limited DoF

Initial Design:
Doublet: N-SF57; V=23.8
S-NPH2: V=18.9

$$V_{Doublet} = \frac{\varphi_{Total}}{\frac{\varphi_1}{V_1} + \frac{\varphi_2}{V_2}} = -5$$



	Initial Design	Desensitized Design
Max surface induced axial color	72 waves	30 waves
Abbe Tolerance Required	<0.1% (required melt fit)	0.5%

Reducing surface axial color in half allowed the use of standard grade catalog glasses vs. requiring melt fitting

Passive Athermalization

- Due to lenses' CTEs and dn/dTs and the housing's CTE, optical systems often go out of focus with changes in temperature
  - This is OK if you have a focus adjustment (man-in-the-loop)
- For stand-alone systems (no man-in-the-loop), it may be necessary to design the optical system to be passively athermal
- A lens can be represented by its plano-convex equivalent
  - F = r/(n-1)
- The thermal derivative of this is

$$\frac{dF}{dT} = \frac{1}{n-1}\frac{dr}{dT} - \frac{r}{(n-1)^2}\frac{dn}{dT} = \frac{r}{n-1}\left(\frac{1}{r}\frac{dr}{dT} - \frac{1}{n-1}\frac{dn}{dT}\right) = F\left(\alpha - \frac{1}{n-1}\frac{dn}{dT}\right)$$

- The change in focal length is then $\Delta F = \nu F \Delta T$ where

$$\nu = \alpha - \frac{1}{n-1}\frac{dn}{dT}$$

  - ν is often referred to as the thermo-optic coefficient

ν Values of Optical Materials (x10^6/°C)

Å Visible glasses

N-BK7	-1.5
BaK4	-0.3
BaK50	11.4
N-SK16	-3.4
SF4	3.8

It is possible to find combinations of visible glasses to make an athermal design with common mounting materials

Å Infrared glasses

Germanium	-127
TI-1173	- 34
ZnS	-28
ZnSe	-35
Silicon	-63
BaF_2	62

Most common IR materials have negative ν, so it is more difficult to make a passive athermal design

Å CTE of common mount materials (x10^6/°C)

Aluminum 6061	23.4
416 stainless	9.9
Invar36	1.5
Titanium	8.7
Beryllium	11.6

Example of Temperature Change

- An IR lens is made of germanium for use at 10 μm
- It has a focal length of 4 inches and an aperture of 2 inches (f/2)
- The diffraction-limited depth of focus is $\pm 2\lambda f^2 = \pm 0.0032$ inches
- If we mount the lens in an aluminum mount, the change in focus is $\Delta_{focus} = 4(-127-23)\text{x}10^{-6}/°\text{C} = -0.0006$ in/°C
- The lens defocus will exceed the diffraction depth of focus over a change in temperature of ±5° C
  - Note that for military applications, the specified temperature range is typically ±50° C

Passive Athermal Design

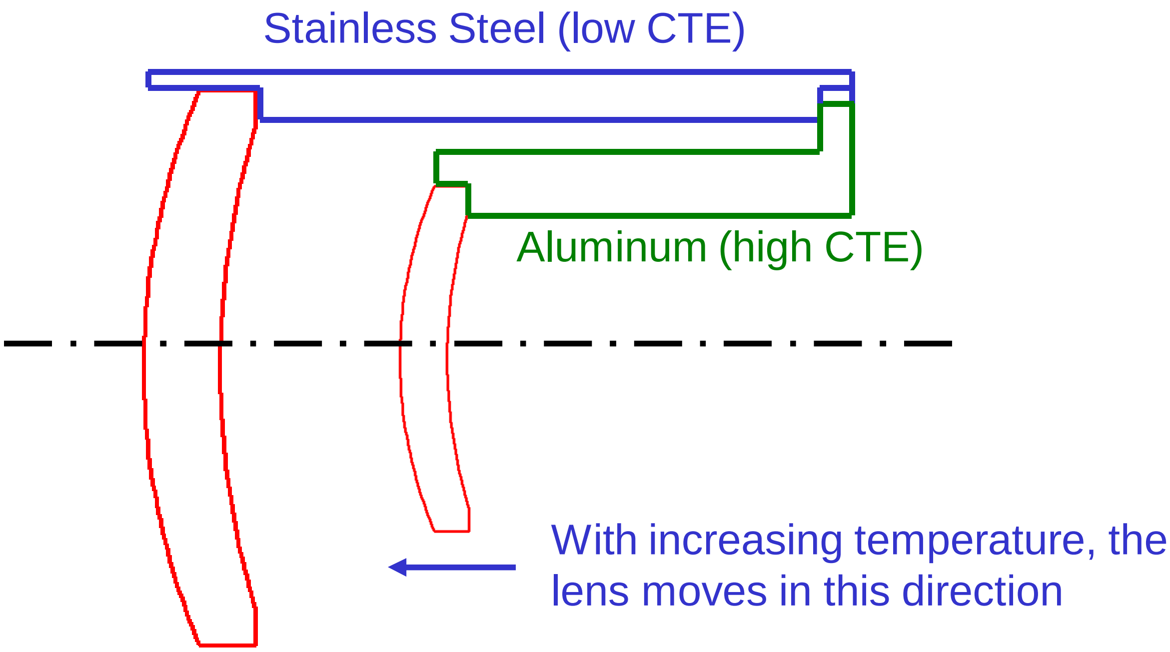
Å To make a lens passively athermal there are two choices:

1. Use a differential mount, using different expansion coefficients to simulate the desired mount CTE (usually negative)
   - Å This assumes a linear relationship between expansions, dn/dT values, and required motions
   - Å The limitation of this method is the non-linearity of CTE values and of dn/dT values over large temperature ranges
   - Å The final design may need to be iterated, due to imprecision or variability in the needed parameters

2. Select the materials for the optics and the lens mounts to make the system optically athermal

Example of a Differential Mount

- We need the second lens to move closer to the first lens with increasing temperature to maintain focus
  - For a simple spacer, this would require a negative spacer CTE
  - Can be done with two different materials with different CTE values



Key Concept for Optical Passive Athermalization

Å The inverse of the thermo-optic coefficient is exactly like a V-number for color dispersion
  - ï Thermal Abbe number is the inverse of the thermo-optic coefficient $\beta = 1/\nu$

Å Doublet equations for color correction work for passive athermalization

Color:

$$\Phi_1 = \Phi_{Total}\frac{V_1}{V_1 - V_2}$$

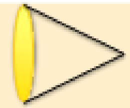
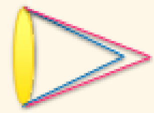
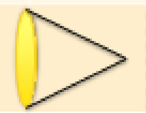
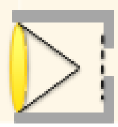
$$\Phi_2 = \Phi_{Total}\frac{V_2}{V_2 - V_1}$$

Thermal in invar housing:

$$\Phi_1 = \Phi_{Total}\frac{V_{Thermal,1}}{V_{Thermal,1} - V_{Thermal,2}}$$

$$\Phi_2 = \Phi_{Total}\frac{V_{Thermal,2}}{V_{Thermal,2} - V_{Thermal,1}}$$

Thermal Defocus and Athermalization Equations

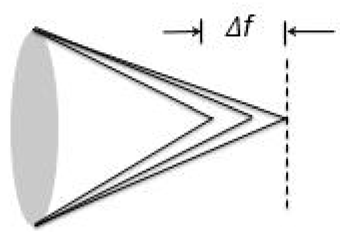
	Doublet	For i Elements	
Total System Power	$\Phi_T = \Phi_1 + \Phi_2$	$\Phi_T = \sum_i \Phi_i$	
Axial Color	$\frac{\Phi_1}{V_1} + \frac{\Phi_2}{V_2} = 0$	$\Delta\Phi = \sum_i \frac{\Phi_i}{V_i} = 0$	
Thermal Defocus (in air)	$\beta_1\Phi_1 + \beta_2\Phi_2 = 0$	$\frac{\Delta\Phi}{\Delta T} = \sum_i -\beta_i \Phi_i = 0$	
Thermal defocus (in a housing with CTE, α_h)	$\beta_1\Phi_1 + \beta_2\Phi_2 = \alpha_h \Phi_T$	$\frac{\Delta\Phi}{\Delta T} = \alpha_h \Phi_T - \sum_i \beta_i \Phi_i = 0$	

Equations assume thin lenses in contact with each other

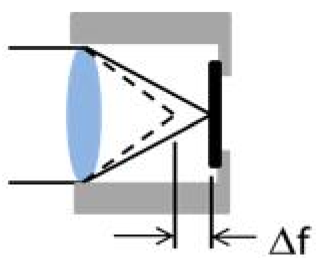
$$\Delta f = \beta f \Delta T$$

$$\beta = \alpha_{lens} - \frac{1}{n-1}\frac{dn}{dT}$$

β = therm-optic coefficient



$$\Delta f = f\left(\beta_{lens} - \alpha_{housing}\right)\Delta T$$



Athermal Chart – β vs. 1/V

Å Consider the equation for a line y = mx + b between two points (x_1,y_1) and (x_2,y_2)

$$y = \left(\frac{y_2 - y_1}{x_2 - x_1}\right)x + b$$

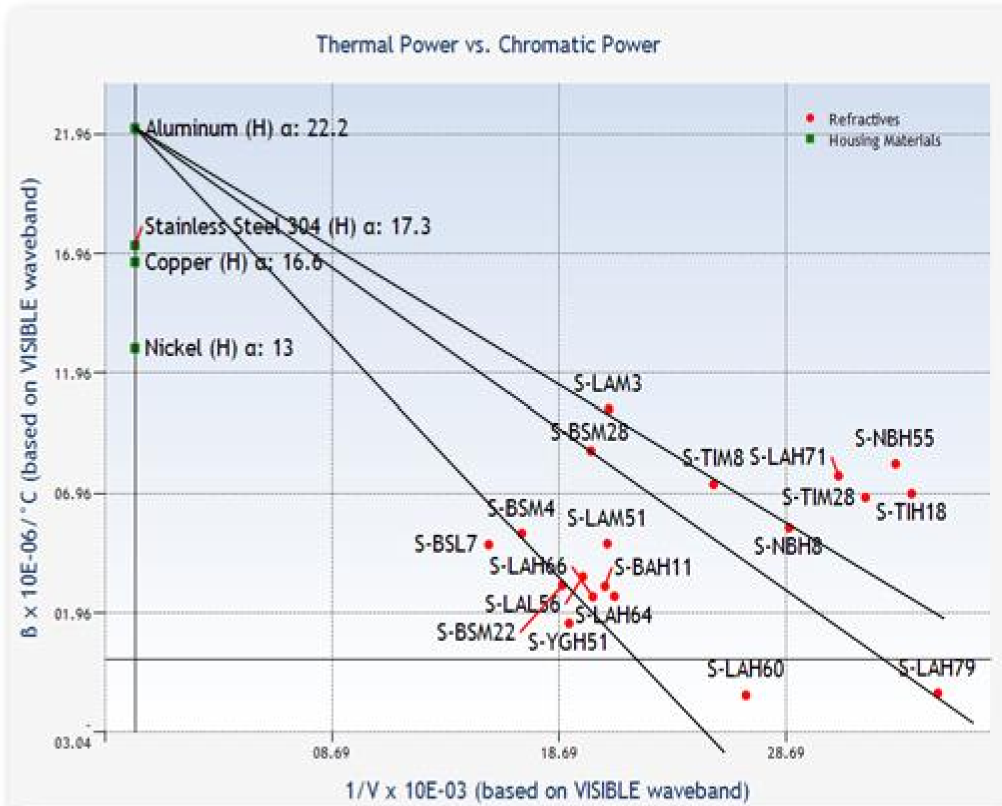
Å Solve for the y-intercept

$$b = \frac{y_1 x_2 - y_2 x_1}{x_2 - x_1}$$

Å If we plot β vs. 1/V, then

$$\alpha_h = \frac{\beta_1 \cdot \frac{1}{V_2} - \beta_2 \cdot \frac{1}{V_1}}{\frac{1}{V_2} - \frac{1}{V_1}}$$

where α_h is the CTE of the housing



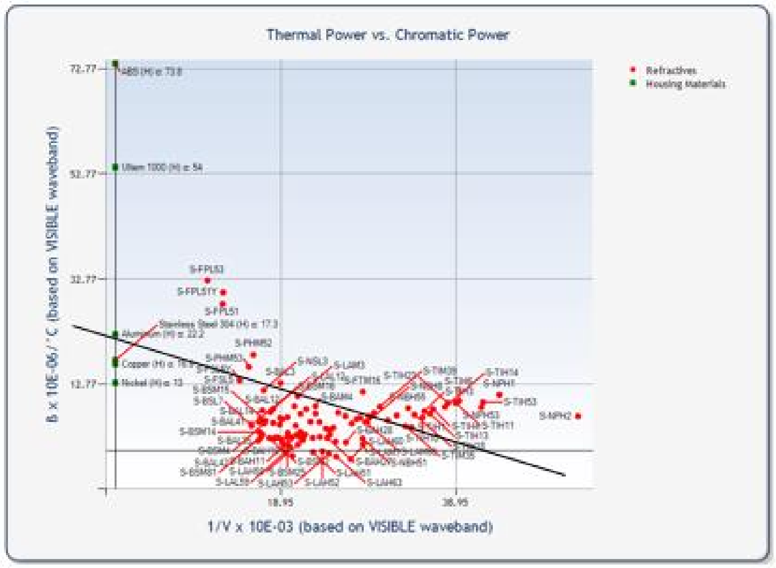
Å Need to find two glasses on a line from the housing material CTE

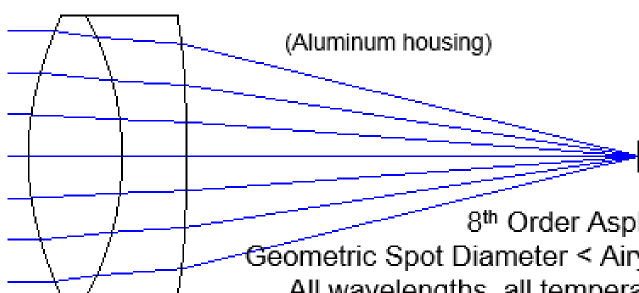
ï Allows two materials to satisfy both color and athermal correction

Example Athermal Design for the Visible

- Want thermal defocus and axial color to be less than the λ/4 depth of focus

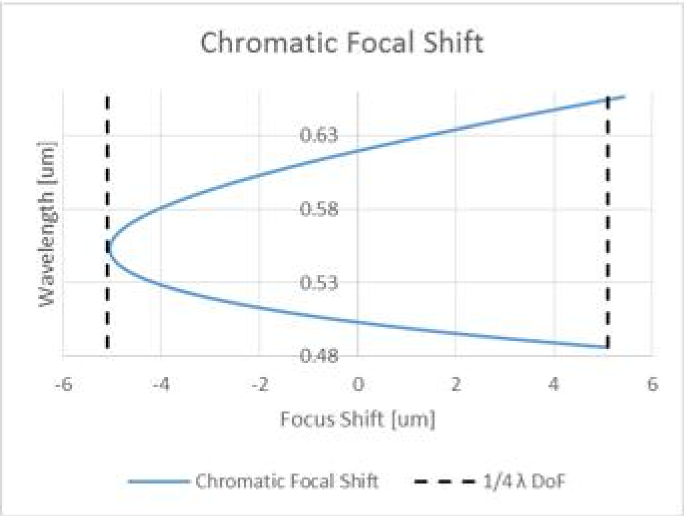
$$\pm 2\lambda(F/\#)^2 = \pm 2(0.587\,\mu m)(2)^2 = 10.2\,\mu m$$

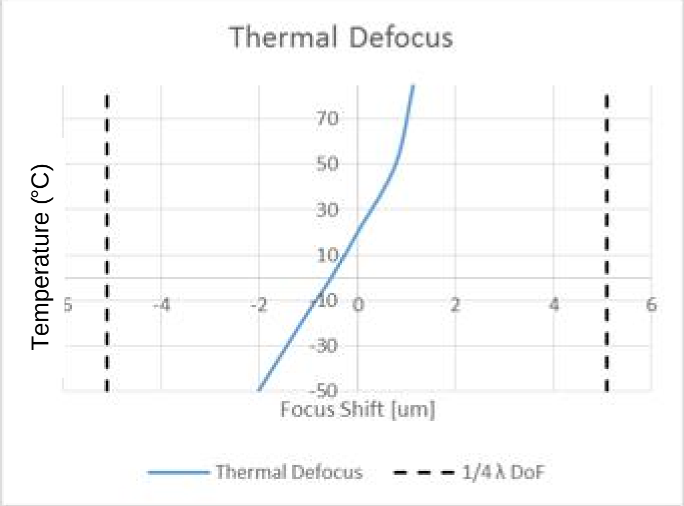




S-PHM53 & S-LAM66

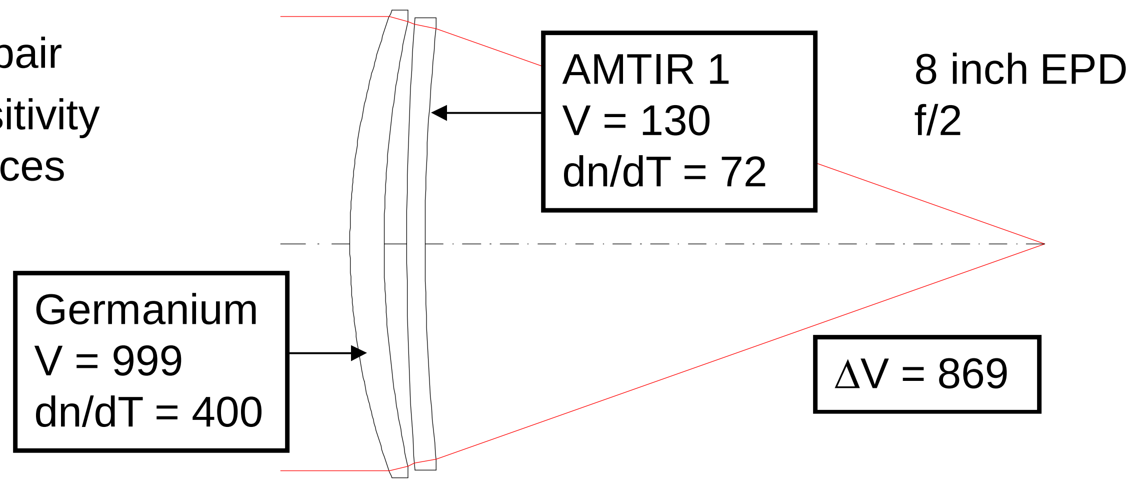
F/2
8th Order Aspheres
Geometric Spot Diameter < Airy disk
All wavelengths, all temperatures
Spherical solution only works to F/4





IR Achromatic Examples (8 – 11.5 μm)

Å Common IR achromatic pair
- ï Up to 25% less sensitivity to dispersion tolerances



Å Reduced dn/dT achromatic pair
- ï 3X lower change in focus due to temperature