Design of a Cooke Triplet

May 6, 2009

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Ryan Cooper
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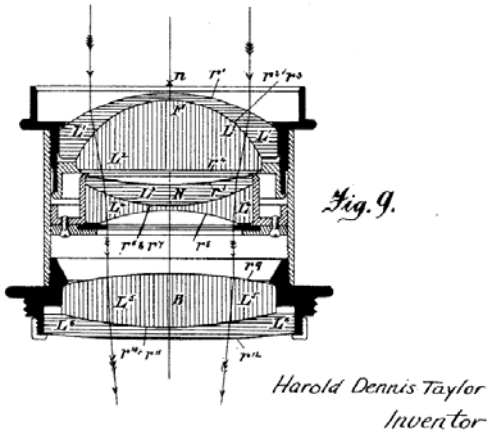


Basics of a Cooke Triplet

- Composition: a negative lens with low V-value (flint) between two lens with high V-values (crowns)

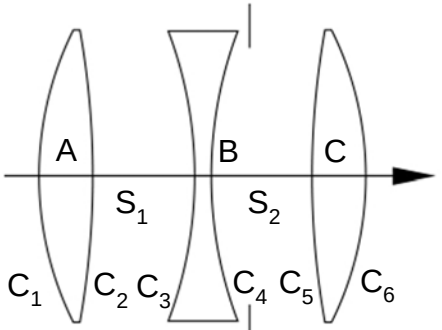


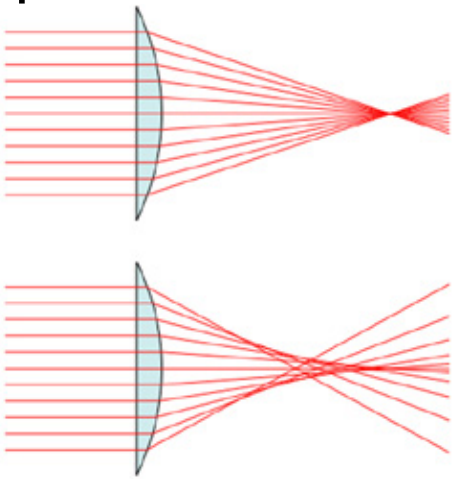
Image from Wikimedia Commons.

- Feature: the smallest number of elements that can correct all 7 Seidel aberrations:
  - *Monochromatic*: spherical aberration, coma, astigmatism, field curvature, distortion.
  - *Chromatic*: axial chromatic aberration and lateral chromatic aberration.

- Design Principles:
  - Choice of lens powers such that their sum ~0
  - Use of spaced positive and negative lenses
  - Use of approximate front-to-back symmetry

Monochromatic Seidel Aberrations

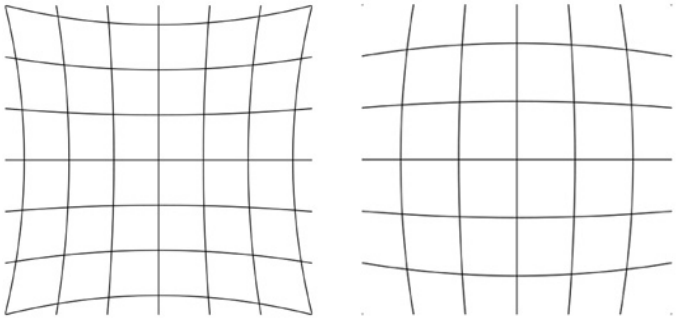
- Spherical aberration:



- Coma:

http://commons.wikimedia.org/wiki/File:Lens-coma.svg

- Distortion:



- Astigmatism:

http://commons.wikimedia.org/wiki/File:Astigmatism.svg

- Field curvature:

Images removed due to copyright restrictions. Please see Fig. 5.2, 5.4, 5.7, 5.8, and 5.9 in Smith, W. *Modern Optical Engineering*.

Design Objective

- Design a Cooke Triplet with minimal Seidel aberrations using Zemax to vary the available degrees of freedom:
  - ✓ 6 curvatures
  - ✓ 3 lens thicknesses
  - ✓ 2 air spaces
  - ✓ 3 glass choices

Total: 14 Variables

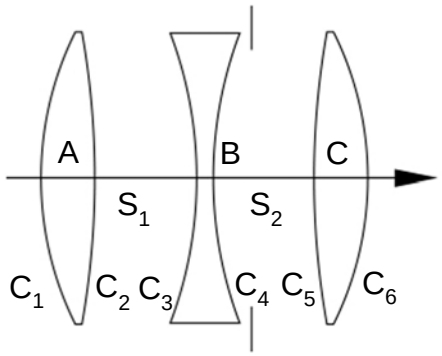
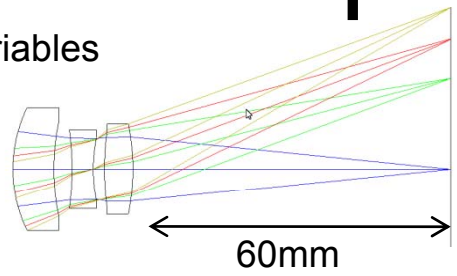


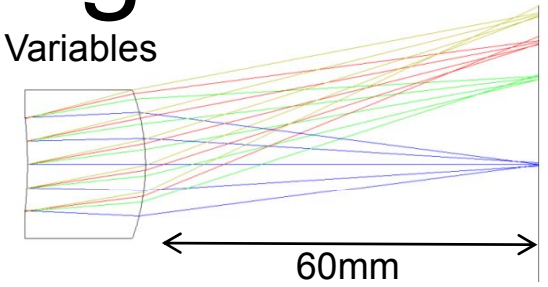
Image from Wikimedia Commons.

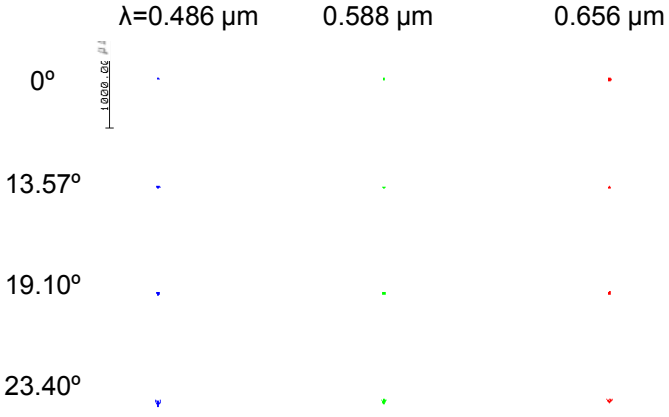
Cooke Triplet vs. Single Lens

14 Variables

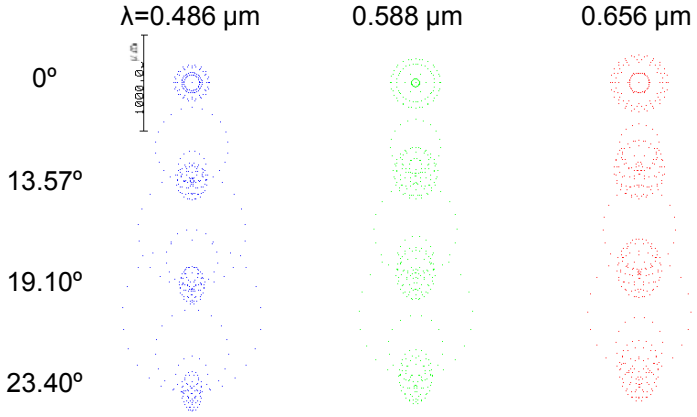


4 Variables

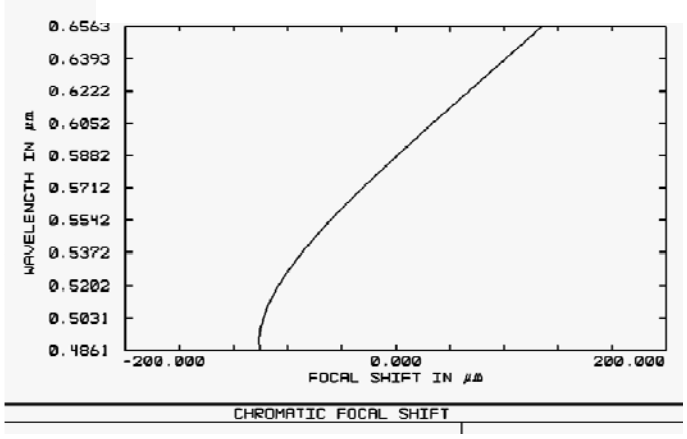


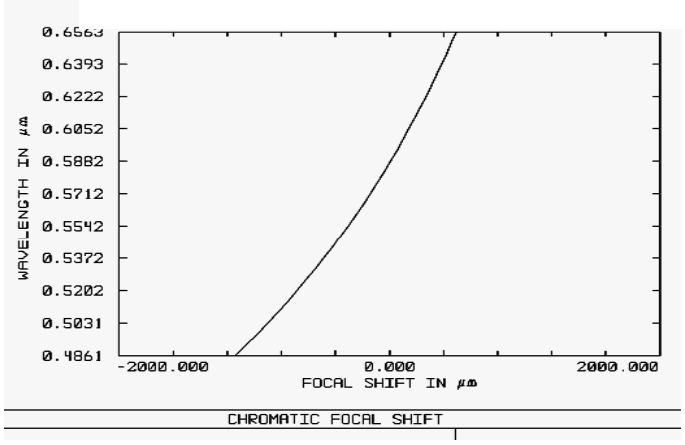


Spot iagrams

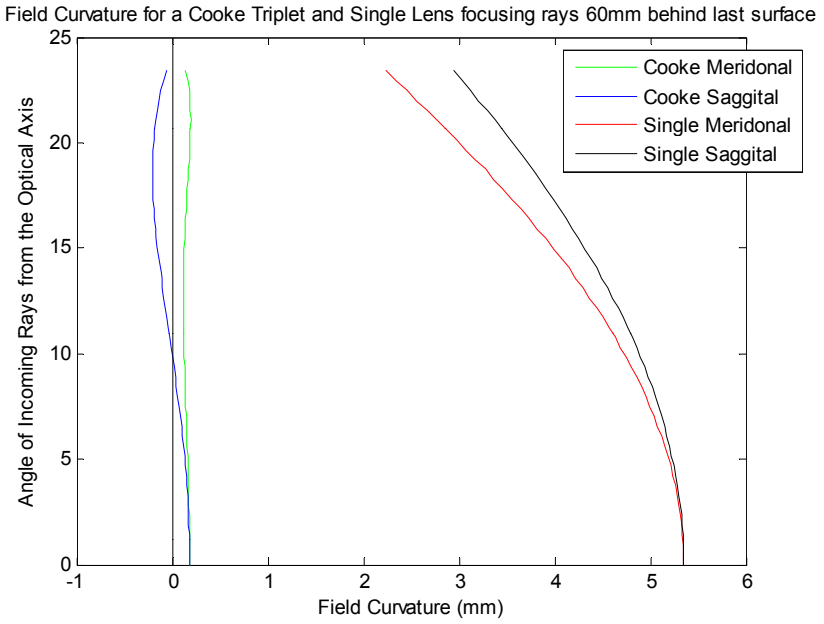


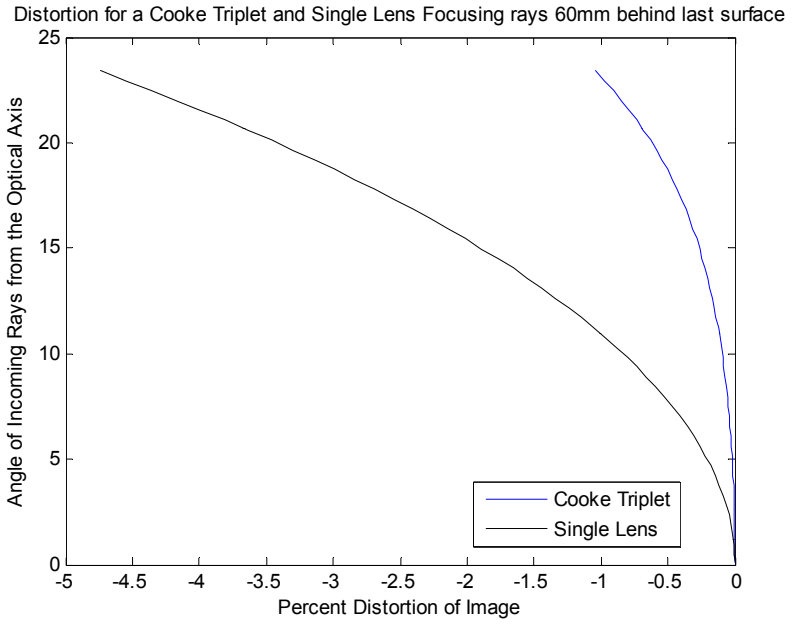
Chromatic Aberration

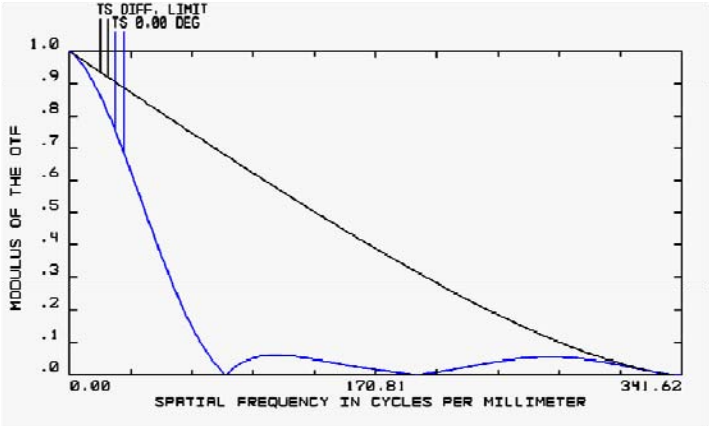




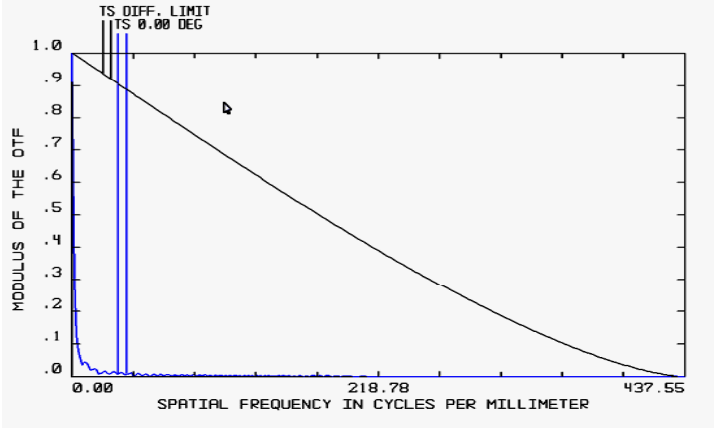
Cooke Triplet vs. Single Lens



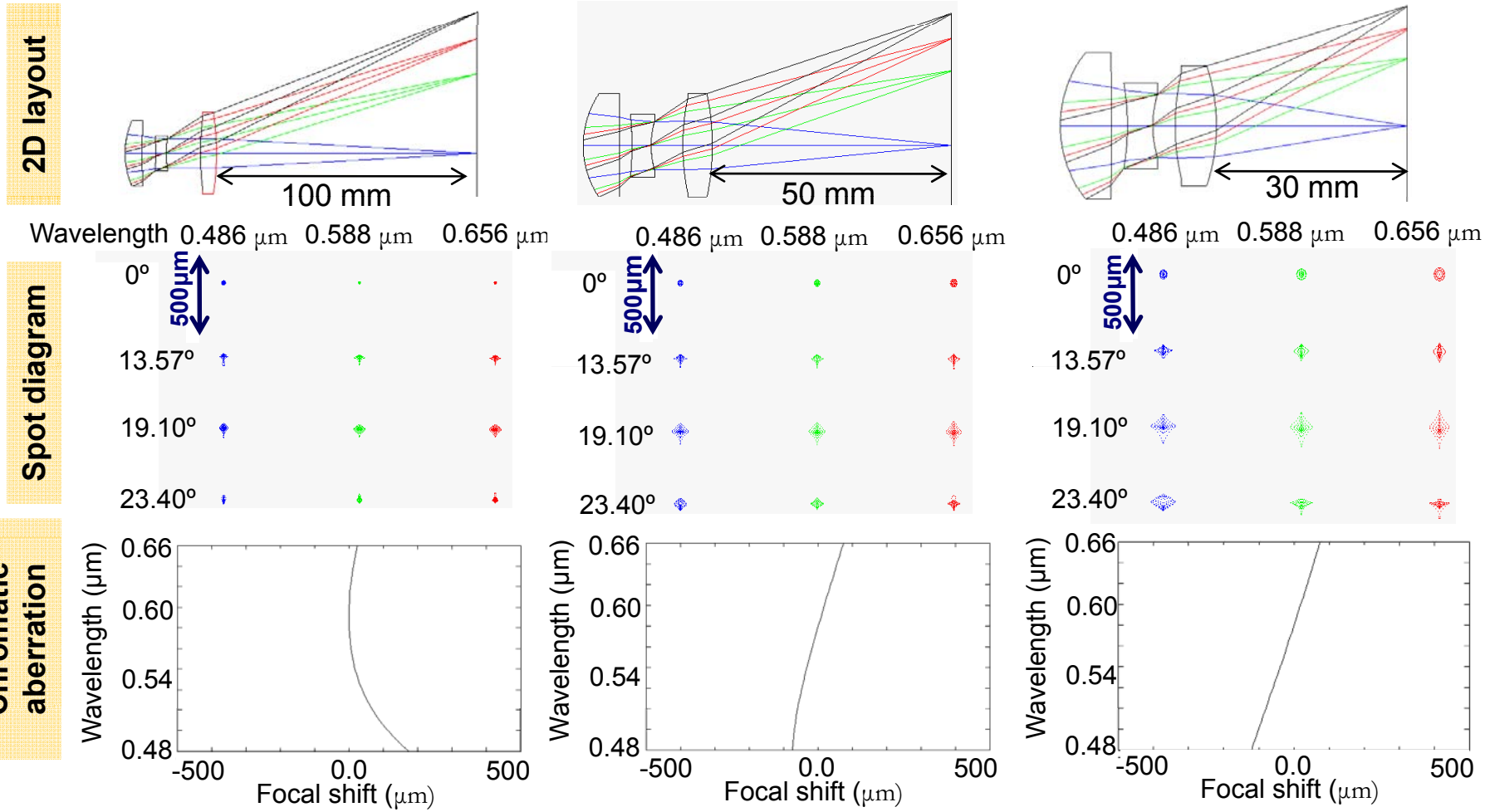




Modulation Transfer Function



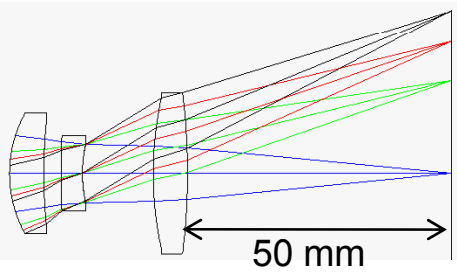
Cooke Triplet (ID=100, 50, 30mm) : Different image distances

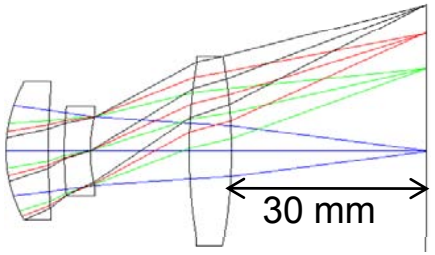


- ✓ 11 variables (glass choice is fixed), infinity object
- ✓ Shorter image distance: Thicker lens and short distance between positive and negative lenses
- ✓ Large spot and aberration from short focal length

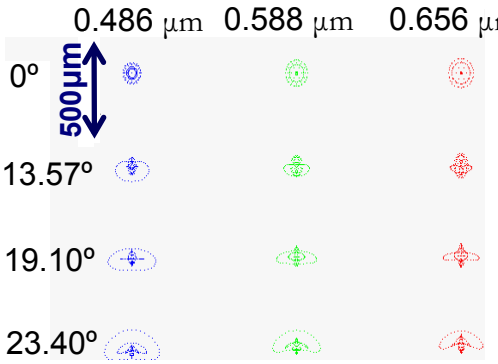
Cooke Triplet (ID=50, 30mm) : Lens thickness limitation

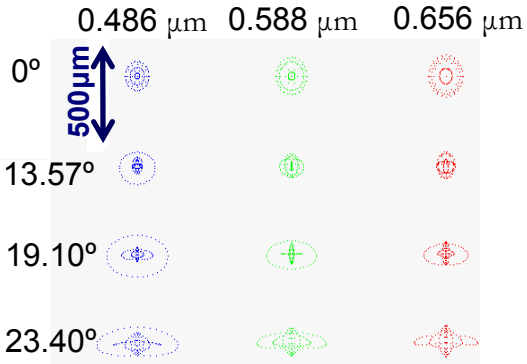
2D layout



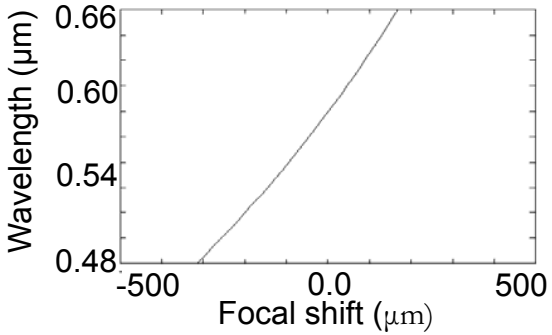


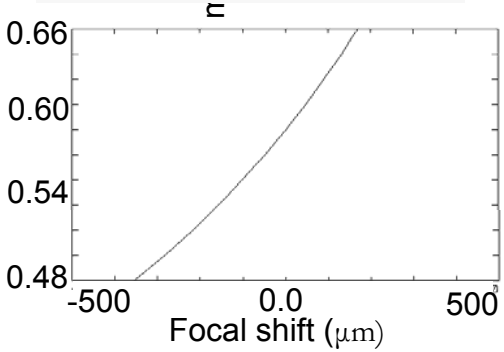
Spot diagram





Chromatic aberration





- ✓ 8 variables (glass choice and lens thickness is fixed), infinity object
- ✓ Lens thickness : 2 positive lens (6.5 mm), and 1 negative lens (4 mm)
- ✓ Lens thickness is very critical to decrease aberration (cannot ignore in optimization)
- ✓ Thickness constraint increases the distance between negative and 2nd positive lens

Glass Optimization

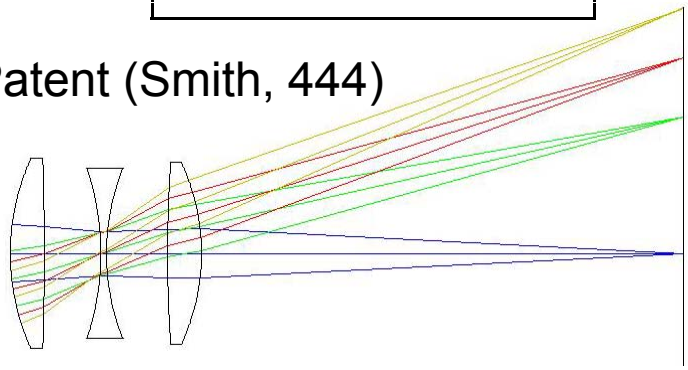
Constant distances and minimal changes to curvatures:

Glass	n	V-value
SK4	1.61	58.62
FN11	1.62	36.17
SK4	1.61	58.62

Optimization →

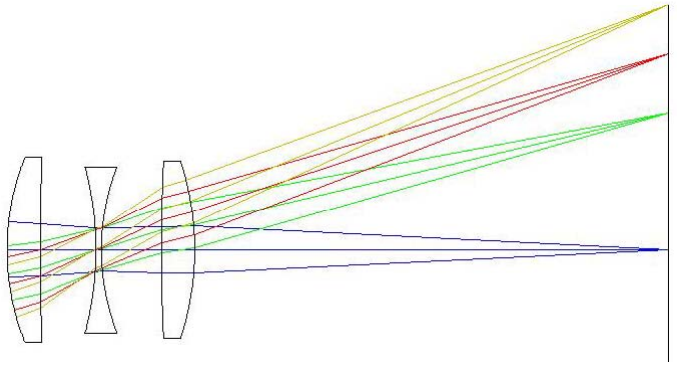
Glass	n	V-value
LAK33	1.75	52.43
BASF2	1.62	30.97
LAK33	1.75	52.43

Patent (Smith, 444)

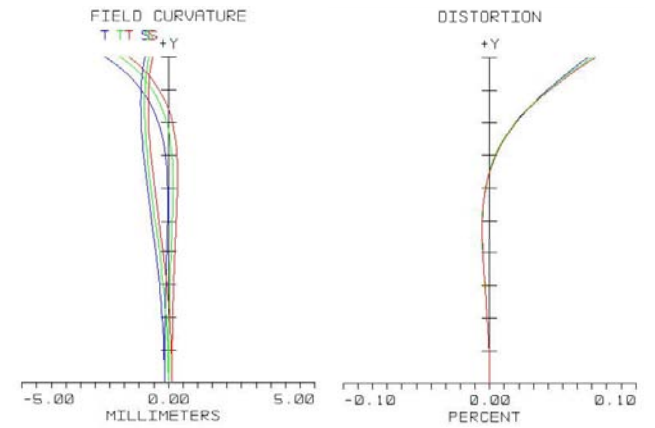


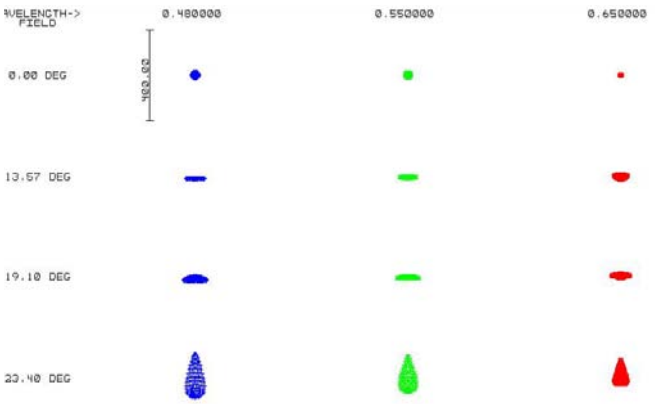
Surf	Radius	Thickness	Diameter
1	40.1	6.0	33.4
2	-537.0	10.0	33.4
3	-47.0	1.0	30.0
4	40.0	10.8	30.0
5	234.5	6.0	32.0
6	-37.9	85.3	32.0

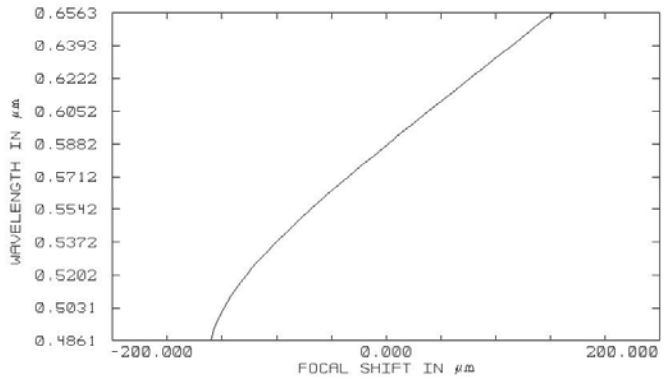
- Negative element with same n and higher dispersion.
- Positive element with higher n and higher dispersion.

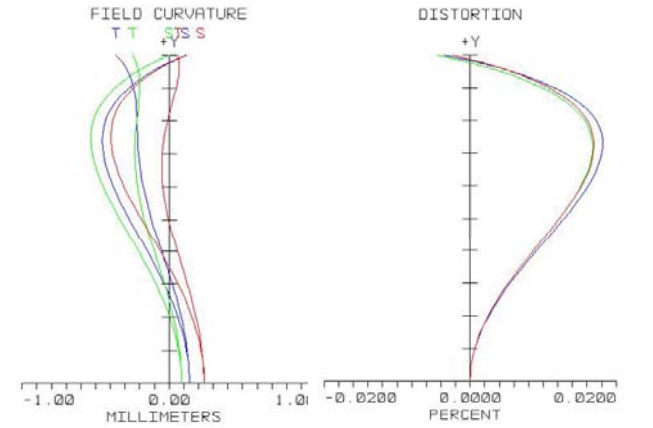


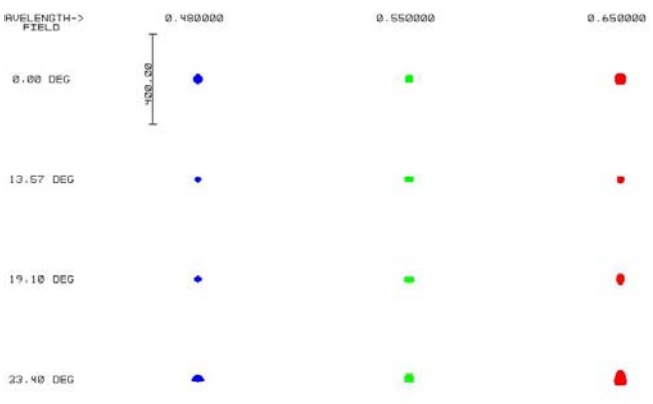
Patent (Smith, 444)

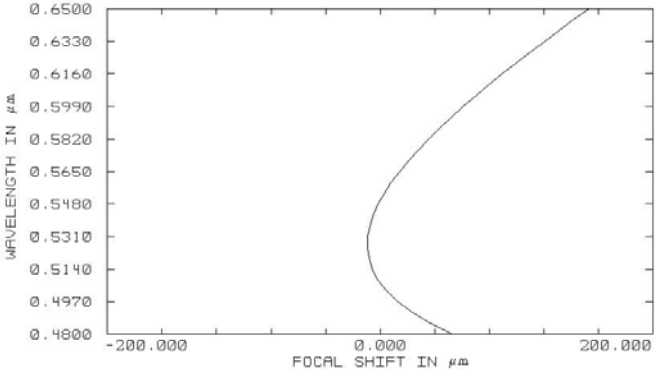










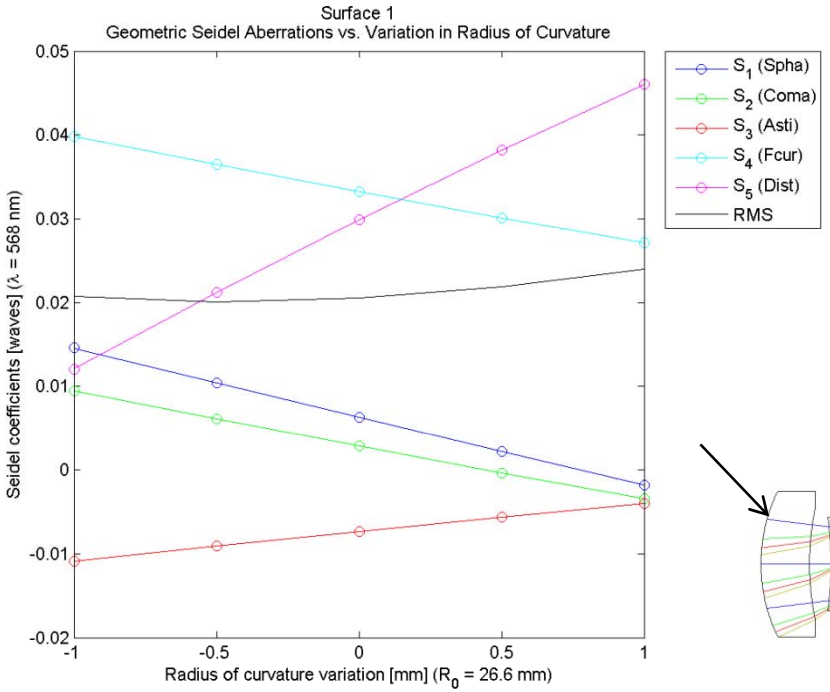


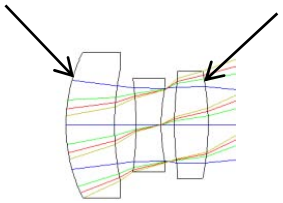
Optimized Design

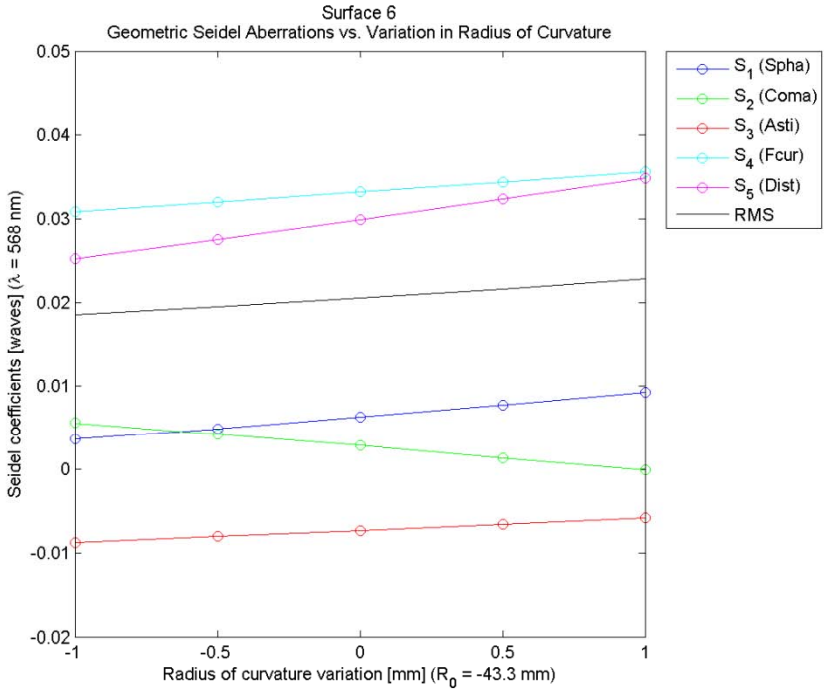
- Increase in (n_{crown} - n_{flint}) reduces field curvature and distortion.
- Increase in (n_{crown} - n_{flint}) reduces astigmatism and coma.
- Increase in (n_{crown} - n_{flint}) reduces chromatic aberration.

Variations from optimal design (1)

- From the optimized triplet, varied each surface's radius of curvature slightly (±1 mm) to determine effect of a given surface on aberrations



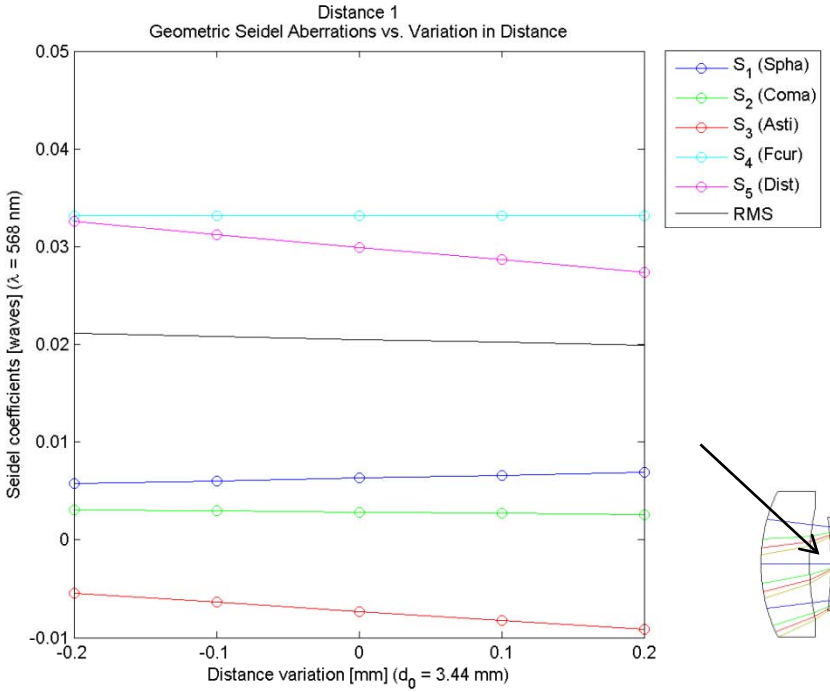


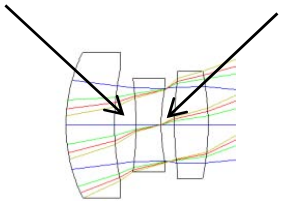


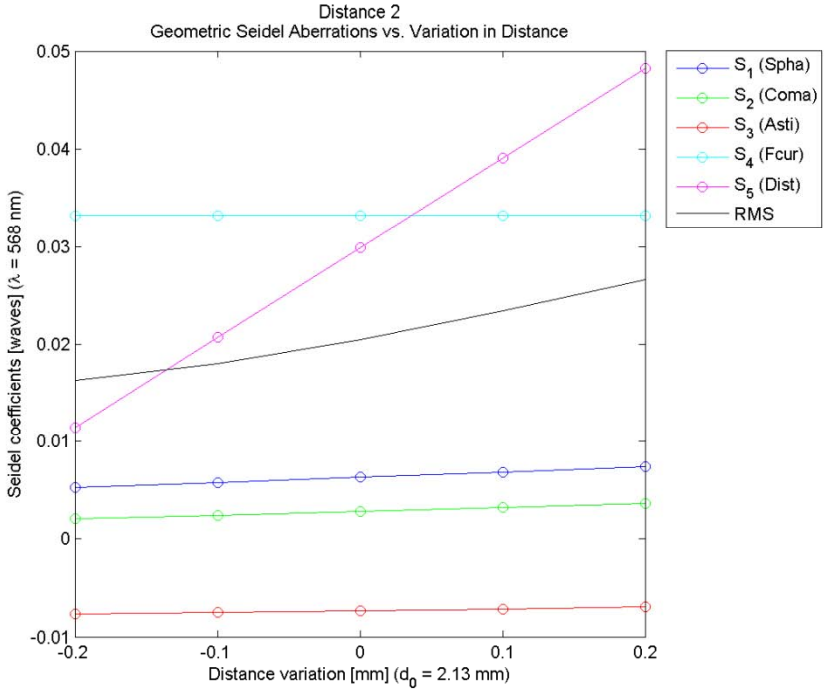
- First lens is relatively highly curved → contribution to distortion is pronounced
- Also considerably more sensitivity in first lens for spherical aberration, coma, and field curvature
- Aberrations nearly at a minimum for 1st surface (not so for other lenses); first surface adds the bulk of the aberrations, Zemax will force this surface to a minimum so that "downstream" lenses have less to correct

Variations from optimal design (2)

- Also changed the spacing between the lenses (±0.2 mm) to represent possible challenges with alignment in real systems







- Greater sensitivity to perturbations in the spacing between second and third lenses (“Distance 2”), particularly distortion.
- Note that field curvature is unchanged by variations in distance; due to the fact that field curvature depends on lens power (and focal length), not on lens placement

Conclusions and Future Work

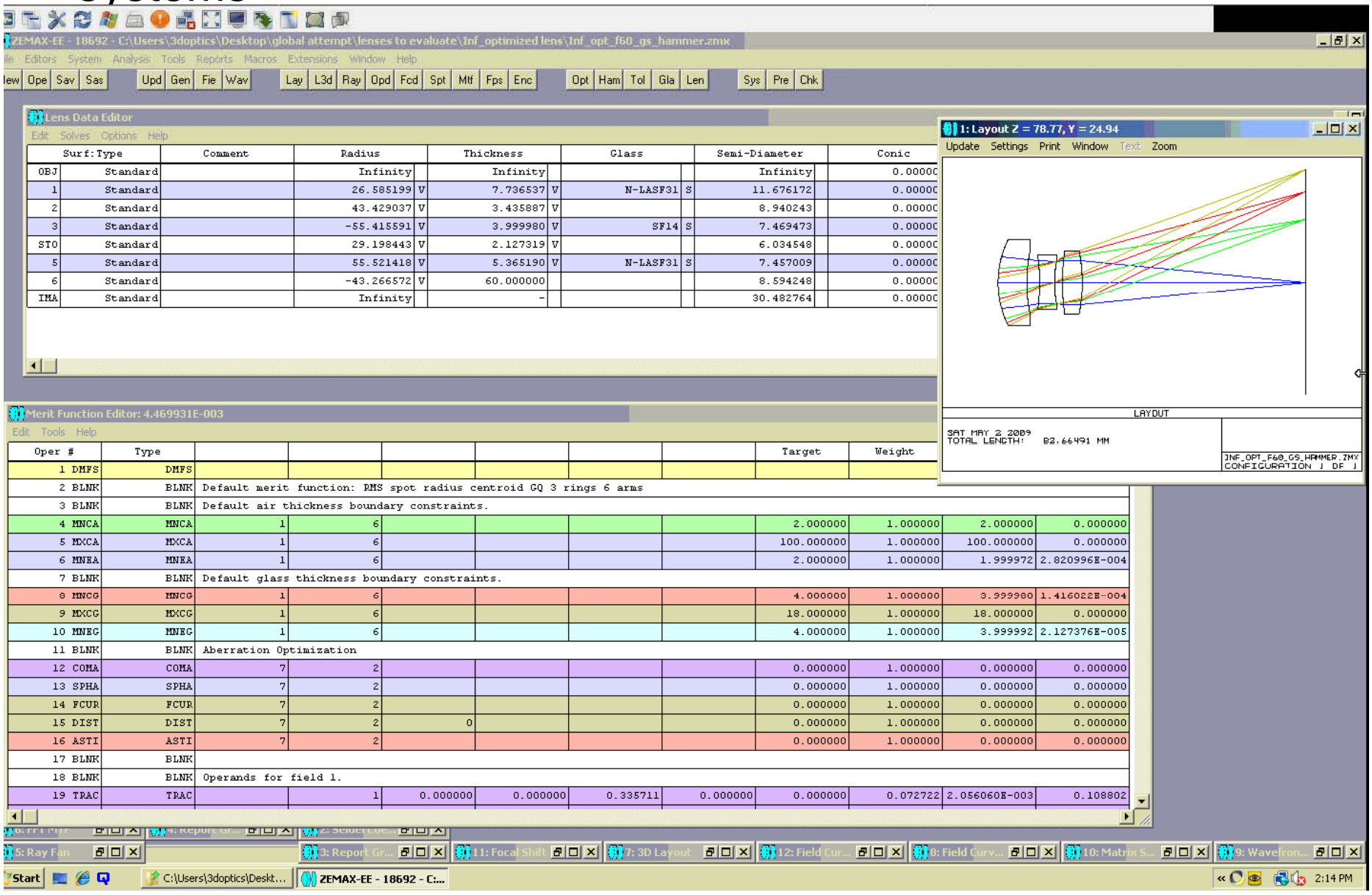
- The first lens in the triplet introduces the majority of the aberrations, the subsequent lens attempt to correct
- Making the first lens aspheric and/or compound to correct some of this initial aberrations could improve the triplet performance further
- Due to the interdependence of all the variables, a large number of iterations (~10^9) are required to find the ‘best’ configuration
- The Cooke triplet greatly reduces the Seidel aberrations while maintaining a relatively large aperture (F/8)

References:

- Smith, W. J. (2007). *Modern optical engineering*. New York, NY: McGraw-Hill Professional.
- Kidger, M. (2001). *Fundamental optical design*. Bellingham, WA: SPIE Publications.
- Goodman, J. W. (1968). *Introduction to Fourier Optics.* San
- Taylor, H. D. (1895). *Lens*. Patent No. 540,122, United States Patent Office.

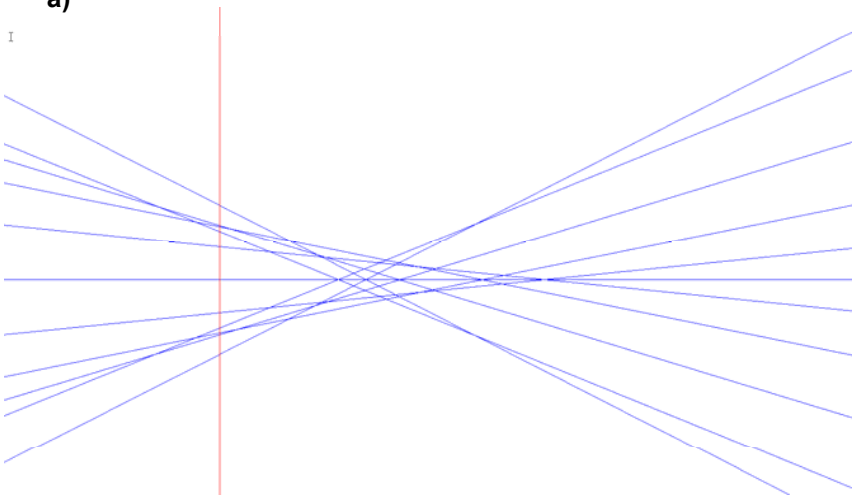
SUPPLEMENTAL INFORMATION

Zemax- model, optimize and analyze the design of optical systems



Ray Diagrams and Ray Fan

a)



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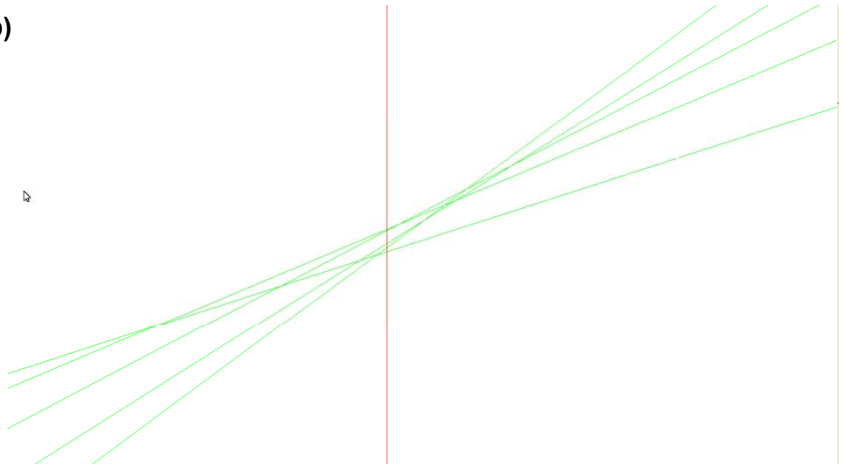

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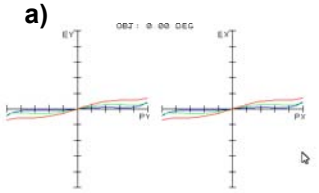

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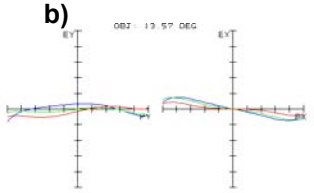

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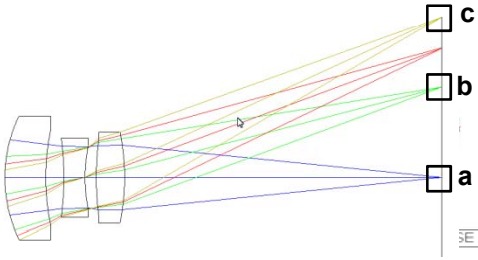

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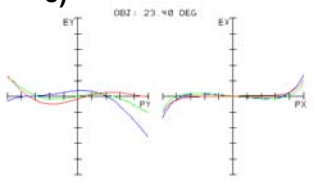
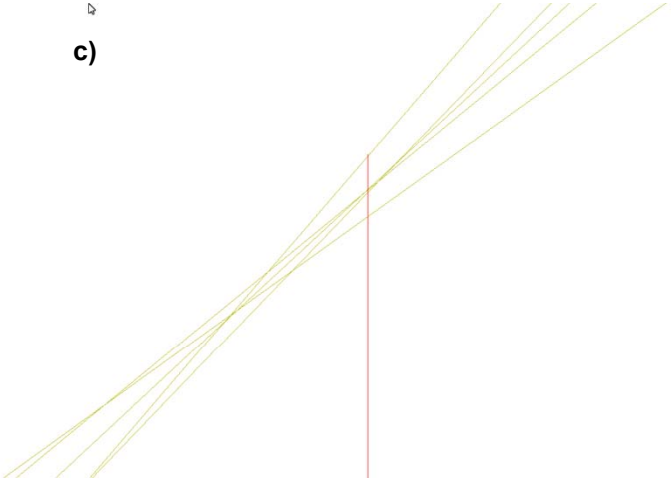


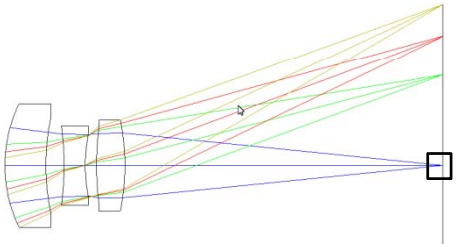
SAT MAY 2 2009
MAXIMUM SCALE: ± 100.000 µm.
0.486 0.588 0.656
SURFACE: IMAGE

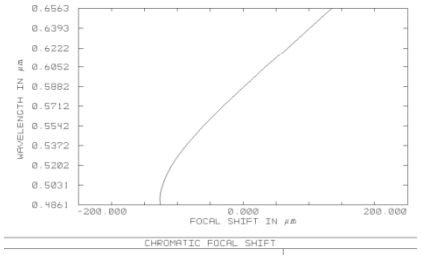
INF_OPT_F60_CS_HAMMER.ZMX
CONFIGURATION 1 OF 1

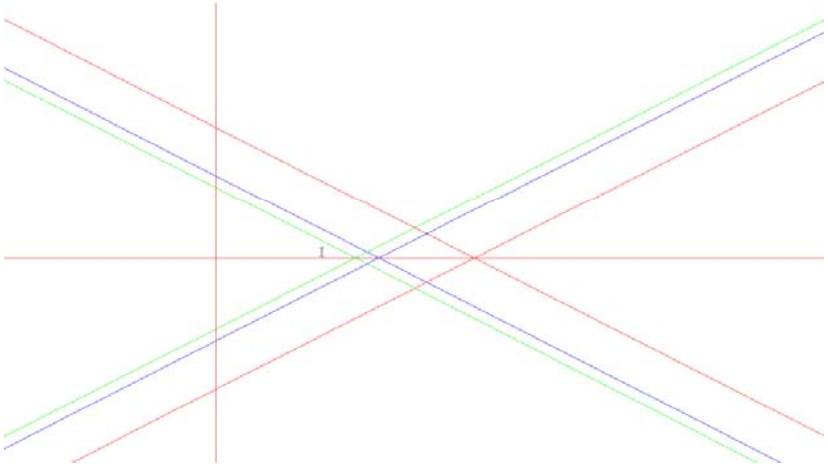
c)



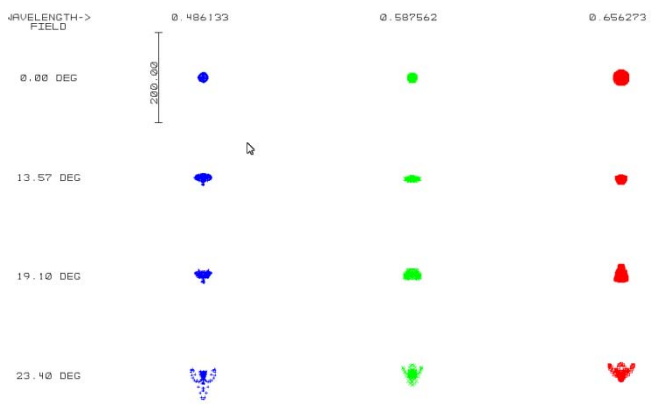
More on Chromatic Abberations

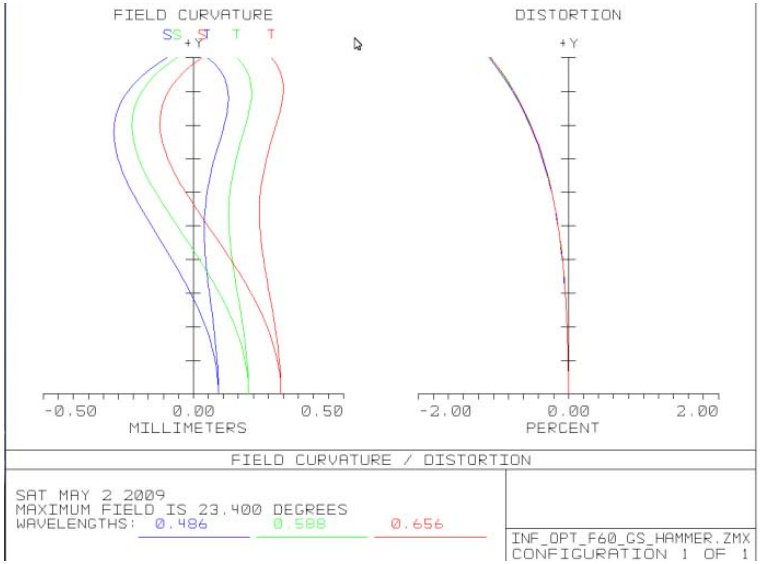






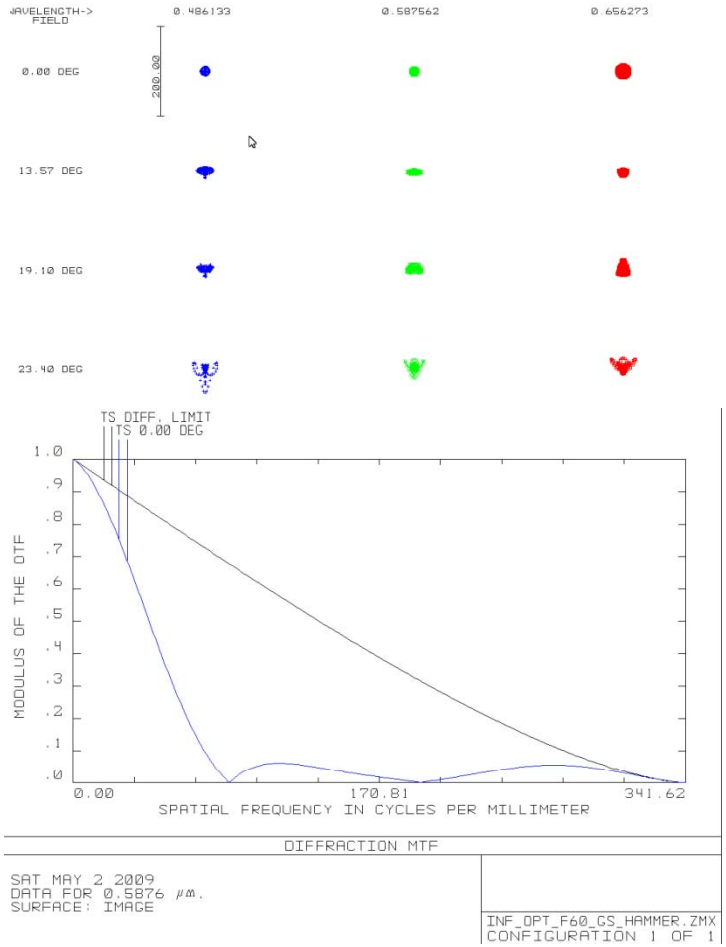
ID=60mm



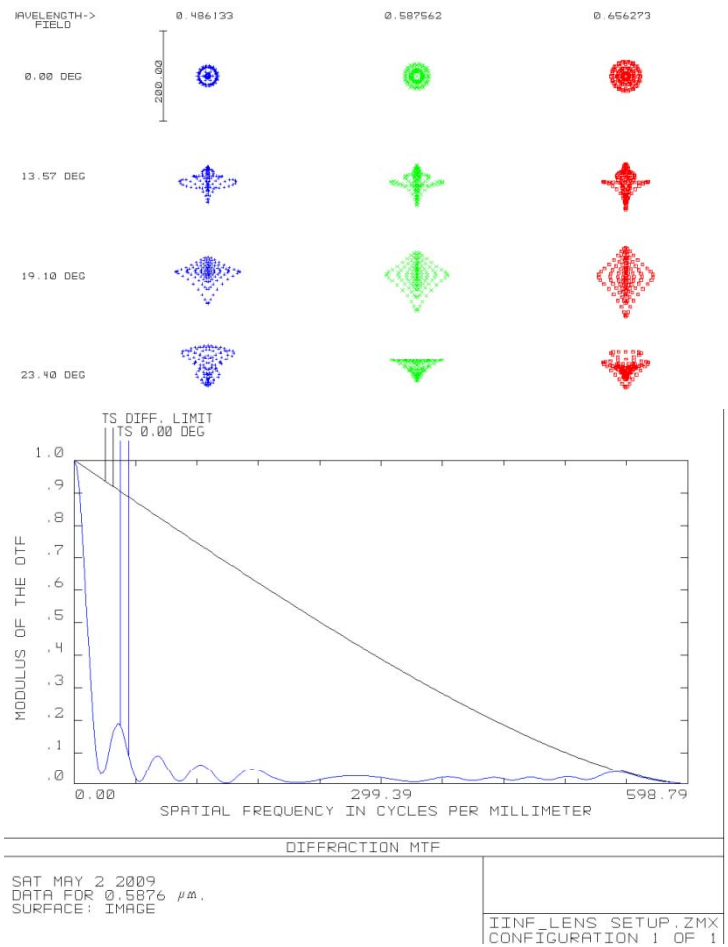


Comparison of ID=60mm and ID=20mm Triplet

ID=60mm

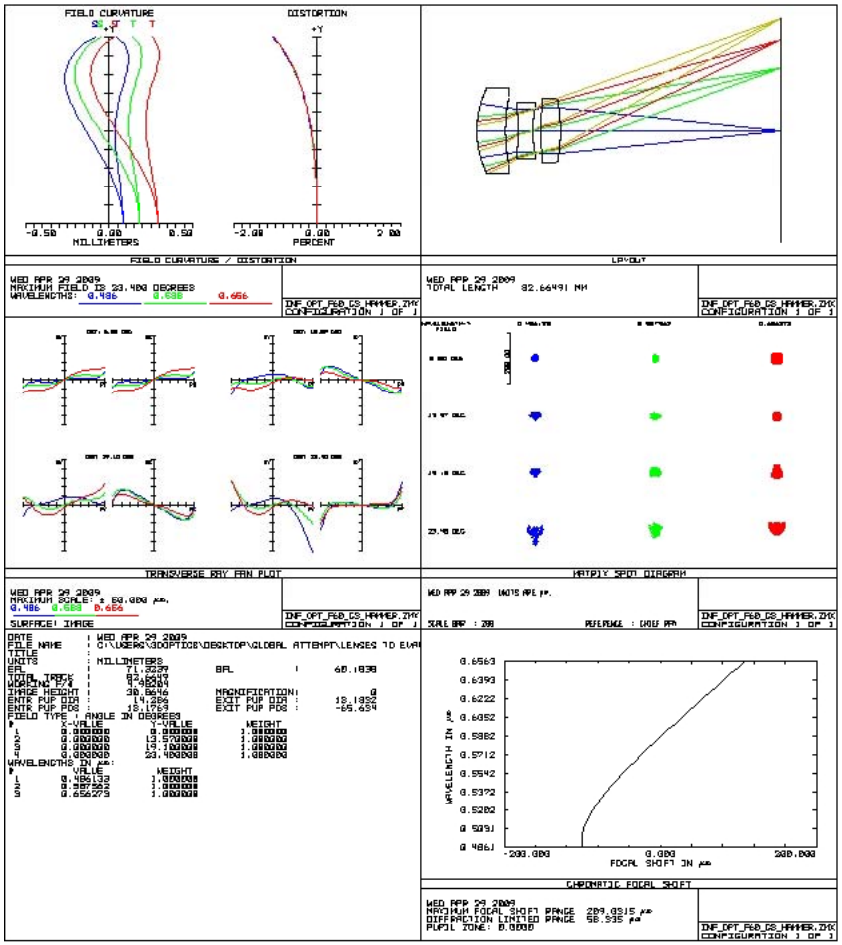


ID=20mm

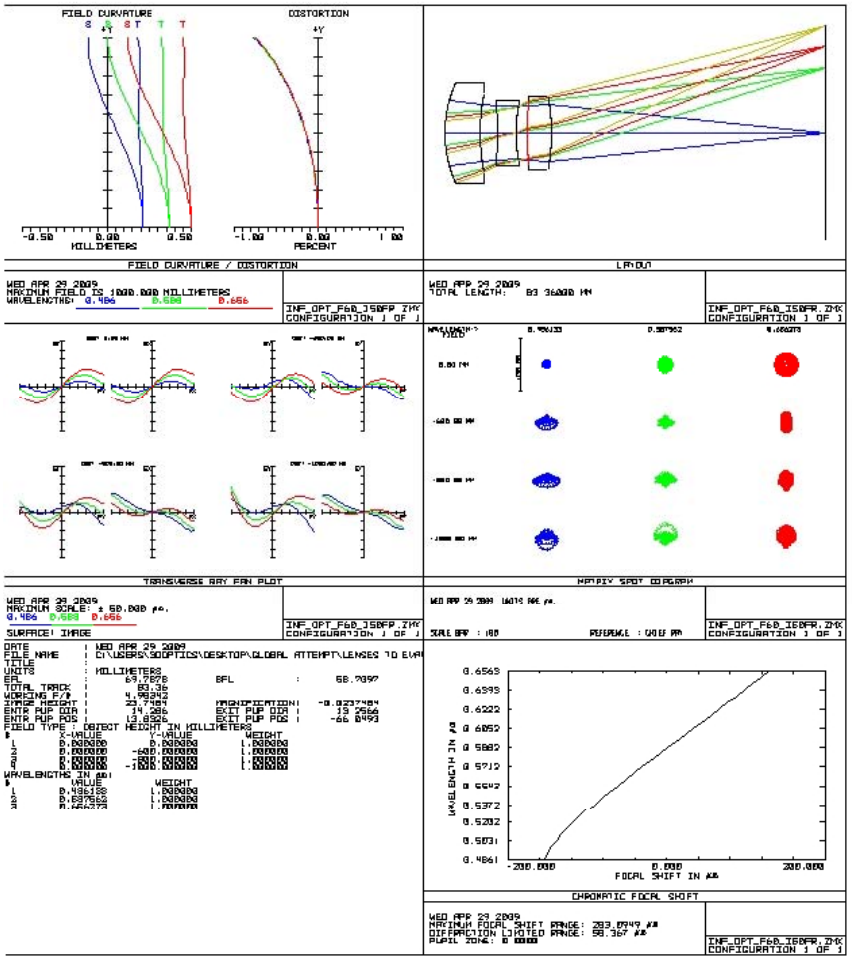


Objects at Finite Distances

OD= Infinity

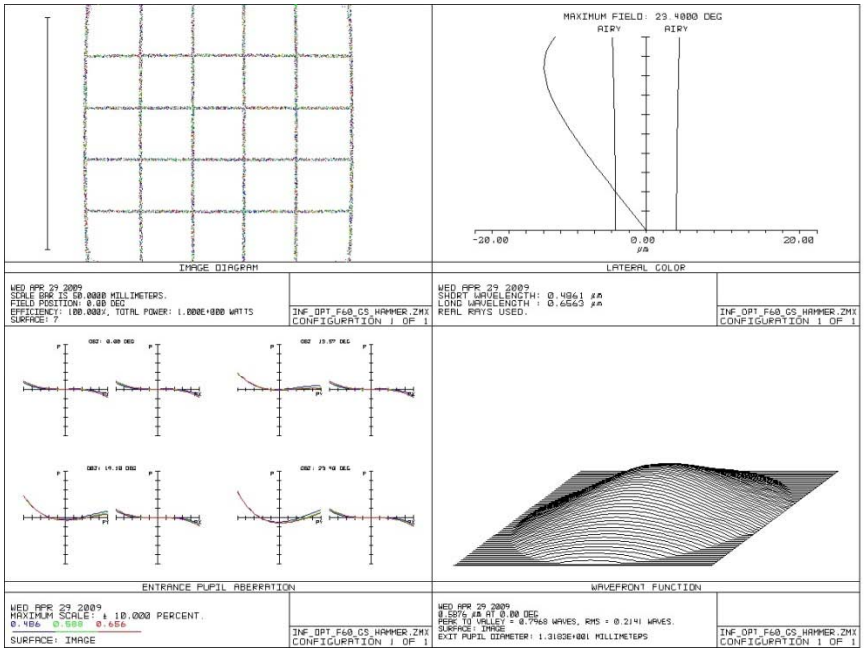


OD= 50xID

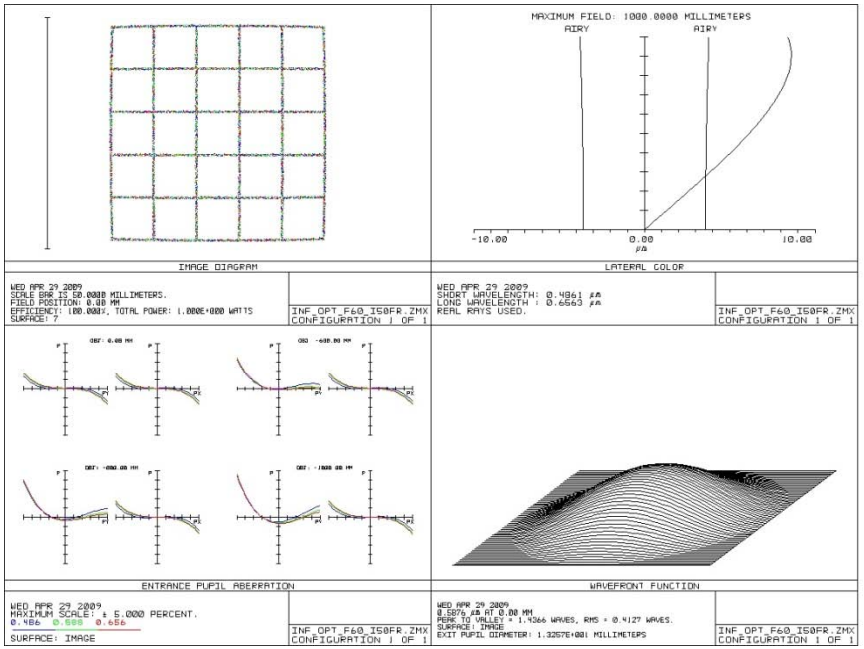


Objects at Finite Distances

OD= Infinity

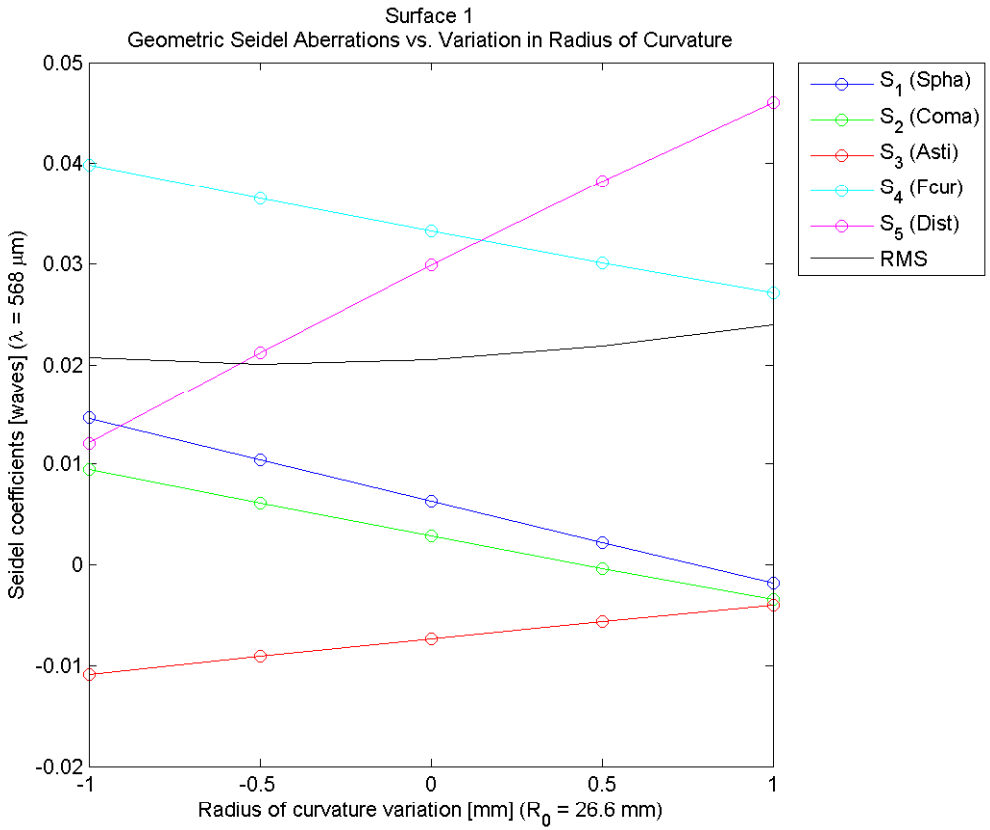


OD= 50xID



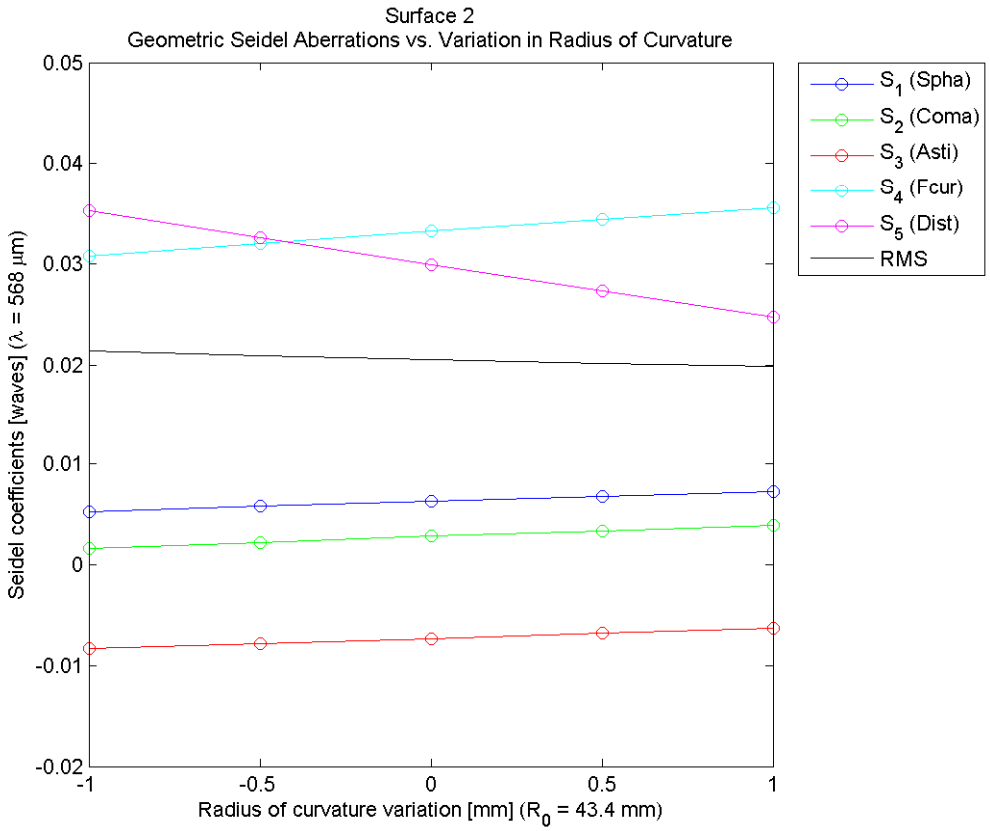
Variations from optimal design

- Surface 1



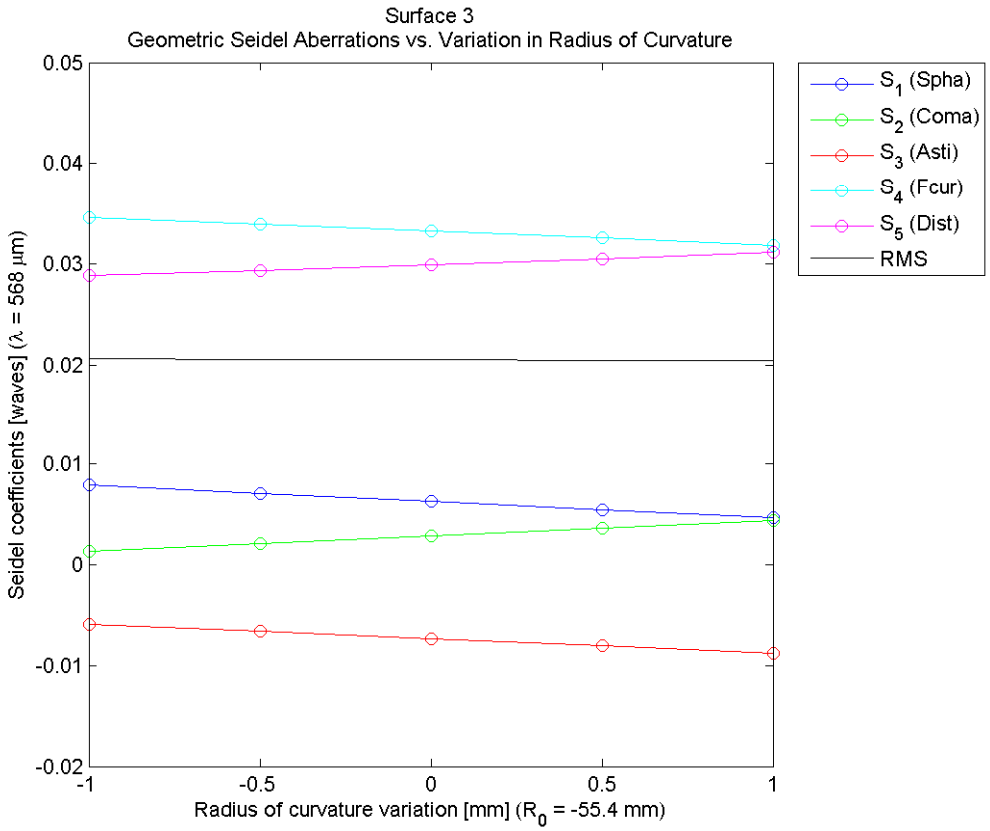
Variations from optimal design

- Surface 2



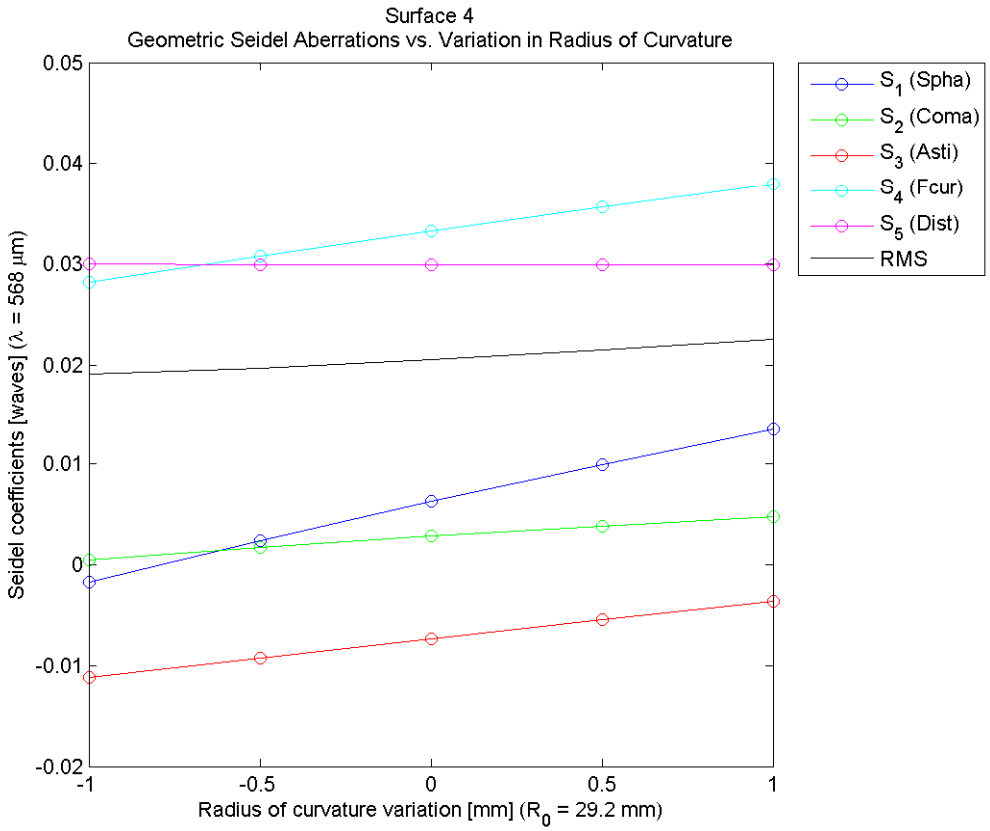
Variations from optimal design

- Surface 3



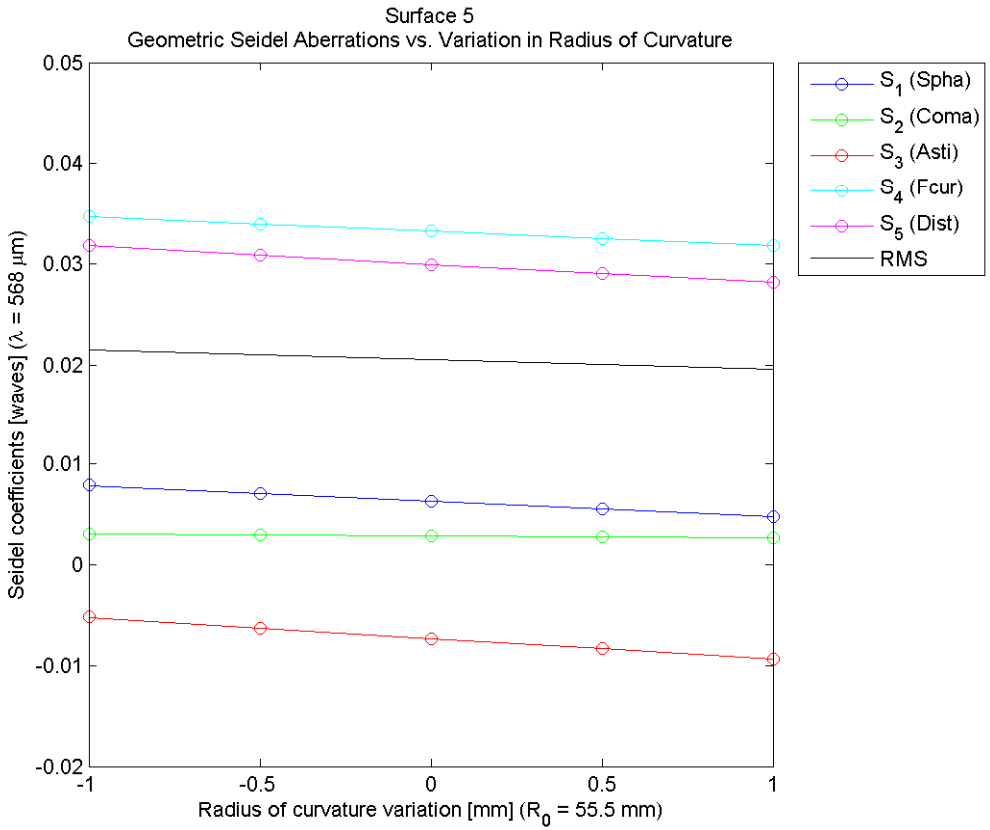
Variations from optimal design

- Surface 4



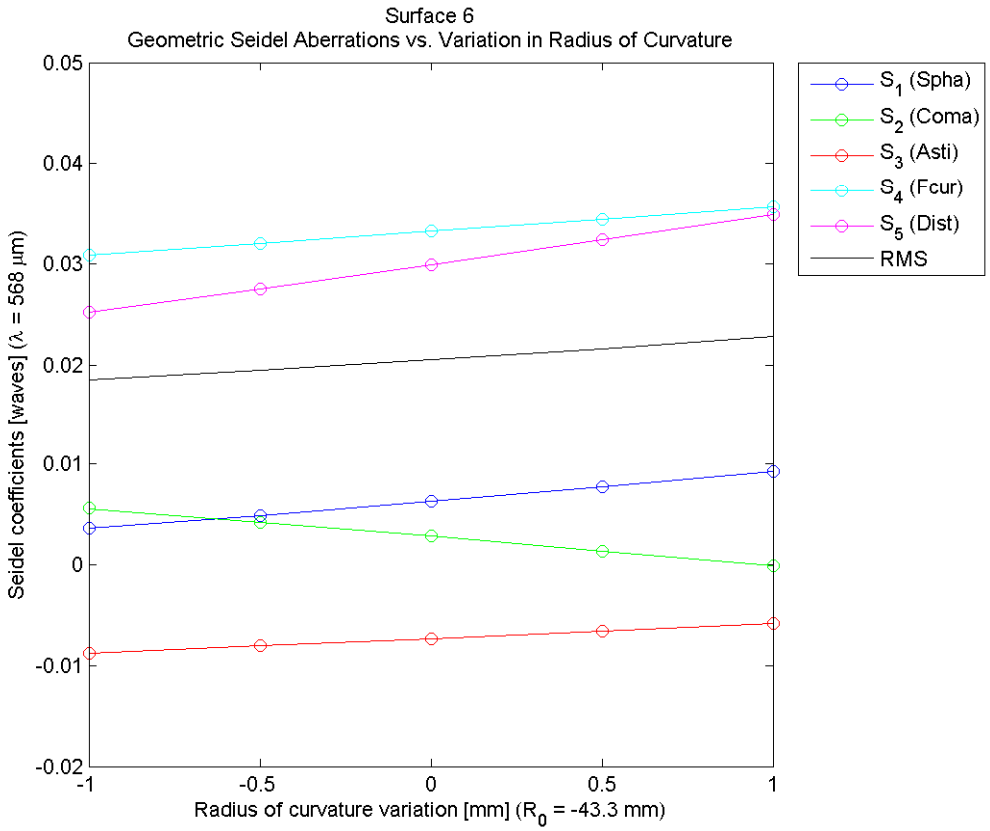
Variations from optimal design

- Surface 5



Variations from optimal design

- Surface 6



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Spring 2009