

Design of a Cooke Triplet

May 6, 2009

Wonjoon Choi
Ryan Cooper
Qunya Ong
Matthew Smith

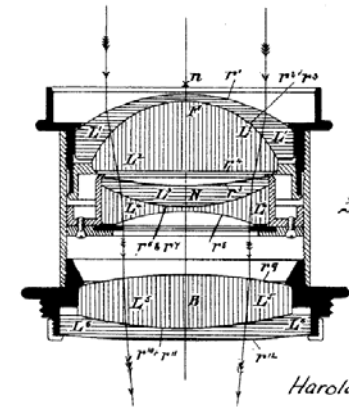


Fig. 9.

*Harold Dennis Taylor
Inventor*

Basics of a Cooke Triplet

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

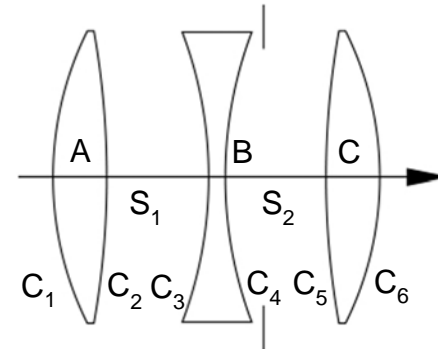
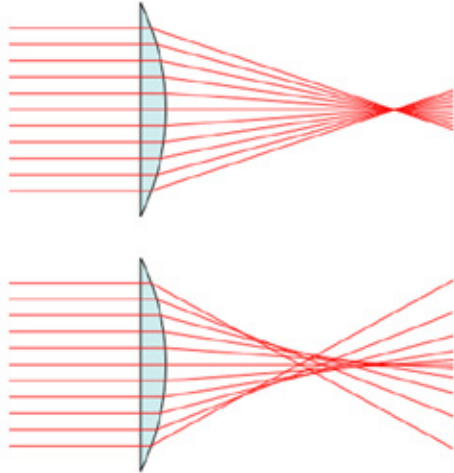


Image from [Wikimedia Commons](#).

- 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

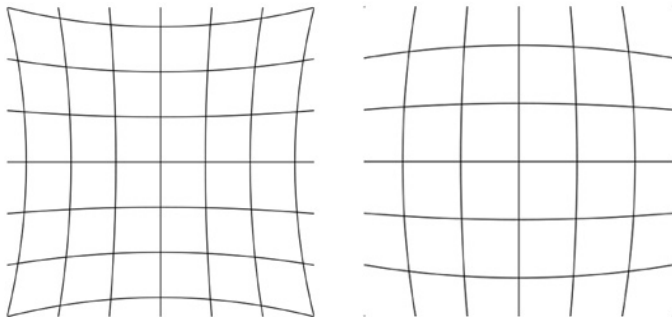
- Spherical aberration:



- 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

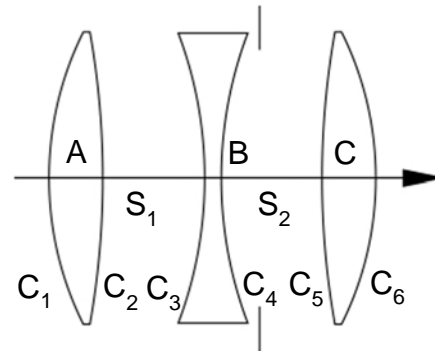
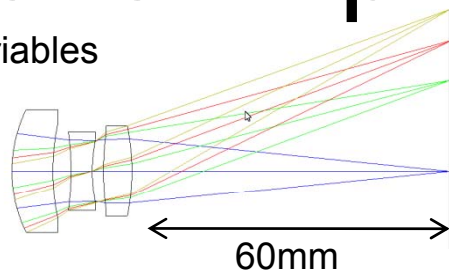


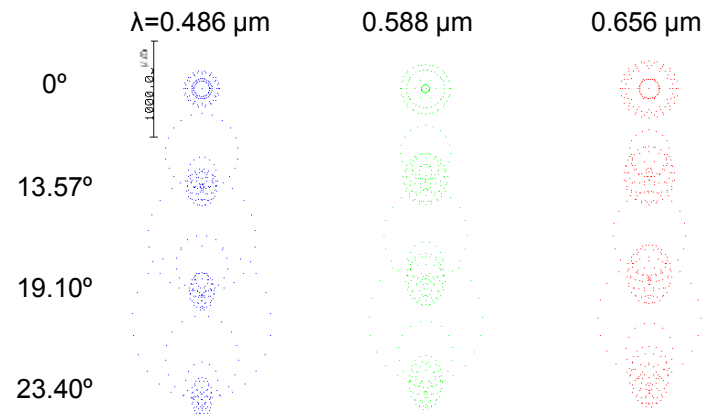
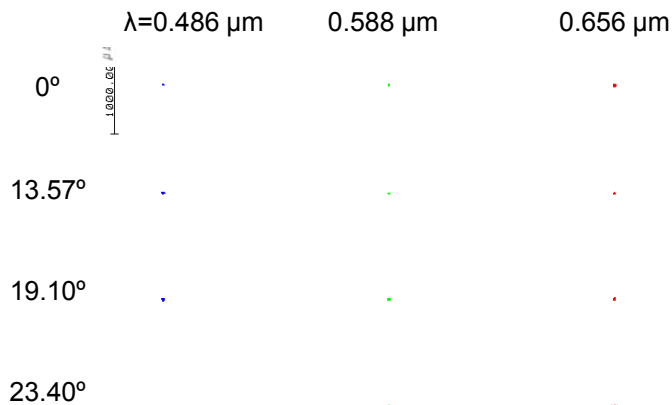
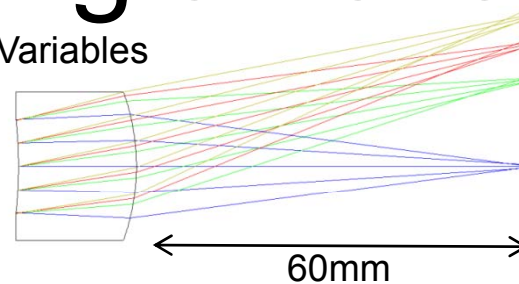
Image from [Wikimedia Commons](#).

Cooke Triplet vs. Single Lens

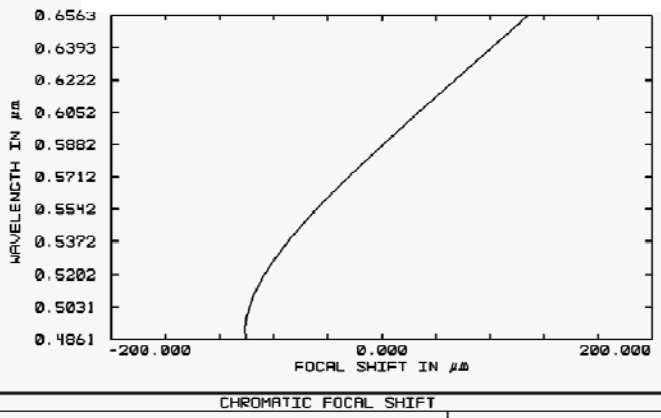
14 Variables



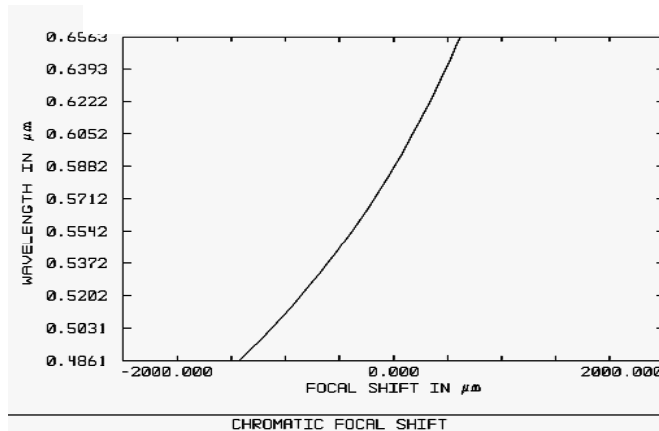
4 Variables



Spot diagrams

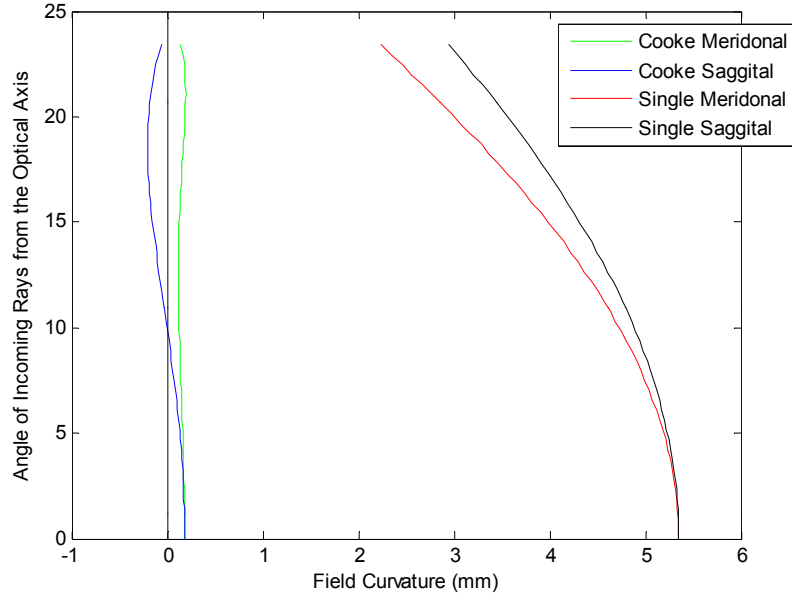


Chromatic Aberration

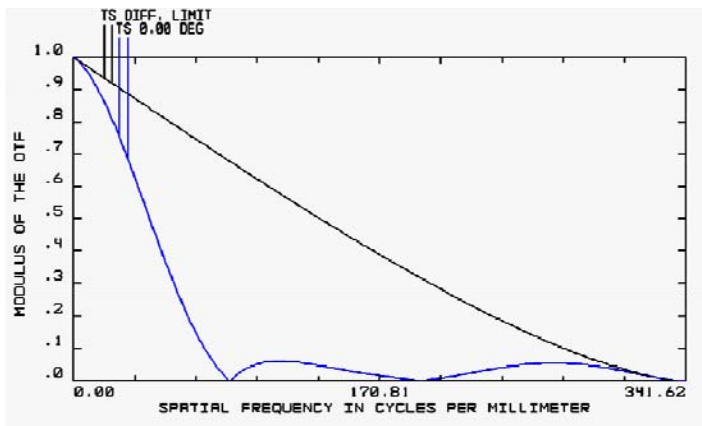
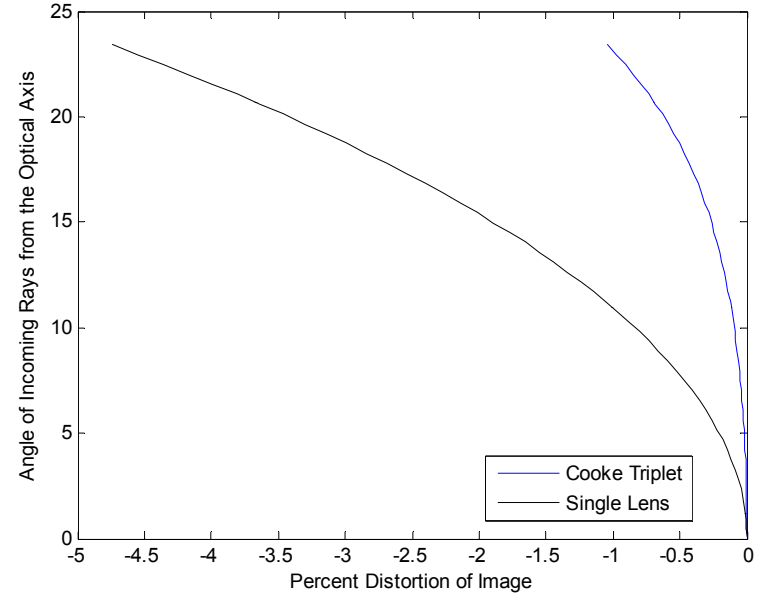


Cooke Triplet vs. Single Lens

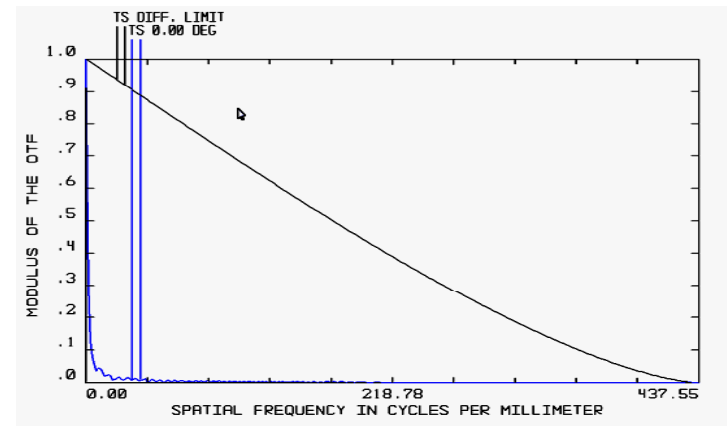
Field Curvature for a Cooke Triplet and Single Lens focusing rays 60mm behind last surface



Distortion for a Cooke Triplet and Single Lens Focusing rays 60mm behind last surface

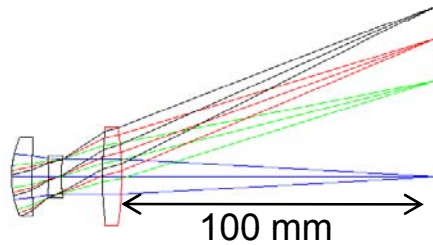


Modulation
Transfer
Function

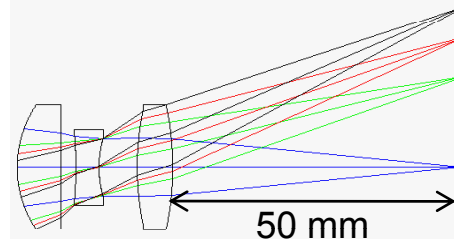


Cooke Triplet (ID=100, 50, 30mm) : Different image distances

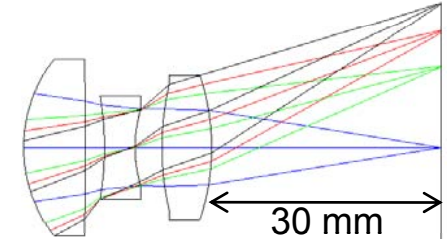
2D layout



100 mm



50 mm



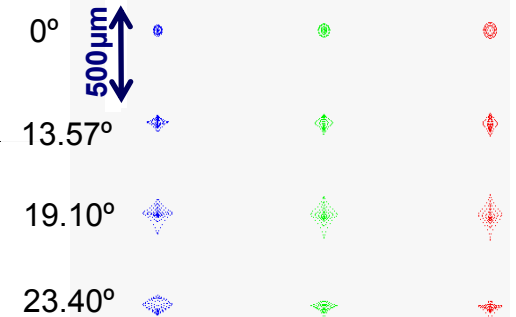
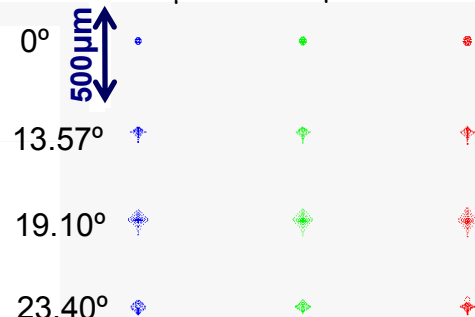
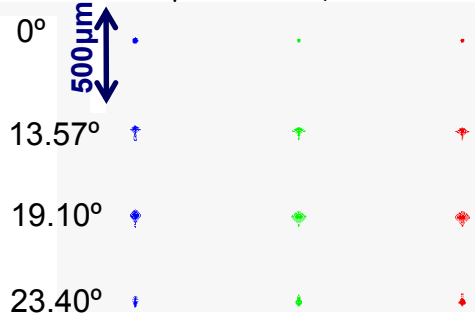
30 mm

Wavelength 0.486 μm 0.588 μm 0.656 μm

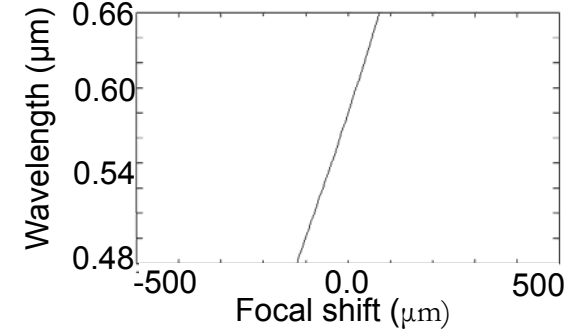
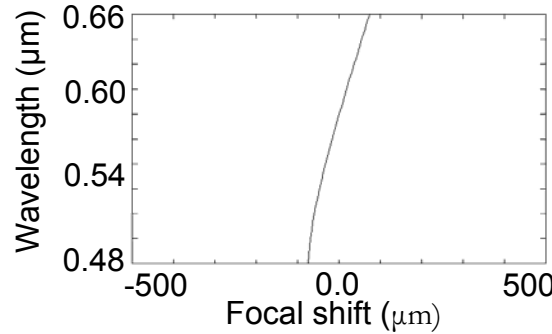
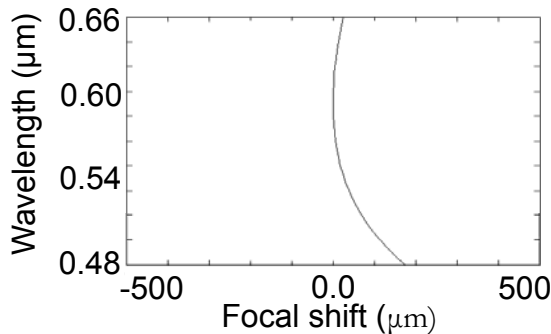
0.486 μm 0.588 μm 0.656 μm

0.486 μm 0.588 μm 0.656 μm

Spot diagram



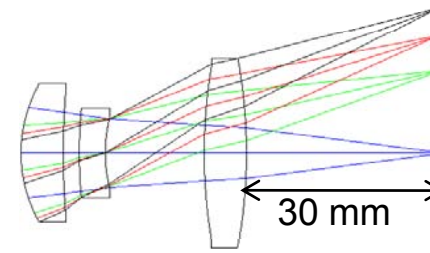
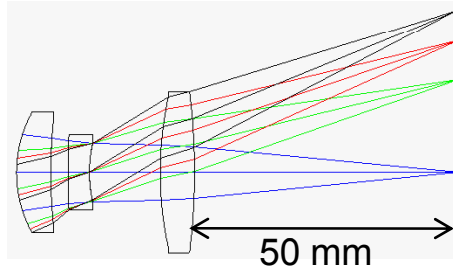
Chromatic aberration



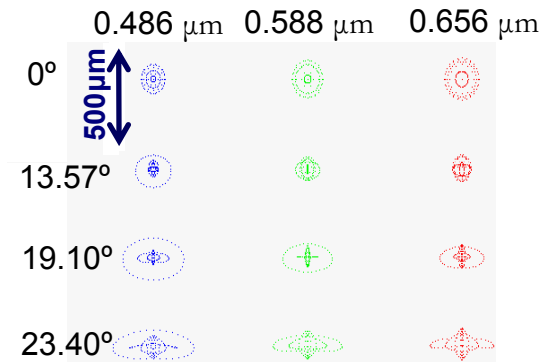
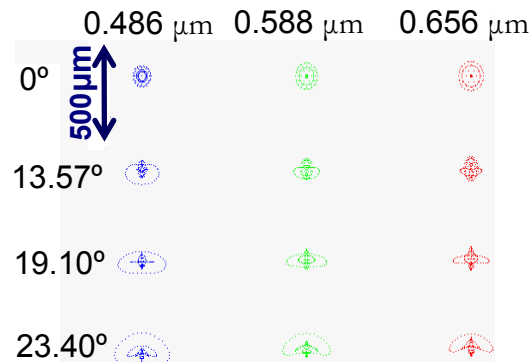
- ✓ 11 variables (glass choice is fixed), infinity object
- ✓ Shorter image distance: Thicker lens and short distance between positive and negative lenses
- ✓ Large spot and aberration from short focal length

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

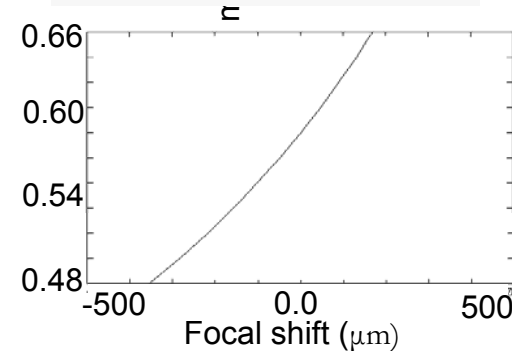
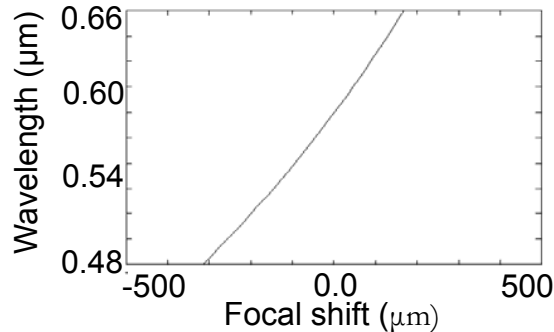
2D layout



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

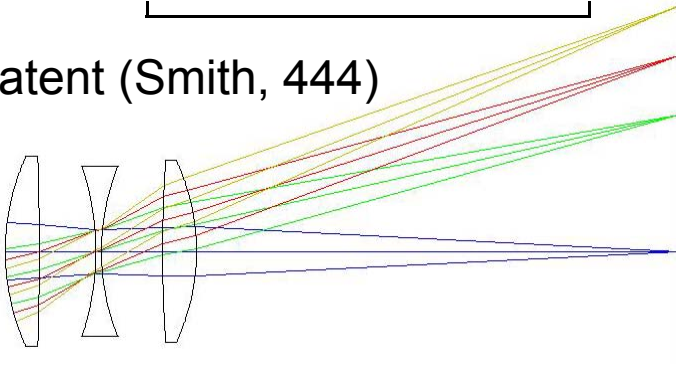
Constant distances and minimal changes to curvatures:

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

Optimization →

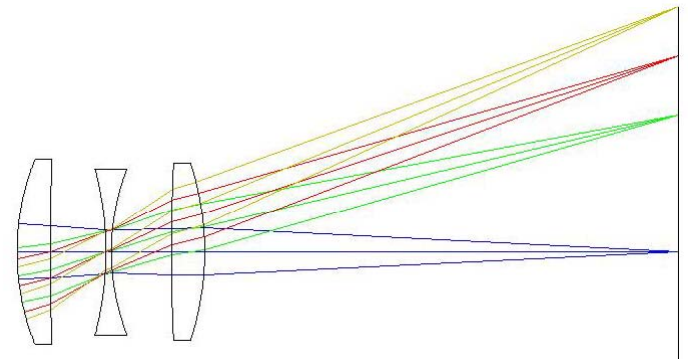
Glass	n	V-value
LAK33	1.75	52.43
BASF2	1.62	30.97
LAK33	1.75	52.43

Patent (Smith, 444)



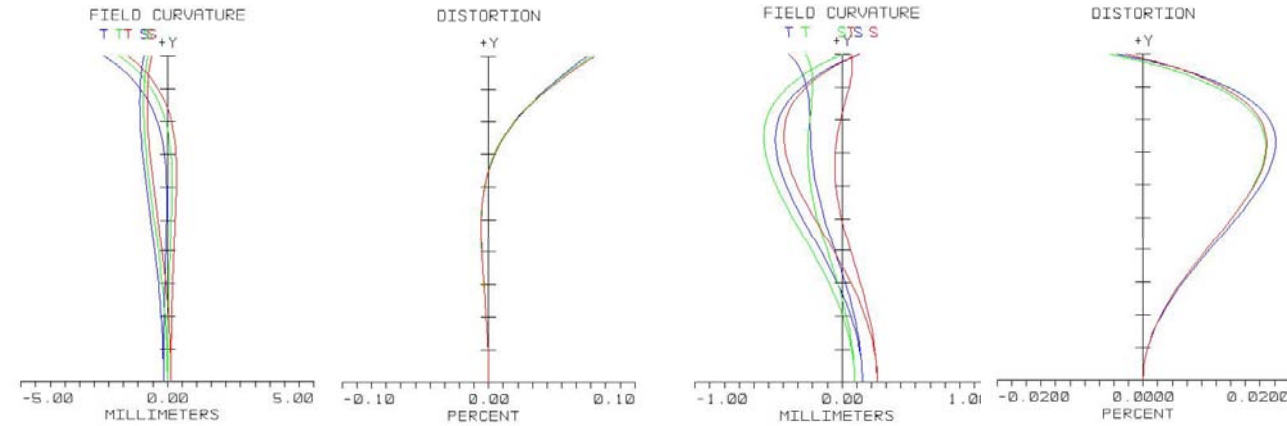
Surf	Radius	Thickness	Diameter
1	40.1	6.0	33.4
2	-537.0	10.0	33.4
3	-47.0	1.0	30.0
4	40.0	10.8	30.0
5	234.5	6.0	32.0
6	-37.9	85.3	32.0

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

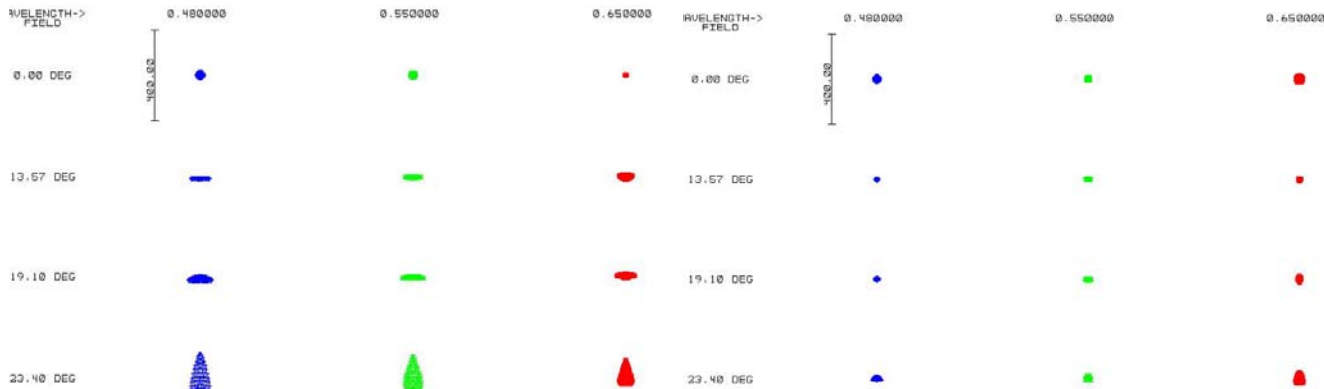


Patent (Smith, 444)

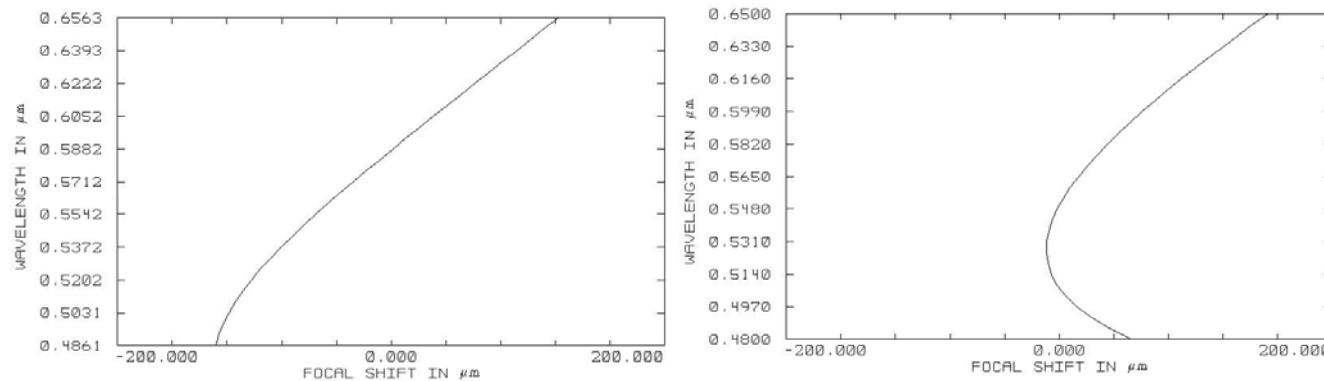
Optimized Design



- Increase in $(n_{\text{crown}} - n_{\text{flint}})$ reduces field curvature and distortion.



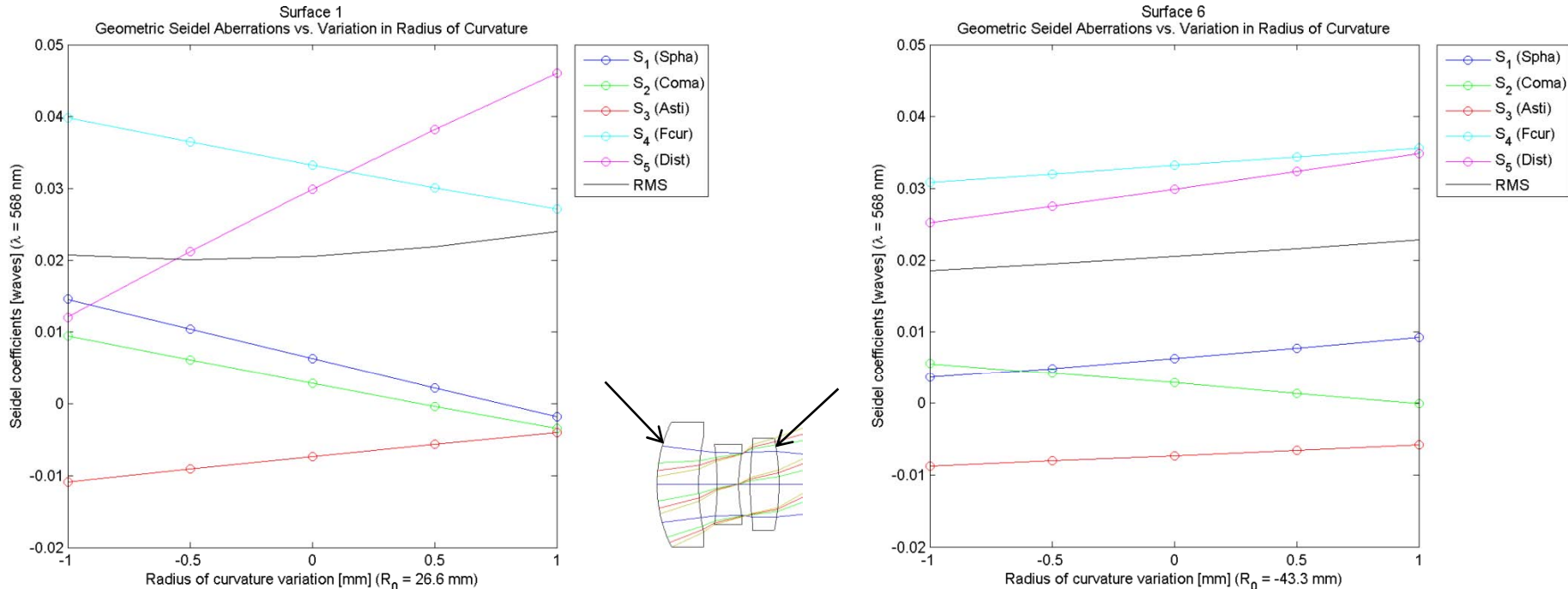
- Increase in $(n_{\text{crown}} - n_{\text{flint}})$ reduces astigmatism and coma.



- Increase in $(n_{\text{crown}} - n_{\text{flint}})$ reduces chromatic aberration.

Variations from optimal design (1)

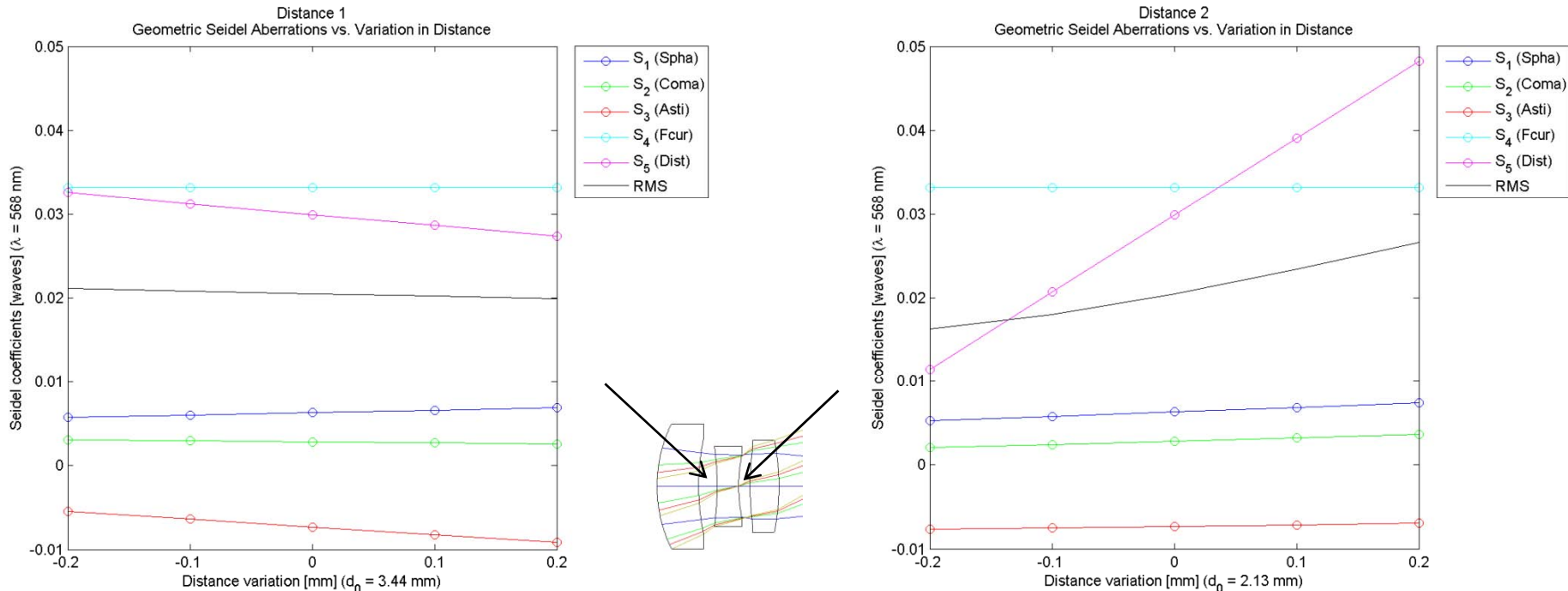
- From the optimized triplet, varied each surface's radius of curvature slightly (± 1 mm) to determine effect of a given surface on aberrations



- First lens is relatively highly curved \rightarrow 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 ($\sim 10^9$) 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

ZEMAX-EE - 18692 - C:\Users\3doptics\Desktop\global attempt\lenses to evaluate\Inf_optimized lens\Inf_opt_f60_gs_hammer.zmx

File Editors System Analysis Tools Reports Macros Extensions Window Help

View Dope Sav Sas Upd Gen File Wav Lay L3d Ray Dpd Fcd Spt Mf Fps Enc Opt Ham Tol Gla Len Sys Pre Chk

Lens Data Editor

Surf #	Type	Comment	Radius	Thickness	Class	Semi-Diameter	Conic
OBJ	Standard		Infinity	Infinity		Infinity	0.00000
1	Standard		26.585199 V	7.736537 V	N-LASF31 S	11.676172	0.00000
2	Standard		43.429037 V	3.435887 V		8.940243	0.00000
3	Standard		-55.415591 V	3.999980 V	SF14 S	7.469473	0.00000
STO	Standard		29.198443 V	2.127319 V		6.034548	0.00000
5	Standard		55.521418 V	5.365190 V	N-LASF31 S	7.457009	0.00000
6	Standard		-43.266572 V	60.000000		8.594248	0.00000
IMA	Standard		Infinity	-		30.482764	0.00000

Merit Function Editor: 4.469931E-003

Oper #	Type	Target	Weight
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2	BLNK	Default merit function: RMS spot radius centroid CQ 3 rings 6 arms	
3	BLNK	Default air thickness boundary constraints.	
4	MNCA	2.000000	1.000000
5	MKCA	100.000000	1.000000
6	MNEA	2.000000	1.999972
7	BLNK	Default glass thickness boundary constraints.	
8	MKCG	4.000000	1.000000
9	MKCG	18.000000	1.000000
10	MNEC	4.000000	3.999992
11	BLNK	Aberration Optimization	
12	COMA	0.000000	1.000000
13	SPHA	0.000000	1.000000
14	FCUR	0.000000	1.000000
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18	BLNK	Operands for field 1.	
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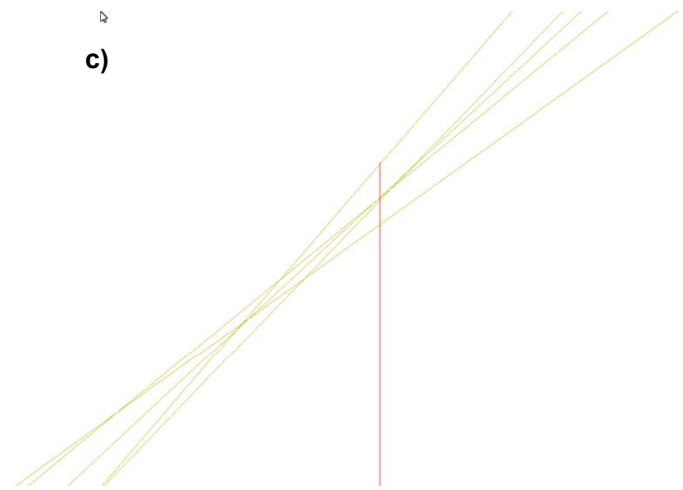
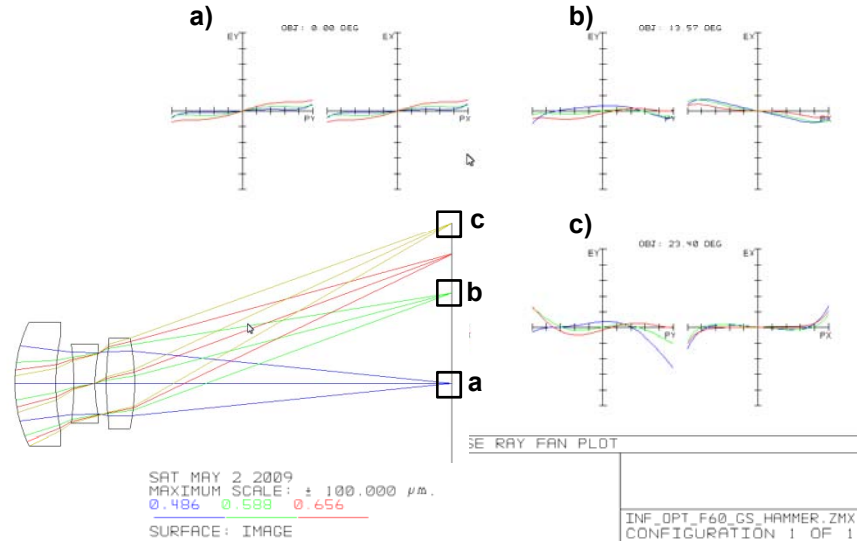
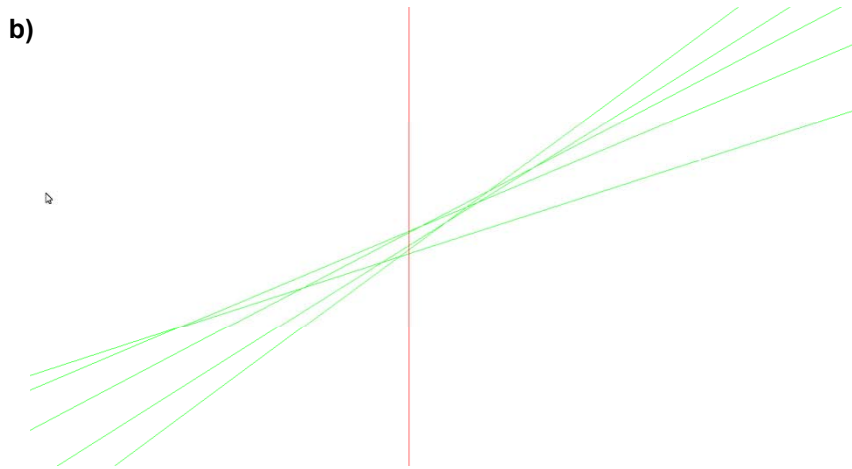
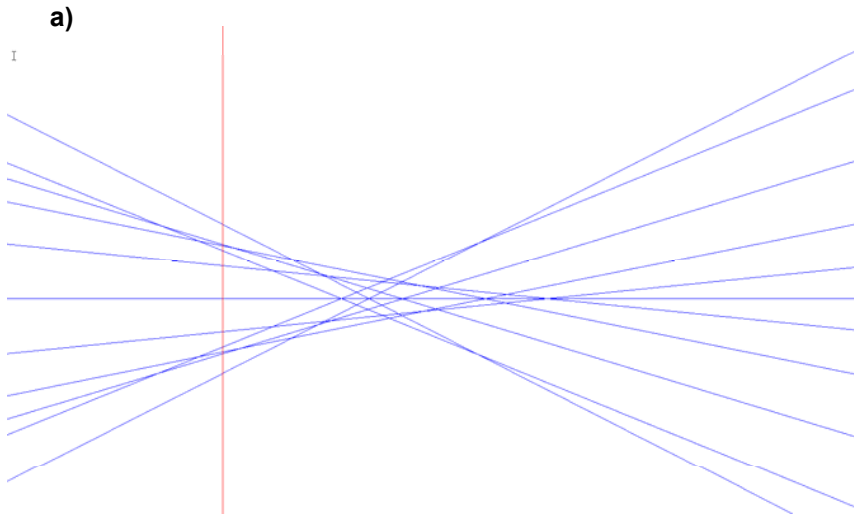
Layout 2 = 78.77, Y = 24.94

SAT MAY 2 2009
TOTAL LENGTH: 82.66491 MM

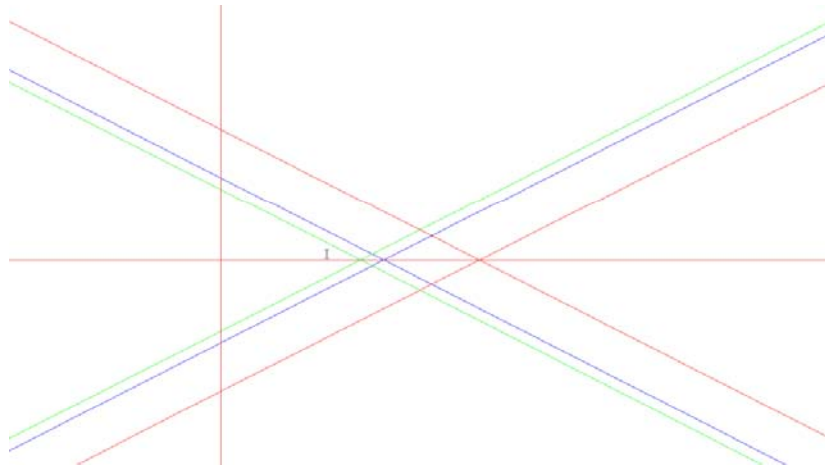
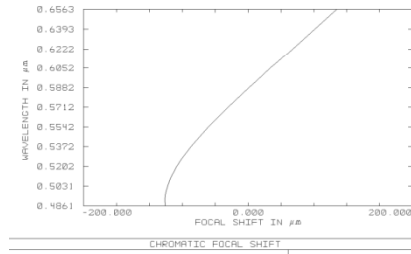
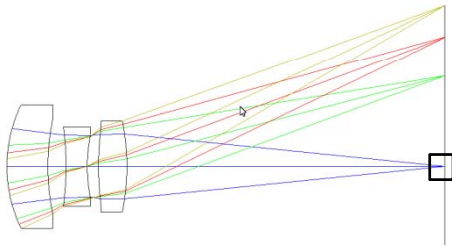
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CONFIGURATION J DF 1

Start C:\Users\3doptics\Desktop\ ZEMAX-EE - 18692 - C... 2:14 PM

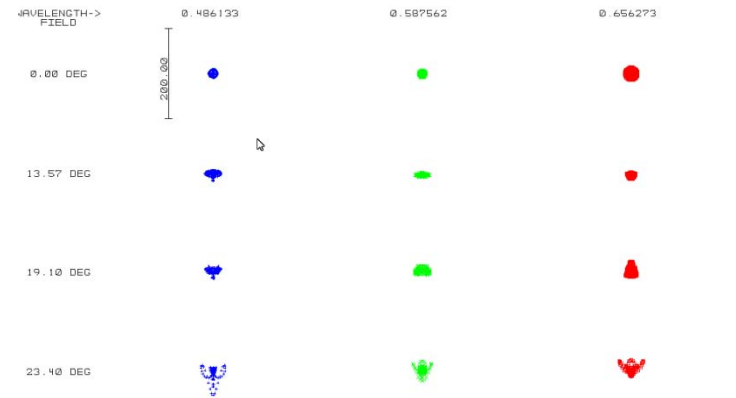
Ray Diagrams and Ray Fan



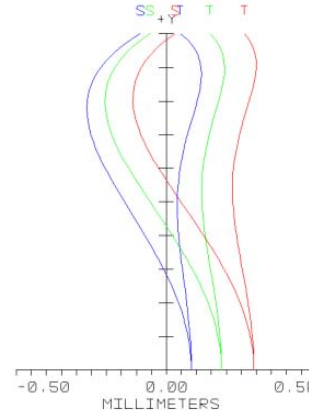
More on Chromatic Abberations



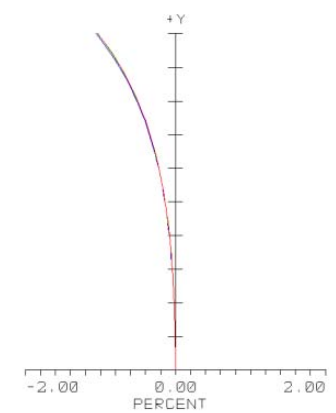
ID=60mm



FIELD CURVATURE



DISTORTION



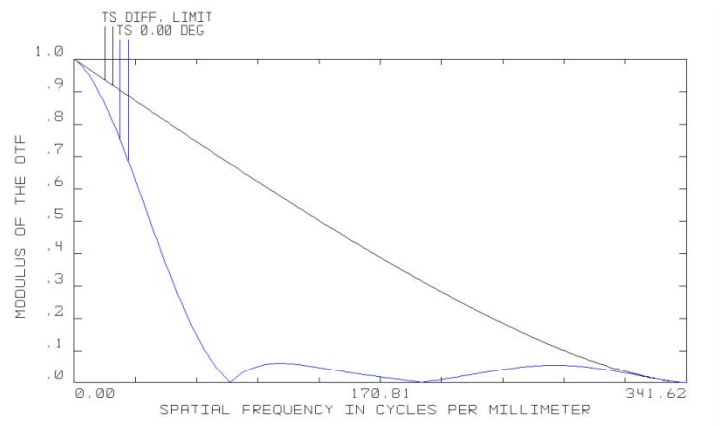
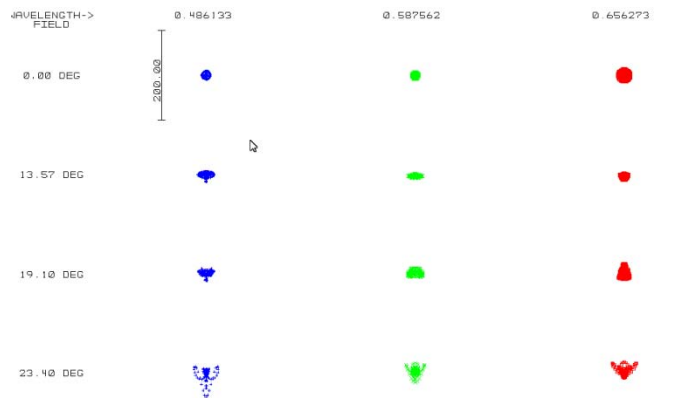
FIELD CURVATURE / DISTORTION

SAT MAY 2 2009
 MAXIMUM FIELD IS 23.400 DEGREES
 WAVELENGTHS: 0.486 0.588 0.656

INF_OPT_F60_GS_HAMMER.ZMX
 CONFIGURATION 1 OF 1

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

ID=60mm

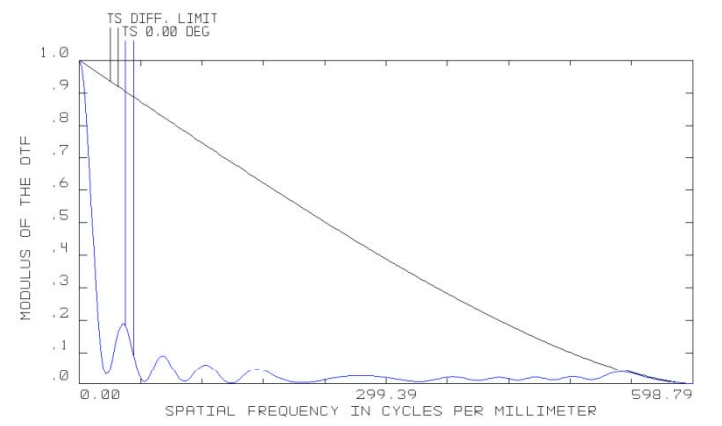
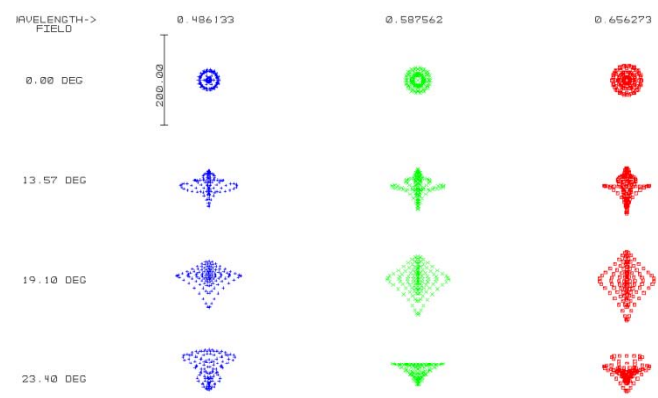


DIFFRACTION MTF

SAT MAY 2 2009
DATA FOR 0.5876 μm .
SURFACE: IMAGE

INF_OPT_F60_GS_HAMMER.ZMX
CONFIGURATION 1 OF 1

ID=20mm



DIFFRACTION MTF

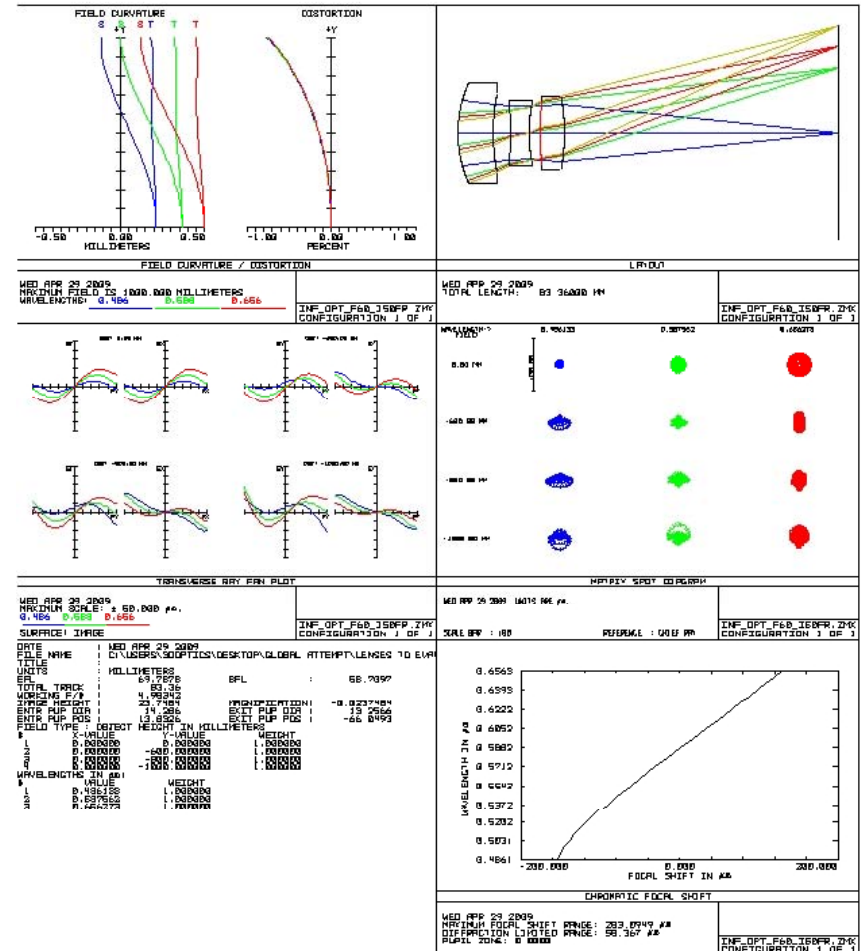
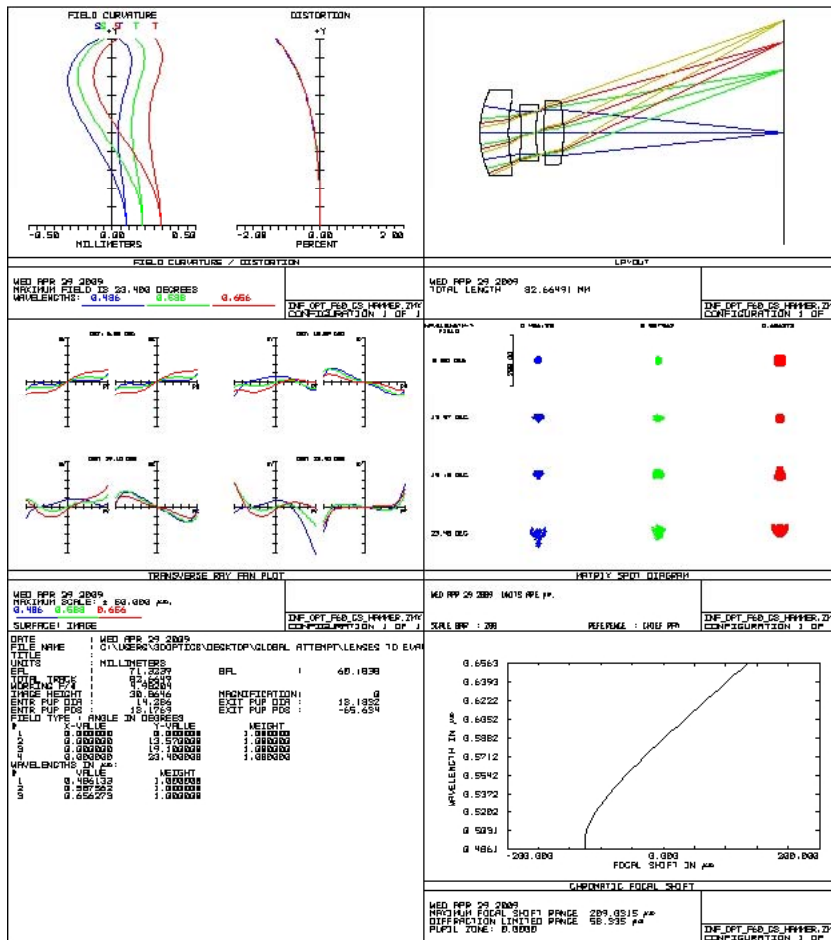
SAT MAY 2 2009
DATA FOR 0.5876 μm .
SURFACE: IMAGE

IINF_LENS_SETUP.ZMX
CONFIGURATION 1 OF 1

Objects at Finite Distances

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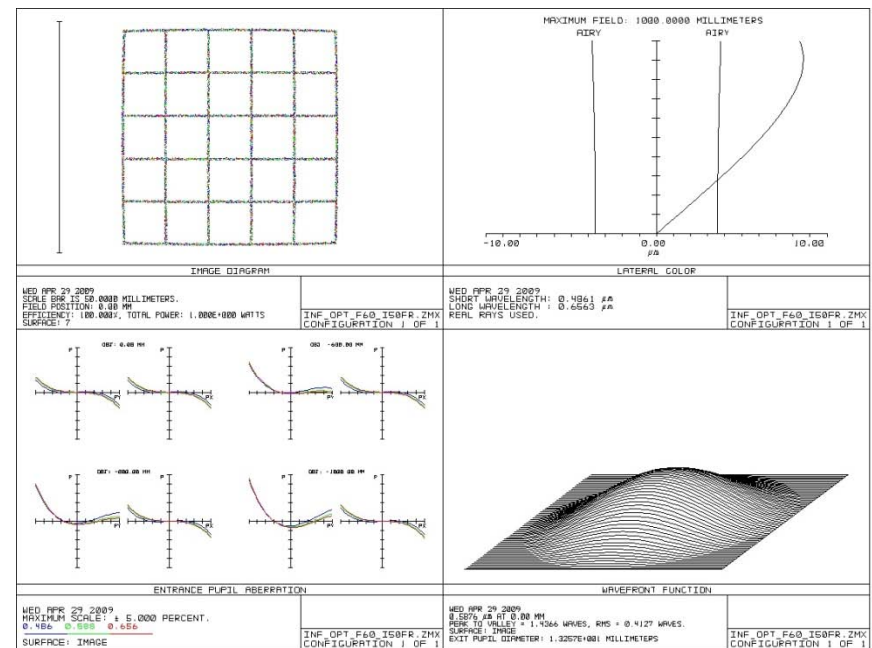
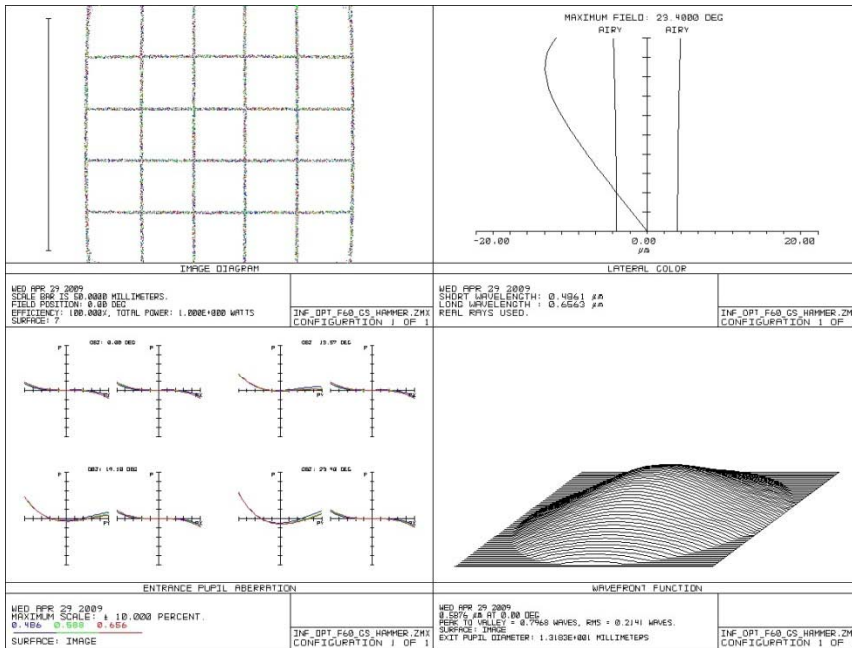
OD= 50xD



Objects at Finite Distances

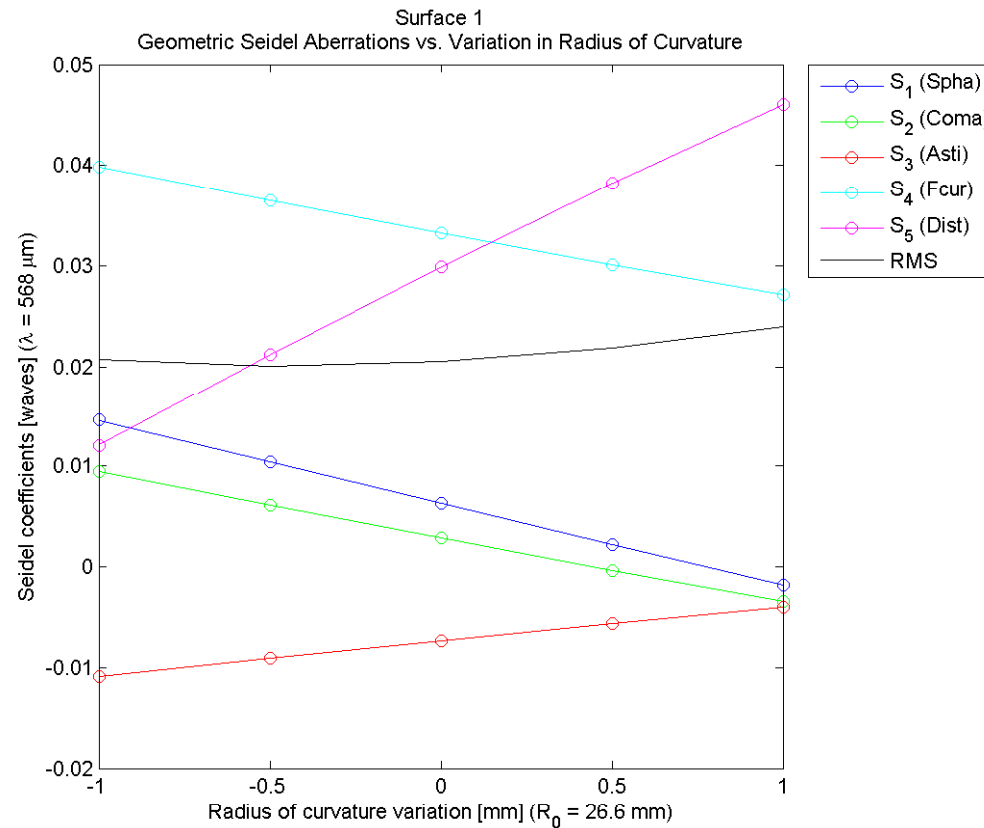
OD= Infinity

OD= 50xD



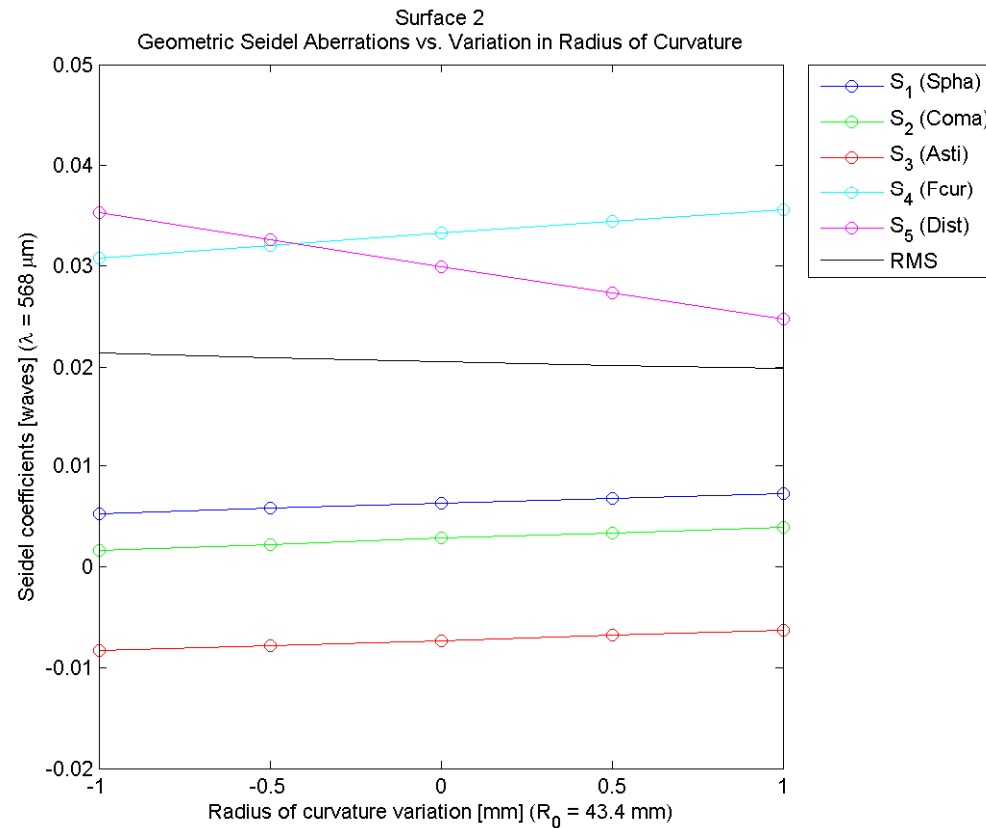
Variations from optimal design

- Surface 1



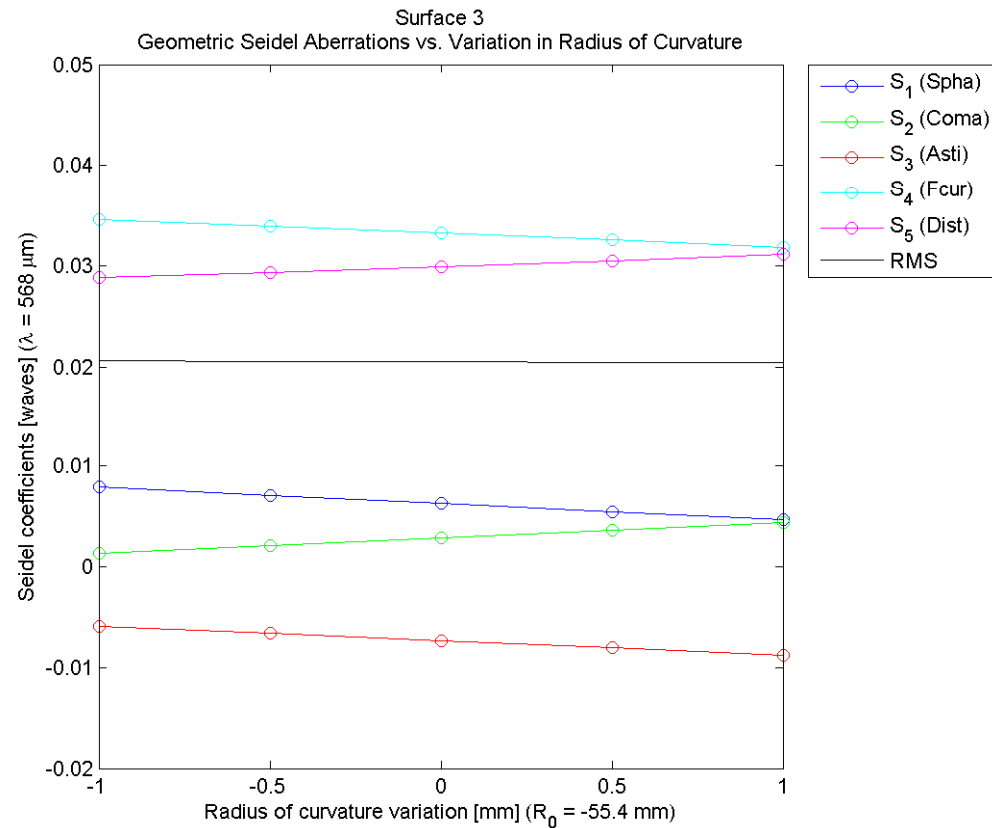
Variations from optimal design

- Surface 2



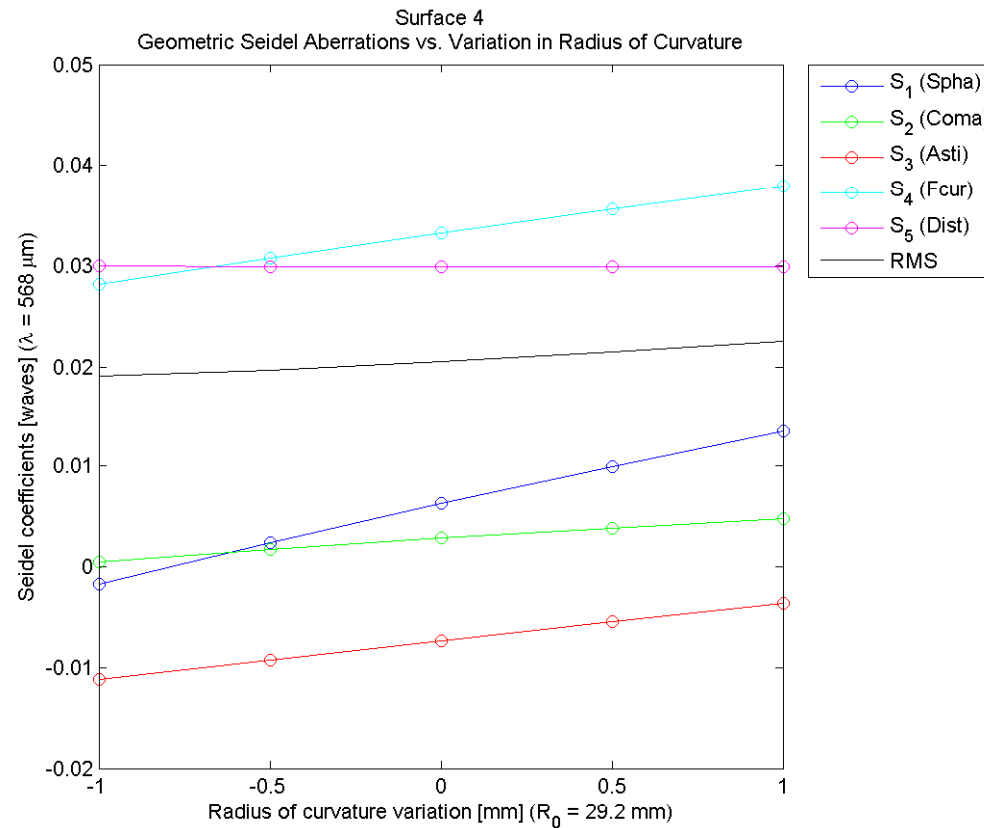
Variations from optimal design

■ Surface 3



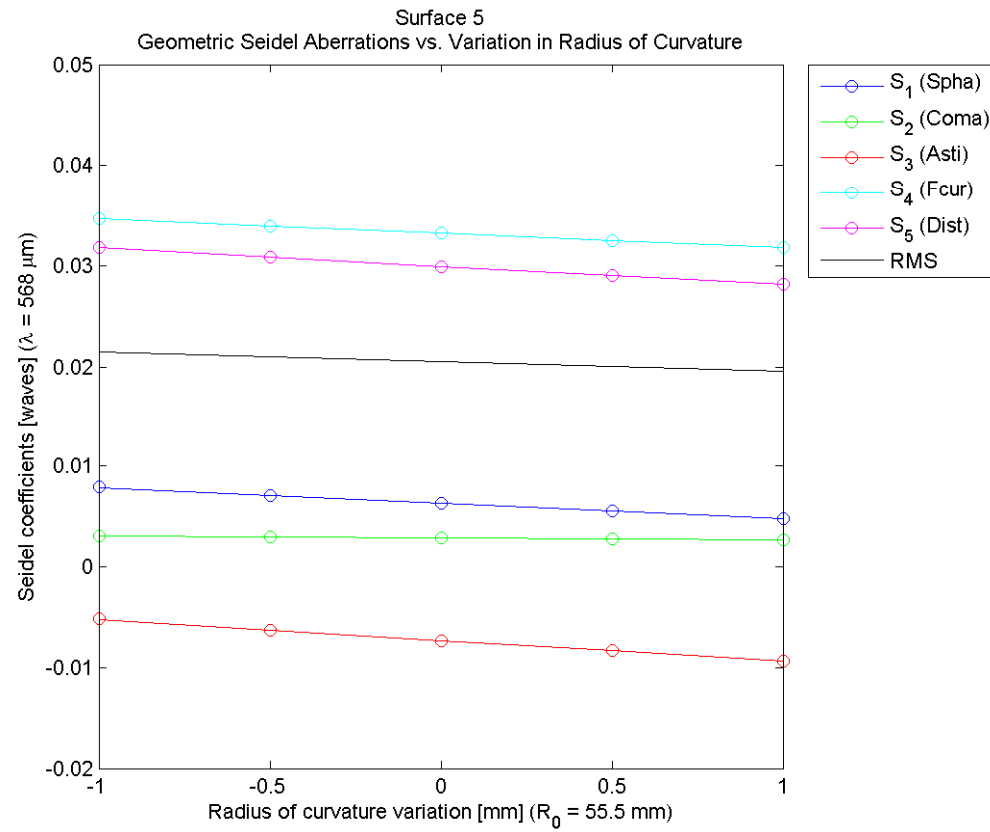
Variations from optimal design

- Surface 4



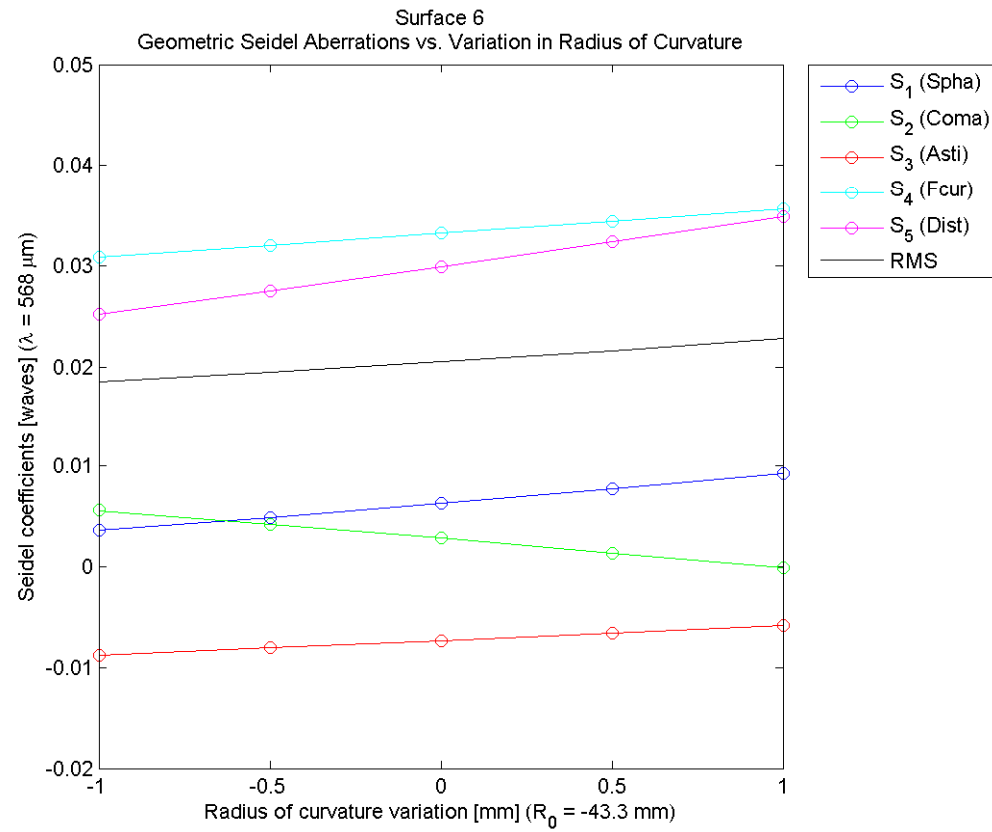
Variations from optimal design

■ Surface 5



Variations from optimal design

■ Surface 6



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