EE 118/218A Final Design Project: Cooke Triplet Optimization

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December 17th, 2019

Outline

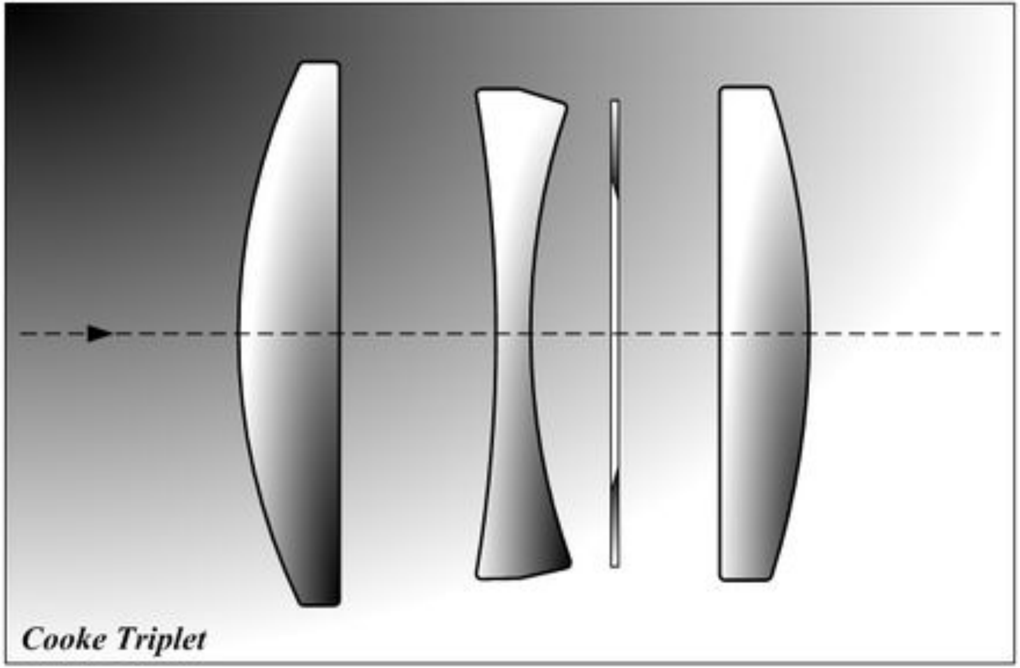
- Project/Problem Introduction
- Optimization Process Details
  - Discrete parameter: Lens Glass Selection
  - Continuous parameters
    - Ray Fan Plots
    - Distortion plots
- Tolerance Analysis
- Conclusion

What is a Cooke Triplet?

Cooke Triplet High-Level Diagram

For each of the 3 lenses, we're interested in:

- material
- curvatures for both sides
- relative positions along the optical axis



Project Goals

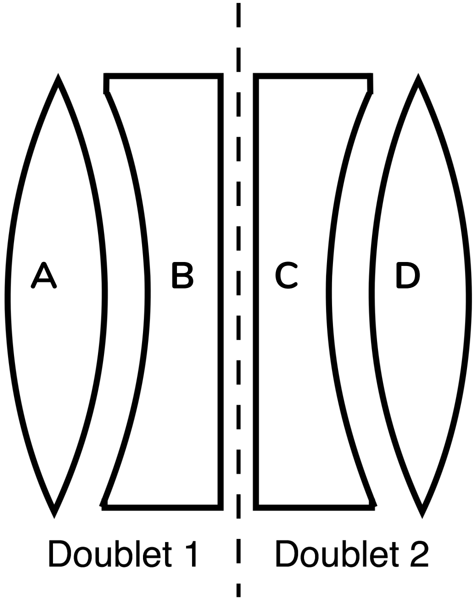
Practice of lens design in Zemax with Cooke Triplet Lens System

- optimizing parameters of the lens system to minimize monochromatic aberrations (Seidel aberrations) and chromatic aberrations

- manufacture tolerance guidelines

1. Discrete Variables in Optimization: Glass selection

Cooke Triplet as two doublets



Able to correct for

(from properties of doublets)

Chromatic aberration

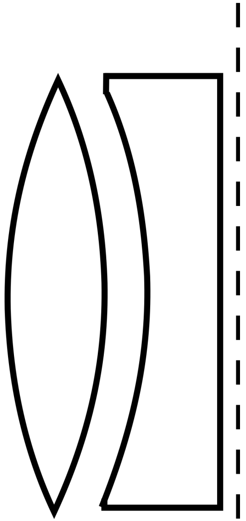
(from properties of symmetry)

Spherical aberration (SA)

Field curvature

Within each doublet, how to select glass?

(chromatic aberration)



Doublet 1

Assumption that airspace in between is almost zero

$$\frac{1}{f_1} = \frac{V_1}{f \cdot (V_1 - V_2)}$$
$$\frac{1}{f_2} = \frac{V_2}{f \cdot (V_1 - V_2)}$$

(eqn 6.59-6.60 HECHT)

where V=(n(blue)-n(red))/(n(yellow)-1), which is the dispersion powers or Abbe number, f=effective focal length for the whole doublet.

Avoid small values of f which would need strongly curved surfaces (induces higher order aberrations!)

the difference in dispersion power must be made large.

Within each doublet, how to select glass?

(Chromatic Aberration)

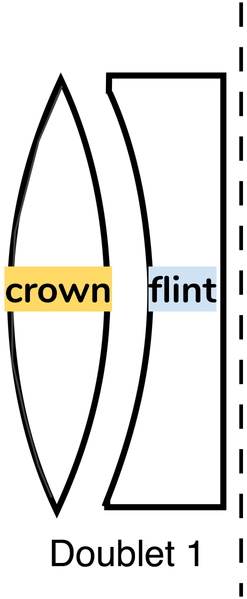
$$\frac{1}{f_1} = \frac{V_1}{f \cdot (V_1 - V_2)}$$
$$\frac{1}{f_2} = \frac{V_2}{f \cdot (V_1 - V_2)}$$

Crown (high V) - flint (low V) combination

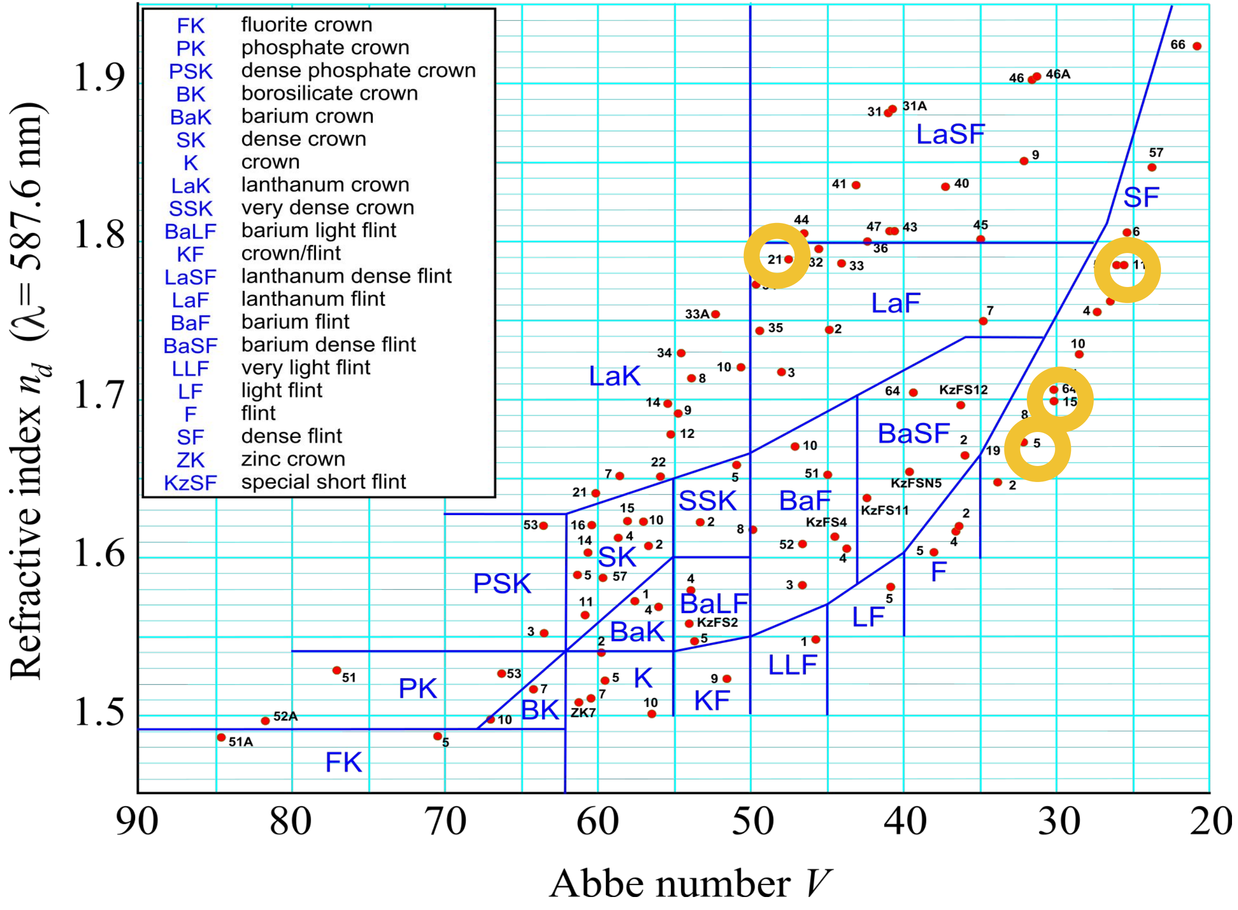
(Petzval Sum)

$$\Delta x = \frac{y_i^2}{2} \sum_{i=1}^{k} \frac{1}{n_i \cdot f_i}$$

Use glass with high refractive index for both



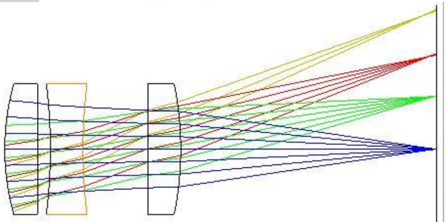
Doublet 1


FK fluorite crown
PK phosphate crown
PSK dense phosphate crown
BK borosilicate crown
BaK barium crown
SK dense crown
K crown
LaK lanthanum crown
SSK very dense crown
BaLF barium light flint
KF crown/flint
LaSF lanthanum dense flint
LaF lanthanum flint
BaF barium flint
BaSF barium dense flint
LLF very light flint
LF light flint
F flint
SF dense flint
ZK zinc crown
KzSF special short flint
Refractive index n_d ($\lambda = 587.6$ nm)
Abbe number V

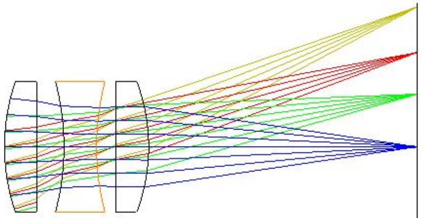
Glass Selection:

Dispersion and layout and image quality

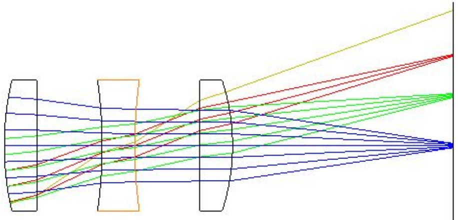
A



B



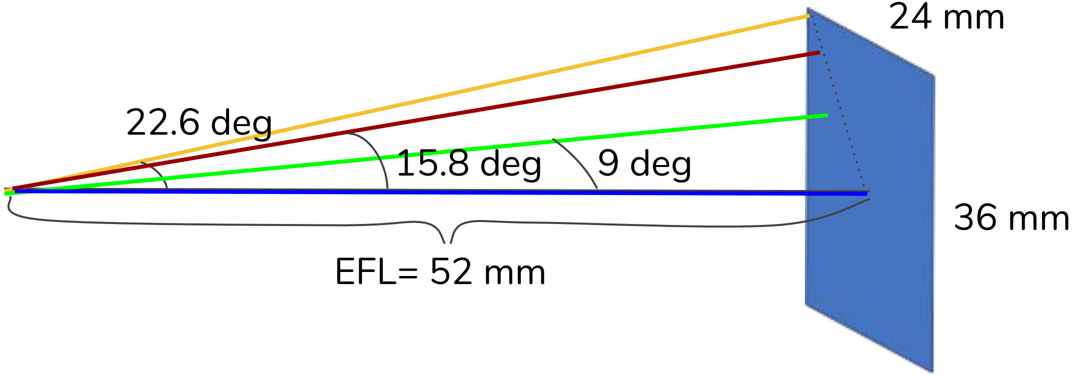
C



(Positive lens): Fixed at LAFN-21, V = 47.49

(Negative lens): SF-9, V = 33.85	SF-15, V = 30.09	SF-11, V = 25.83

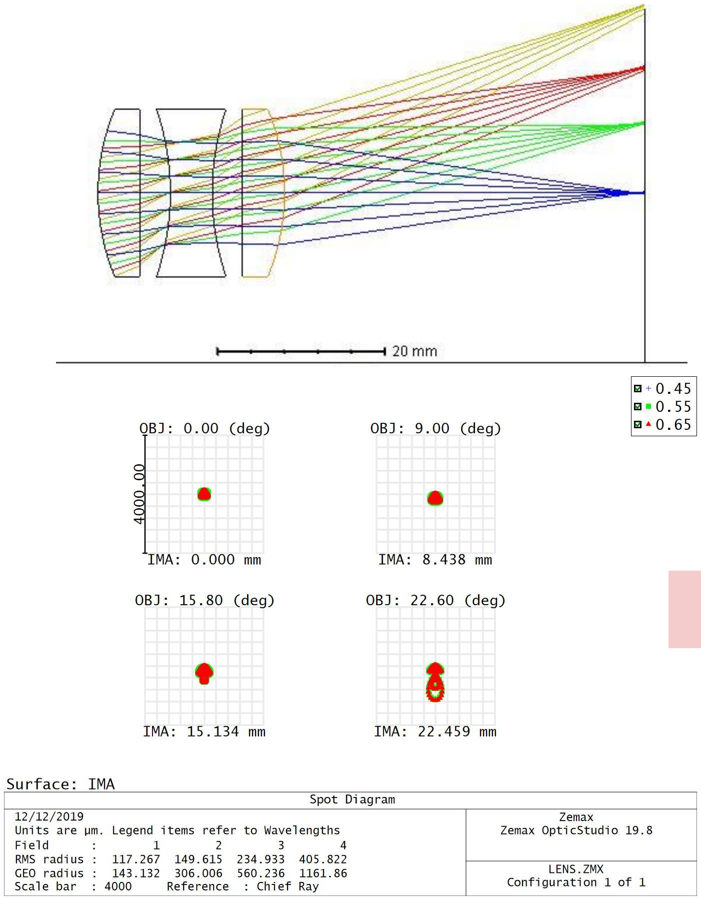
Define Field Points



- Follows the convention/standards mentioned in https://www.willbell.com/tm/ChapterB.3.pdf

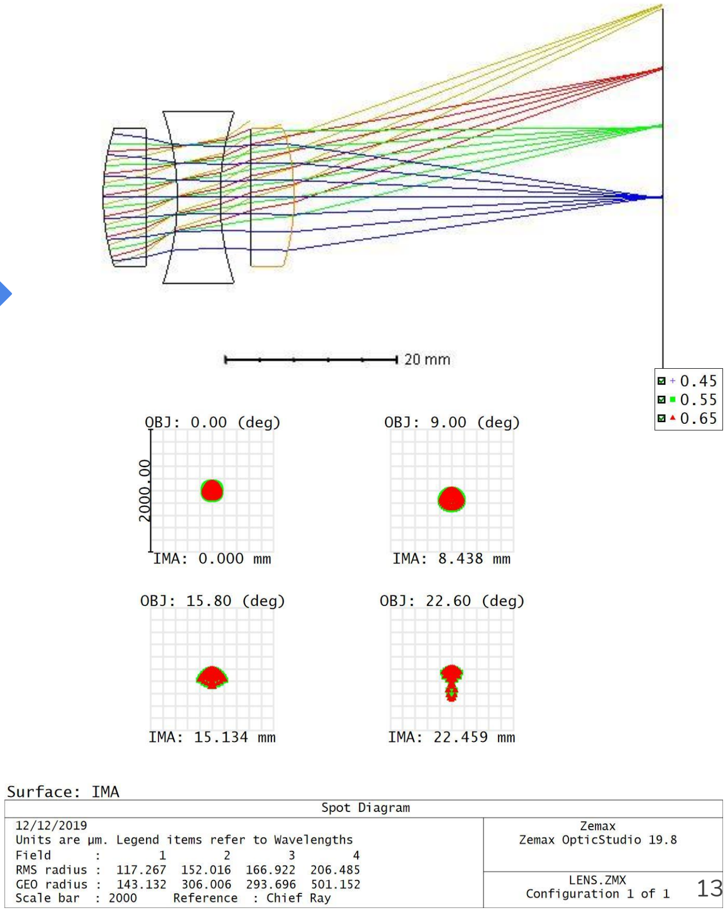
Vignetting

Limits off axis rays and thus improve image quality



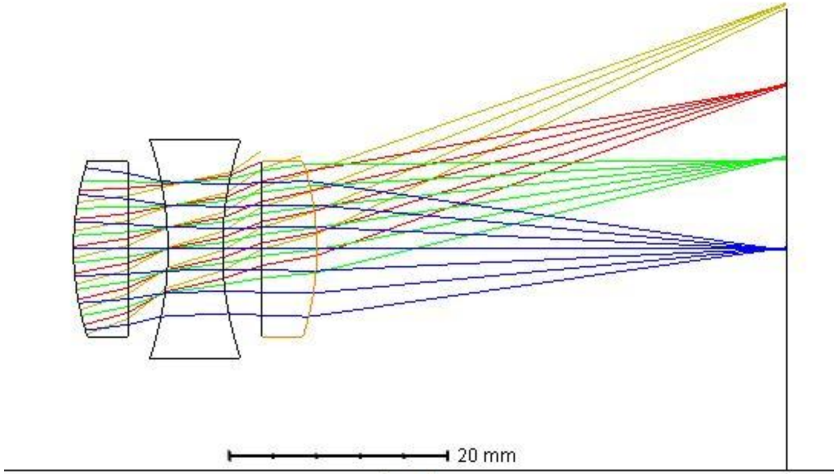
Vignetting →

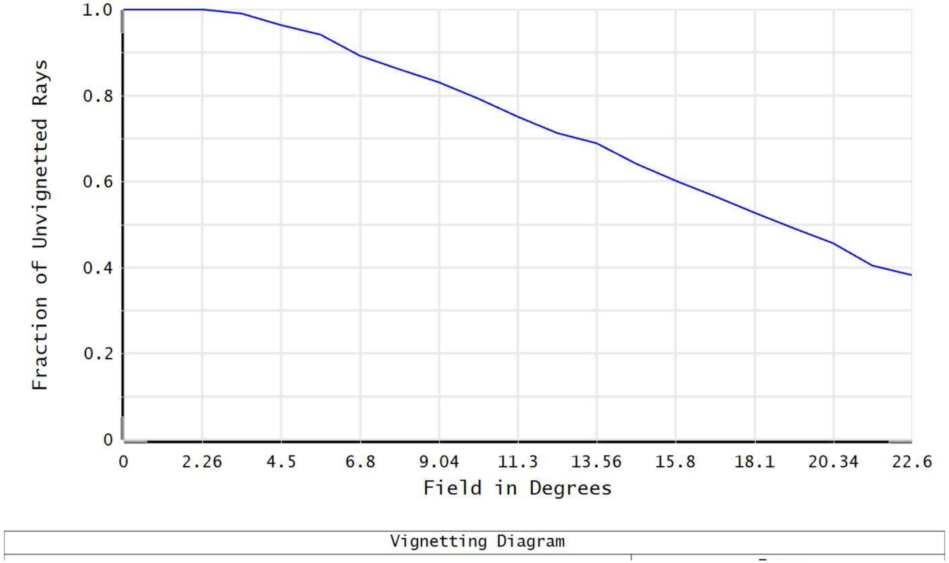
It is about trade-offs!



Vignetting

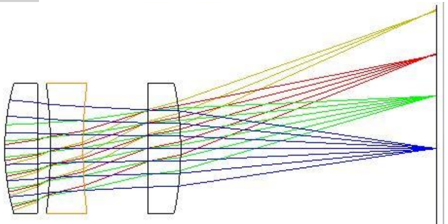
Limits off axis rays and thus improve image quality





Glass Selection:
Dispersion and layout and image quality

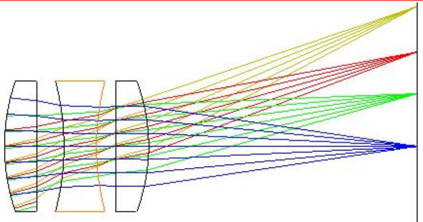
A



(Negative lens) SF-9, V = 33.85

20 mm

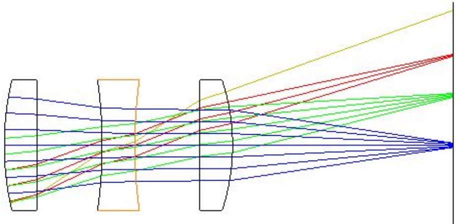
B



SF-15, V = 30.09

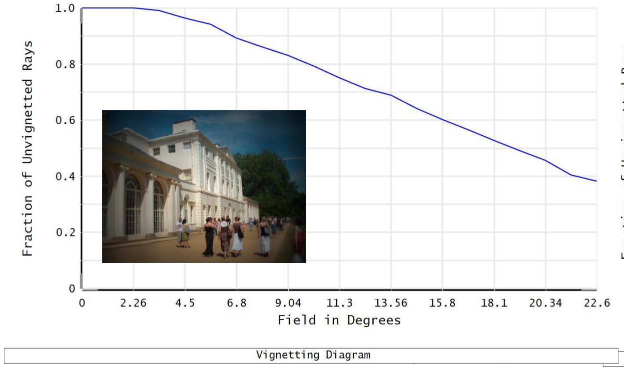
20 mm

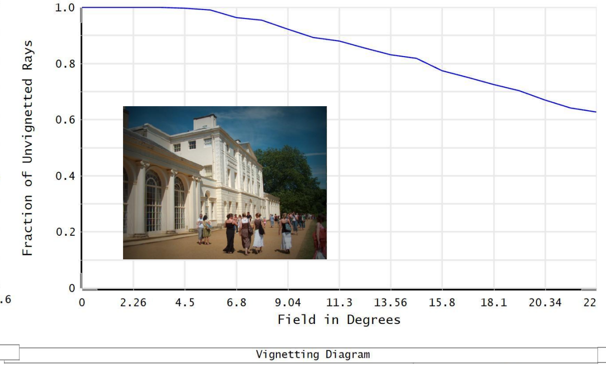
C

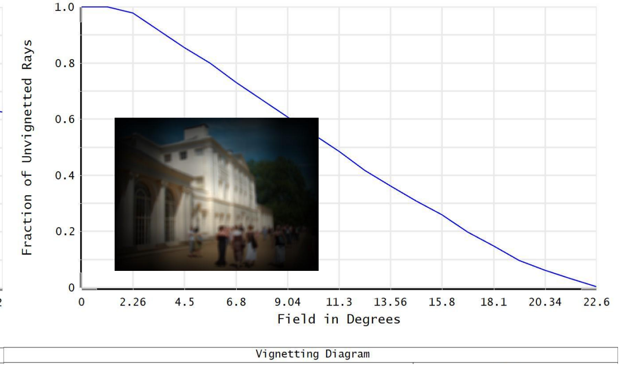


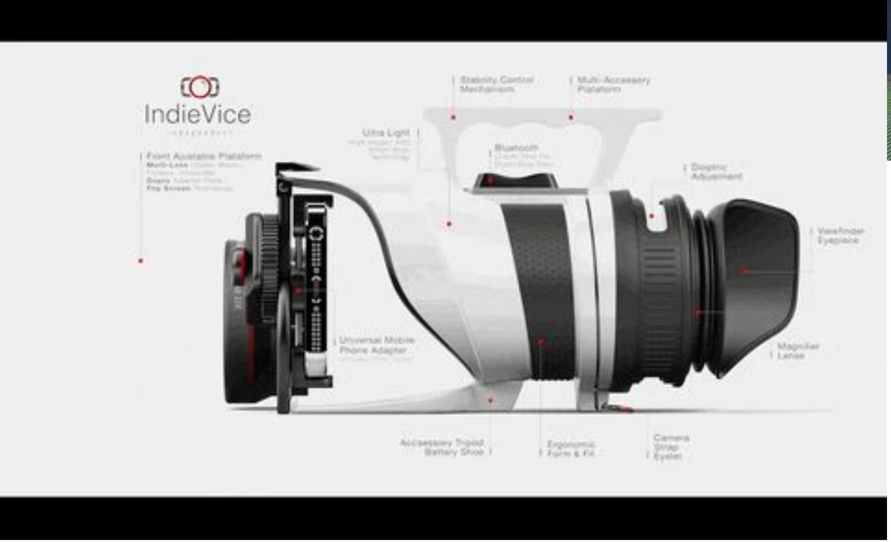
SF-11, V = 25.83

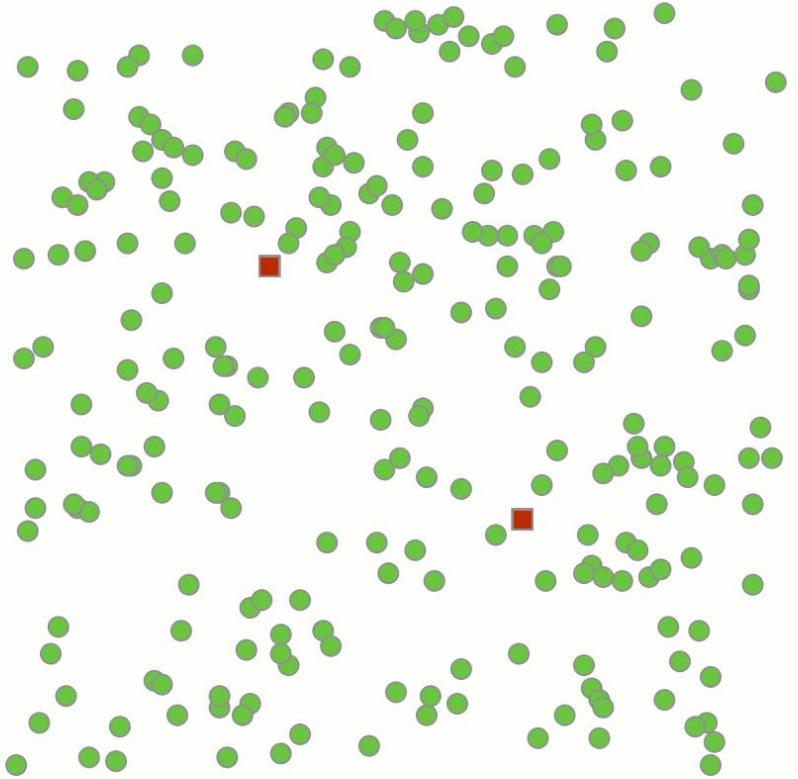
20 mm





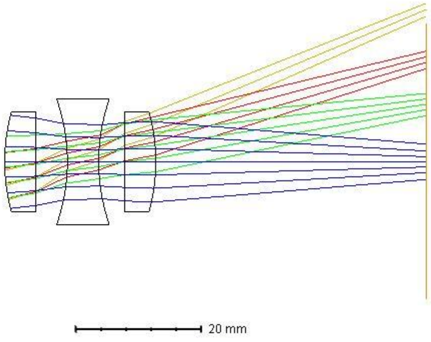




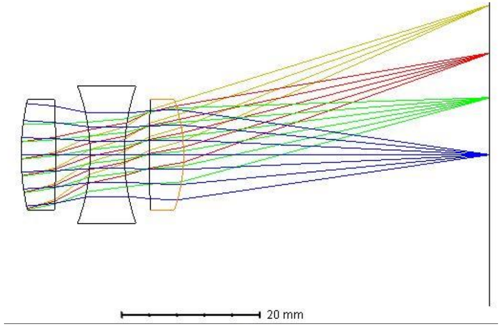


2. Continuous Variables in Optimization

Optimization



$$\min_{V} MF^2 = \frac{\sum W_i (V_i - T_i)^2}{\sum W_i}$$



V (Variables):

All the surface curvatures (6)
All airspaces (3)

T (Constraints)

EFL=52 mm
Default targets to shrink spot size
equal weights at each field point

Initial position:

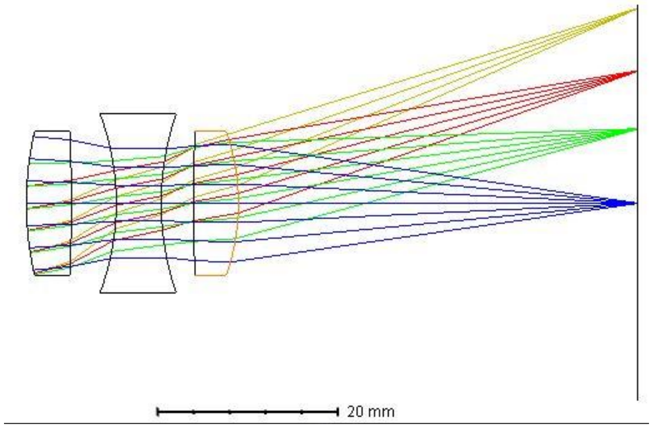
(a) **Positive lenses** (LAF-21)
- Two are the same.
- Convex-planar
  (shape for minimal SA, coma, Hecht Chapter 6)

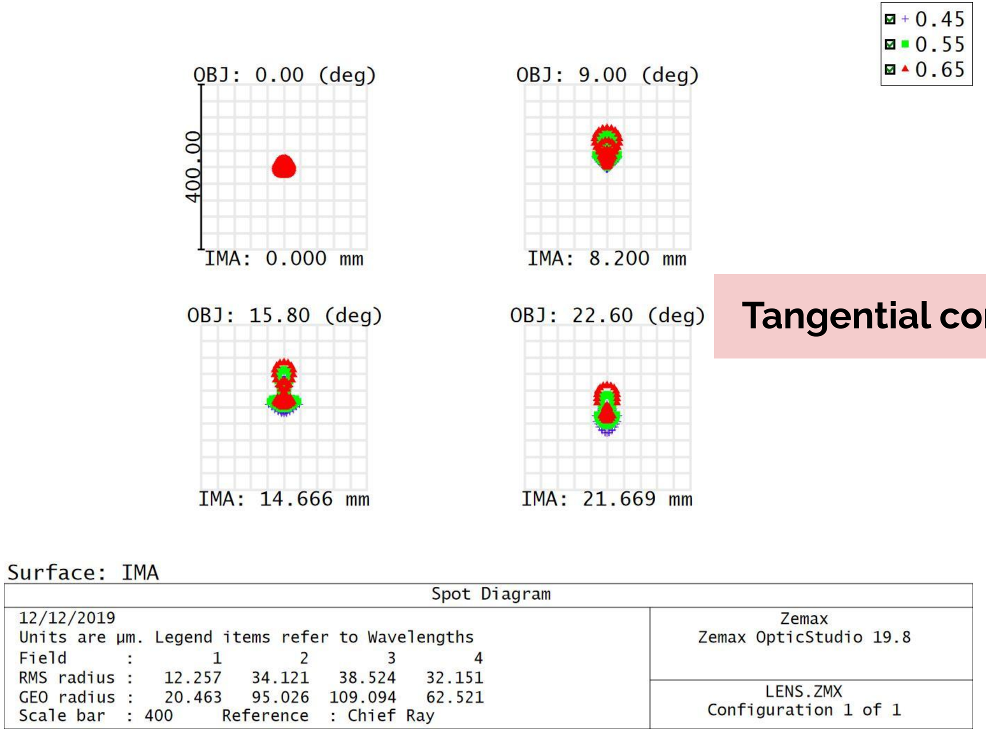
(b) **Negative lens** (SF-15)

(c) All the curvatures are the same:
- |R|=30mm

Comment	Radius		Thickness	
	Infinity		Infinity	
Lens 1 In	35.626	V	5.000	
	-199.886	V	5.000	V
Lens 2 In	-28.230	V	5.000	
Out of Lens 2, Air...	30.657	V	3.589	V
Lens 3 In	165.370	V	5.000	
Out of Lens 3, Air...	-24.641	V	44.446	V
	Infinity		-	

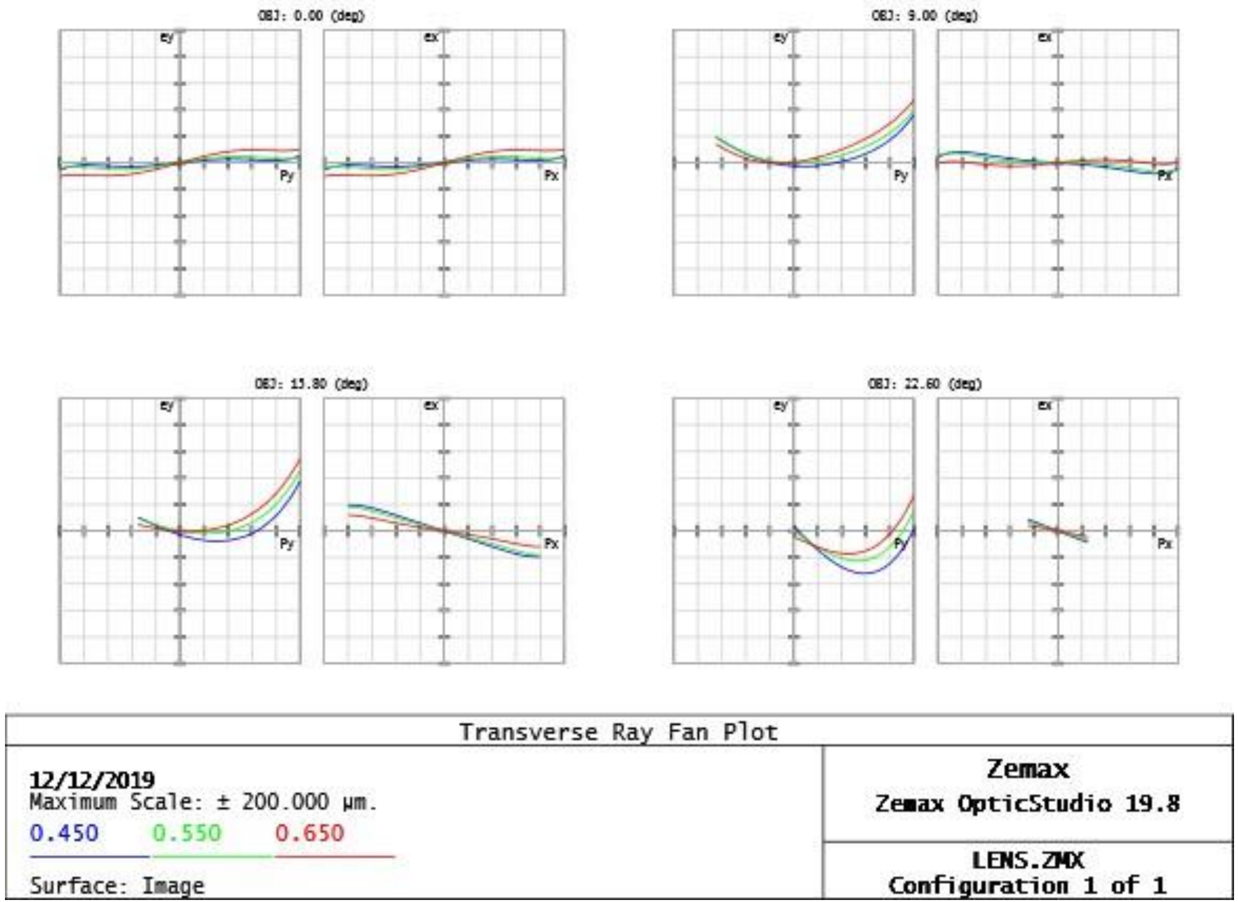
System Performance





Tangential coma

System Performance

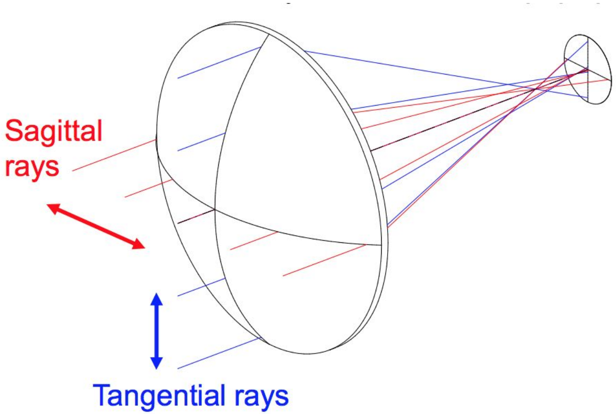


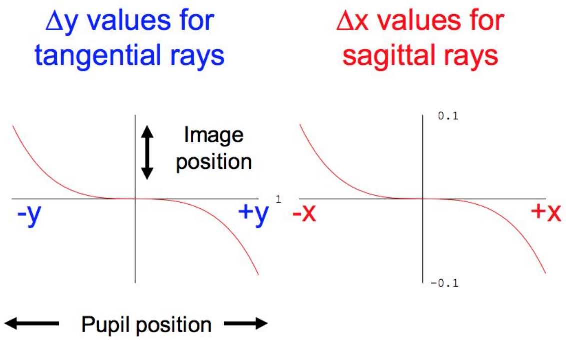
Notes on “Ray Fan Plot”

Transverse Ray Aberration

the distance (orthogonal to the optical axis) to chief ray

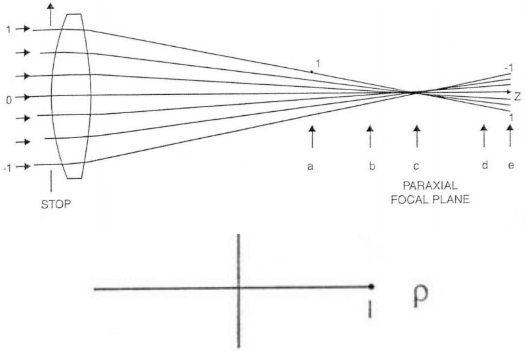
Ray Fan Plots



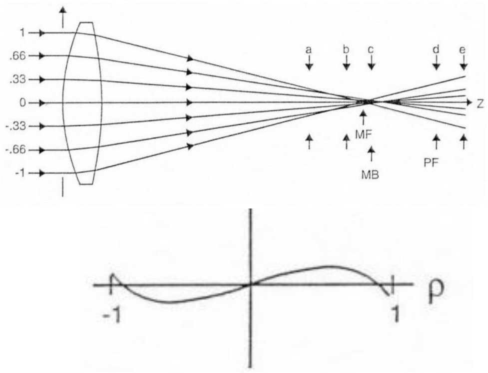


https://wp.optics.arizona.edu/jsasian/wp-content/uploads/sites/33/2016/03/Opti517-Optical-Quality-2014.pdf

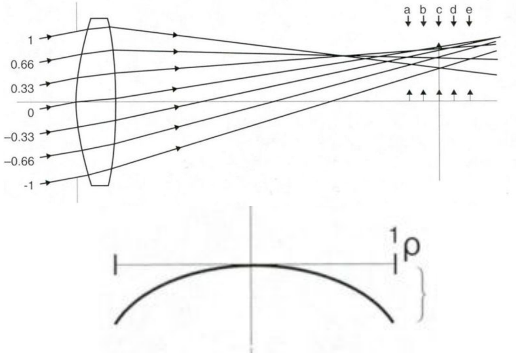
Notes on “Ray Fan Plot”



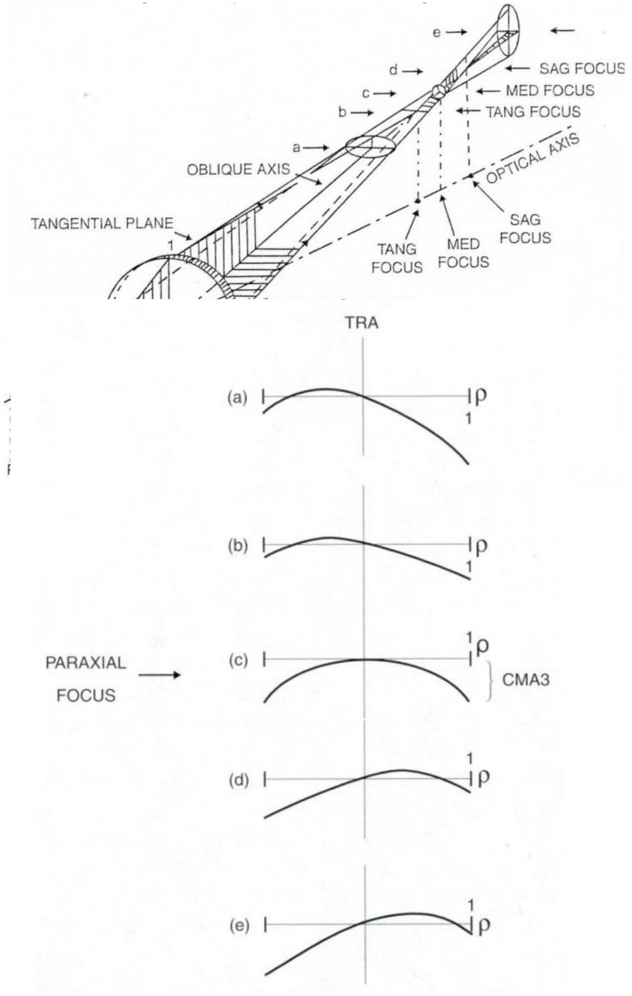
No aberration



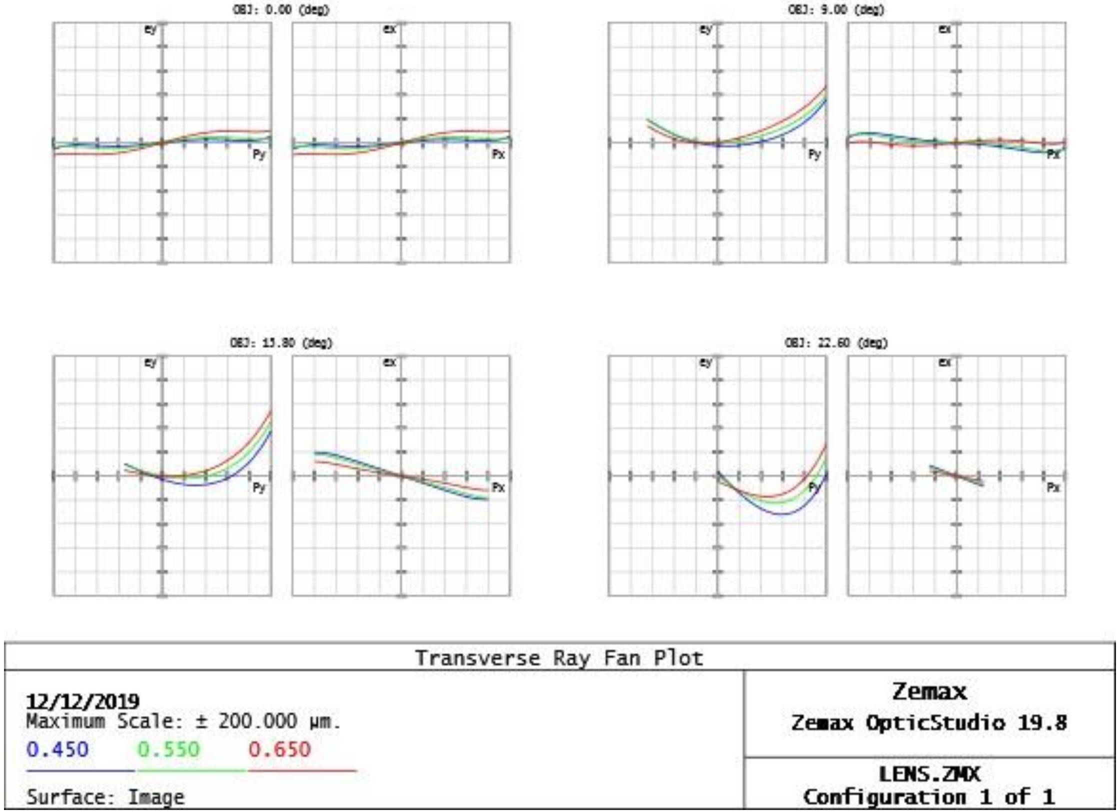
Spherical



Coma

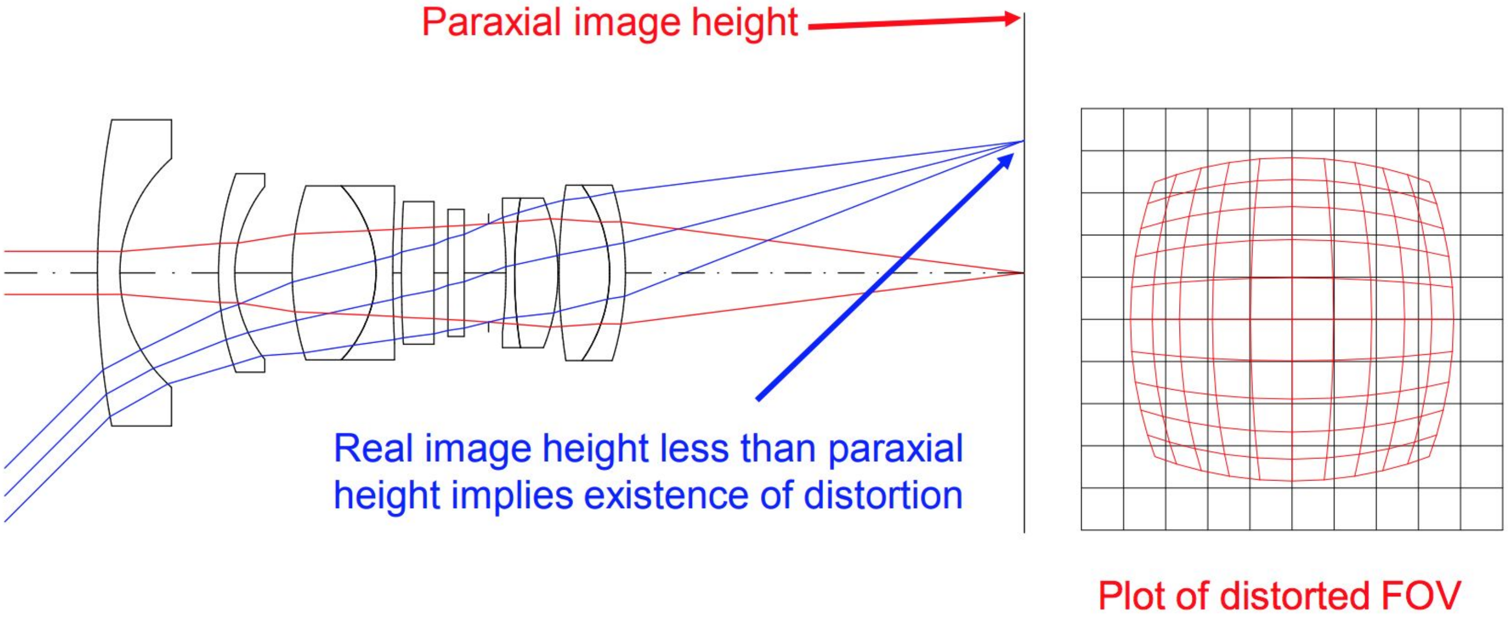


System Performance



System Performance

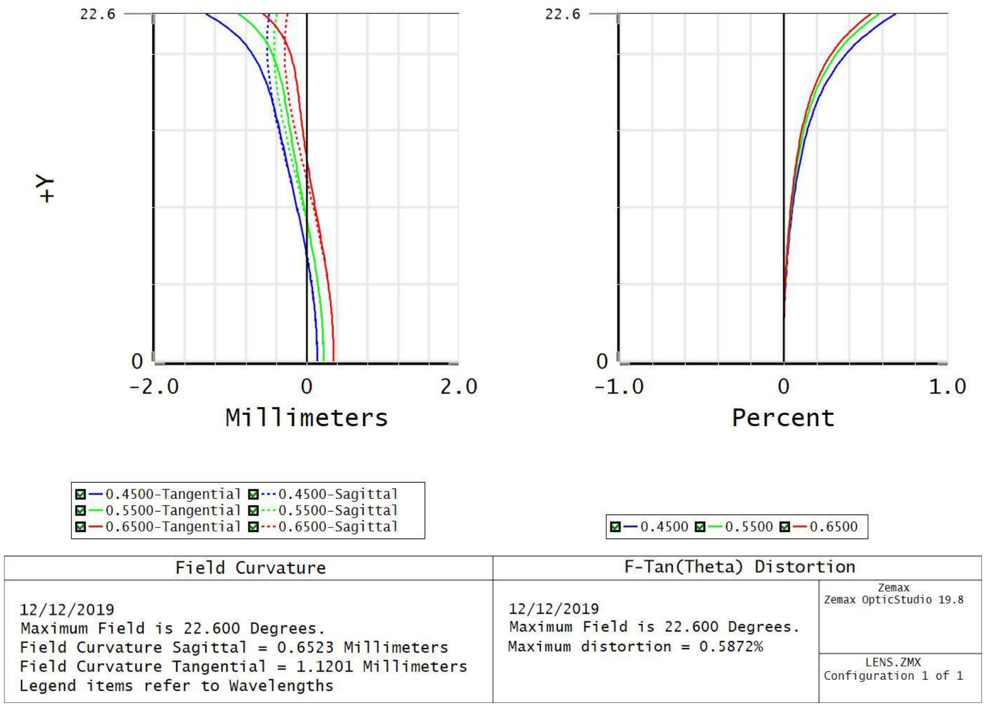
Distortion Plot will have to be another plot



https://wp.optics.arizona.edu/jsasian/wp-content/uploads/sites/33/2016/03/Opti517-Optical-Quality-2014.pdf

System Performance

Distortion



Optimization result

Simulated images

Original

Optimization result

Simulated images

Through lens

Can we do better?

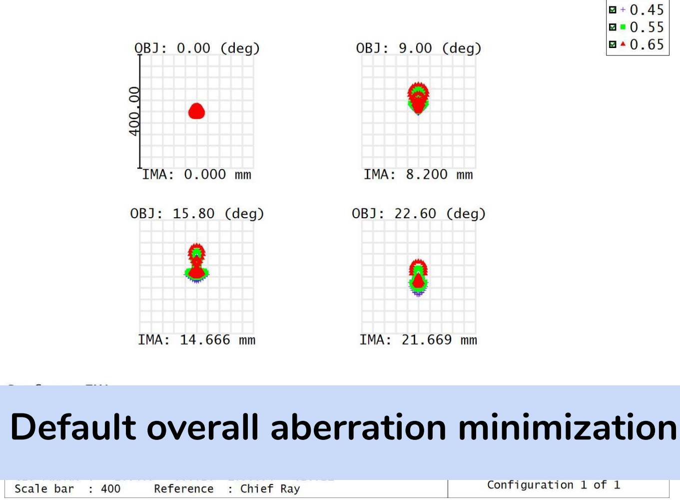
$$\min_{V} \; MF^2 = \frac{\sum W_i (V_i - T_i)^2}{\sum W_i}$$

<u>V (Variables)</u>:
All the surface curvatures (6)
All airspaces (3)

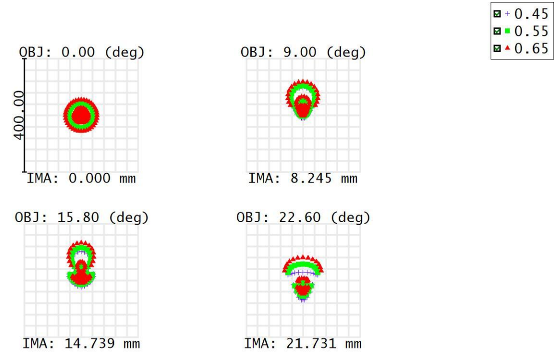
<u>T (Constraints)</u>
EFL=52 mm
Default targets to shrink spot size

- This is because monochromatic aberrations (spherical, coma, astigmatism, field curvature, all higher-order aberrations) interact in a complicated way.

- Specifically adding a couple aberrations could make overall performance worse.



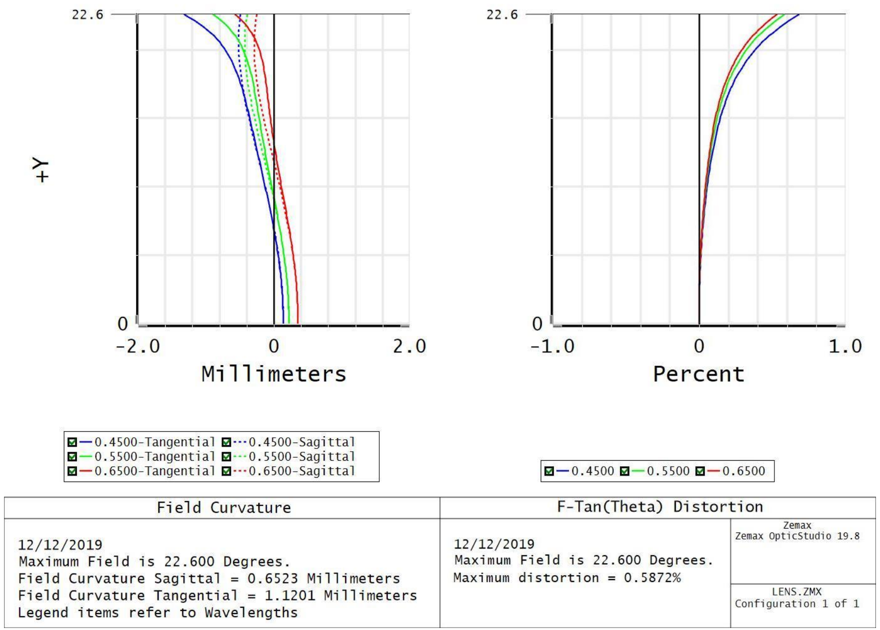
Default overall aberration minimization

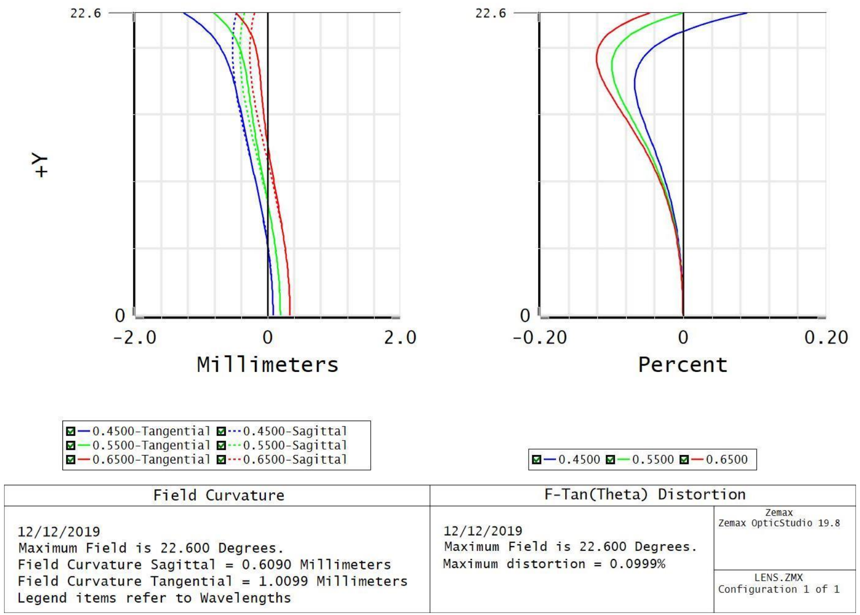


Specific spherical aberration term added into the merit function

Optimization in detail (3)

But distortion could be explicitly added so that overall symmetry is prefered.





Optimization in detail (3)

But distortion could be explicitly added so that overall symmetry is prefered.

Original

Optimization in detail (3)

But distortion could be explicitly added so that overall symmetry is prefered.

Distortion corrected

Optimization in detail (3)

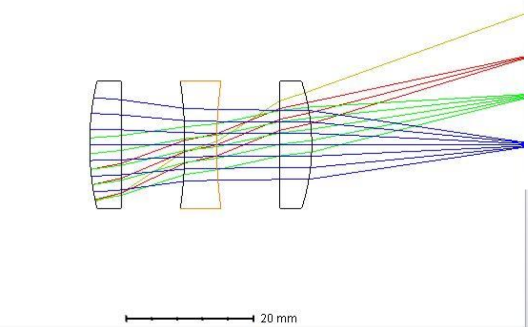
But distortion could be explicitly added so that overall symmetry is prefered.

Initial Optimization

A word on the power of Zemax on optimization

There are some constraints we did not explicitly show before, such as the thickness of an airspace is great than or equal to zero.

How do we actually input that into Zemax?



21	BLNK						
22	TTHI	4	4	0.000	0.000	10.004	0.00
23	OPGT	22		3.000	1.000	3.000	0.00
24	OPLT	22		10.000	1.000	10.004	1.244E-0
25							
26							
27							

3. Tolerance Analysis

Tolerance Analysis

Tolerance Analysis is…

An analysis of the influence of parameter errors from manufacturing on final performance

Why?

Ensure that the system will meet the performance specifications.

Analyzed Parameters:

radius of curvature, thickness, tilt, decenter, etc.

Tolerance

Analyzed Parameters in detail

Surface tolerance: Radius, thickness, decenter, tilt, irregularity

Element tolerance: decenter, tilt

Index tolerance: refractive index, abbe number

Plus tolerances between lens

42 parameters in total

Sensitivity

Worst offenders:

Type			Value	Criterion	Change
TEDX	5	6	-0.10000000	3.20441850	0.10414281
TEDX	5	6	0.10000000	3.20441850	0.10414281
TEDX	3	4	-0.10000000	3.19075345	0.09047775
TEDX	3	4	0.10000000	3.19075345	0.09047775
TETX	3	4	-0.10000000	3.17899592	0.07872023
TETX	3	4	0.10000000	3.17899592	0.07872023
TIRX	3		-0.05000000	3.16815145	0.06787576
TIRX	3		0.05000000	3.16815145	0.06787576
TIRX	6		-0.05000000	3.15321001	0.05293431
TIRX	6		0.05000000	3.15321001	0.05293431

TEDX: element decenters
TETX: element tilt
TIRX: total indicator runout in lens unit

Accuracy

Metric: RMS Wavefront

90% >	3.82531648
80% >	3.46004409
50% >	3.27946968
20% >	3.19400353

Conclusion

- Lens design can be modeled as an optimization problem.
- To efficiently solve optimization, we need to nail down some constraints with understanding of optics.
- Aberrations interact in a complex way. Correcting for aberration is a complex task.
- The design process could be complicated by the uncertainty involved in manufacturing.

References

- Cooke Triplet Review
  - https://www.willbell.com/tm/ChapterB.3.pdf
- Aberrations in Lens Design
  - http://www.montana.edu/jshaw/documents/10%20EELE582_S15_Ray_Aberrations.pdf
  - http://www.photonics.intec.ugent.be/education/IVPV/res_handbook/v1ch33.pdf
  - https://wp.optics.arizona.edu/jsasian/wp-content/uploads/sites/33/2016/03/Opti517-Optical-Quality-2014.pdf
- Tolerance
  - https://my.zemax.com/en-US/Knowledge-Base/kb-article/?ka=KA-01675
  - https://my.zemax.com/en-US/Knowledge-Base/kb-article/?ka=KA-01417
  - https://wp.optics.arizona.edu/optomech/wp-content/uploads/sites/53/2016/10/521.Tutorial.Zemax-Tolerancing.Haynes.pdf