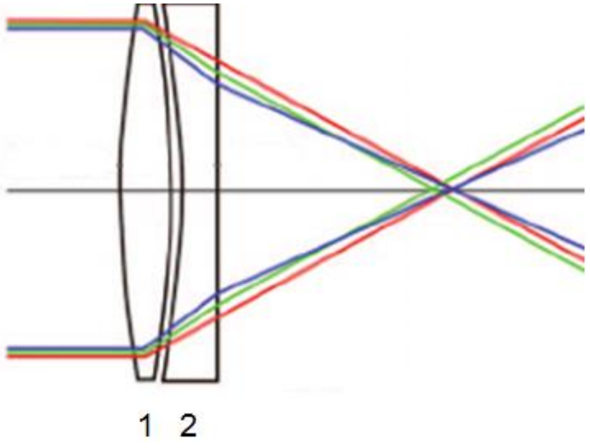
Lecture 9

Chomatic Aberrations



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Aberration Types

1. Spherical aberration
2. Coma
3. Astigmatism
4. Field Curvature
5. Distortion
6. Chromatic Aberration

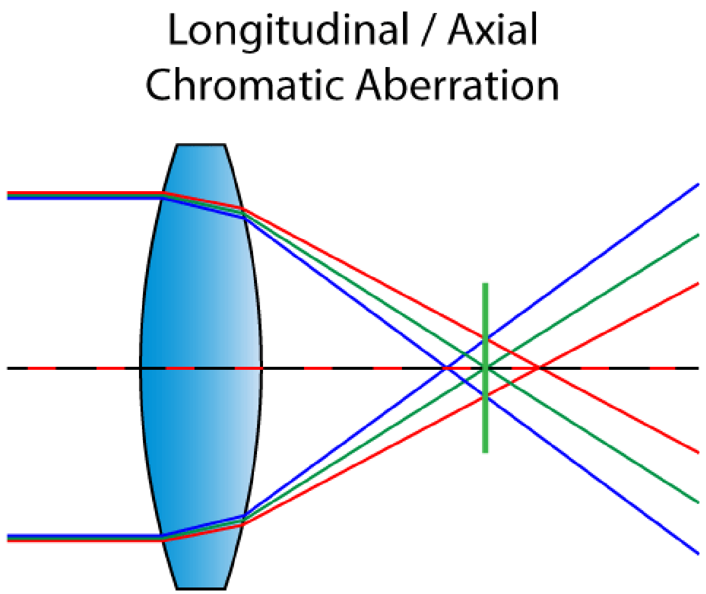
occur with monochromatic light (1–5)

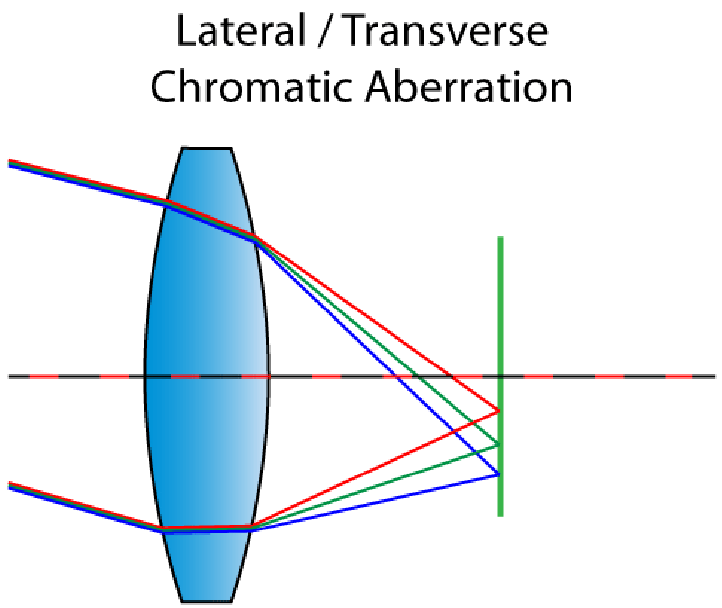
due to dispersion of optical material (6)

Content

What is Chromatic Aberration?

- A lens will not focus different colors (wavelengths) at the same place on the optical axis since focal length depends on refractive index of the material.
- This color dependent deficiency is called the <u>chromatic aberration</u>.






Uncorrected
Corrected

Example 1: Demo for Chromatic Aberration

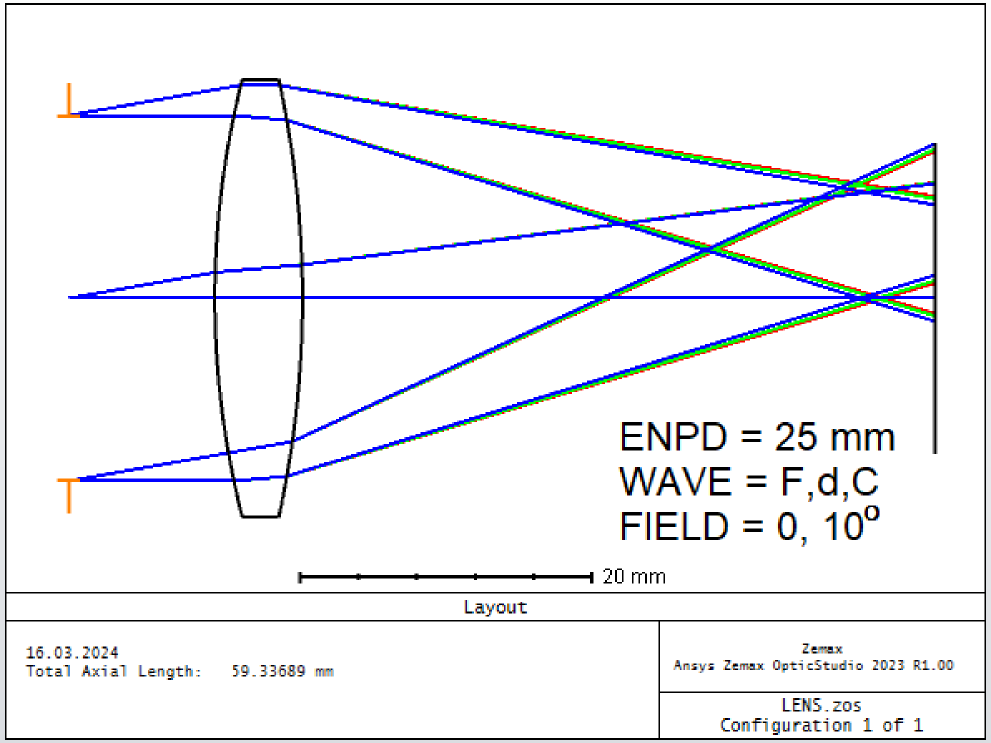
Lens Data

Update: All Windows

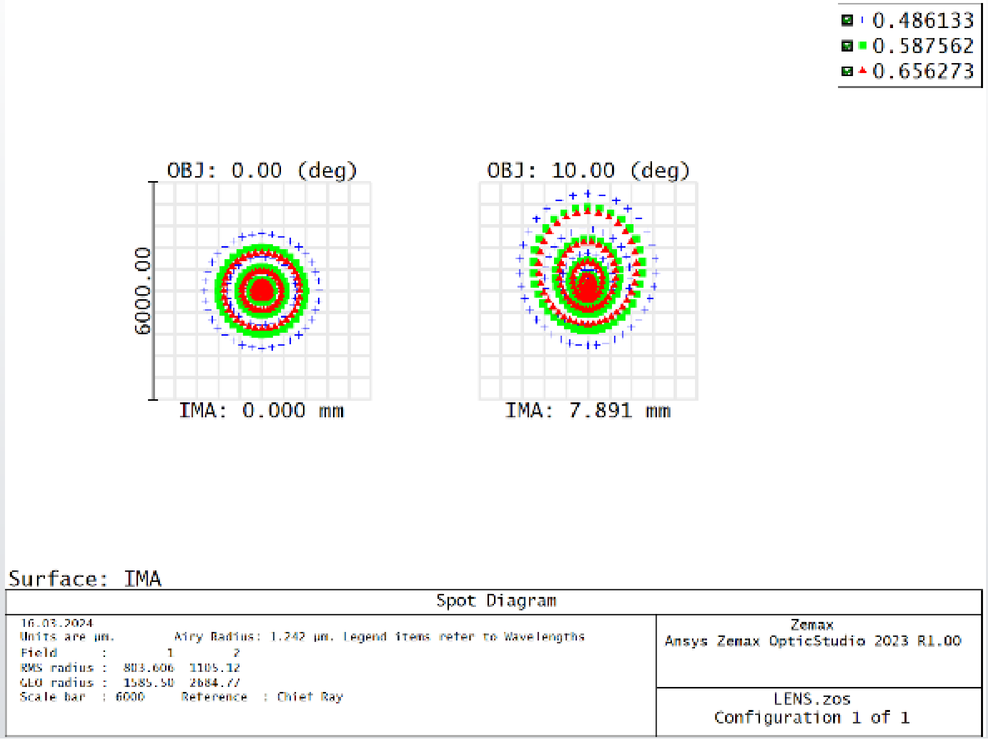
Surface 1 Properties — Configuration 1/1

	Surface Type		Comment	Radius	Thickness		Material	Clear Semi-		Chip Zone	Mech Semi-Dia	Conic	Coati	TCE x 1E-6
0	OBJECT	Standard		Infinity	Infinity			Infinity		0.000	Infinity	0.000		0.000
1	STOP	Standard		Infinity	10.000			12.500		0.000	12.500	0.000		0.000
2	(aper)	Standard		60.000	6.000		SF10	15.000	U	0.000	15.000	0.000		-
3	(aper)	Standard		-70.000	43.337	M		15.000	U	0.000	15.000	0.000		0.000
4	IMAGE	Standard		Infinity	-			10.576		0.000	10.576	0.000		0.000

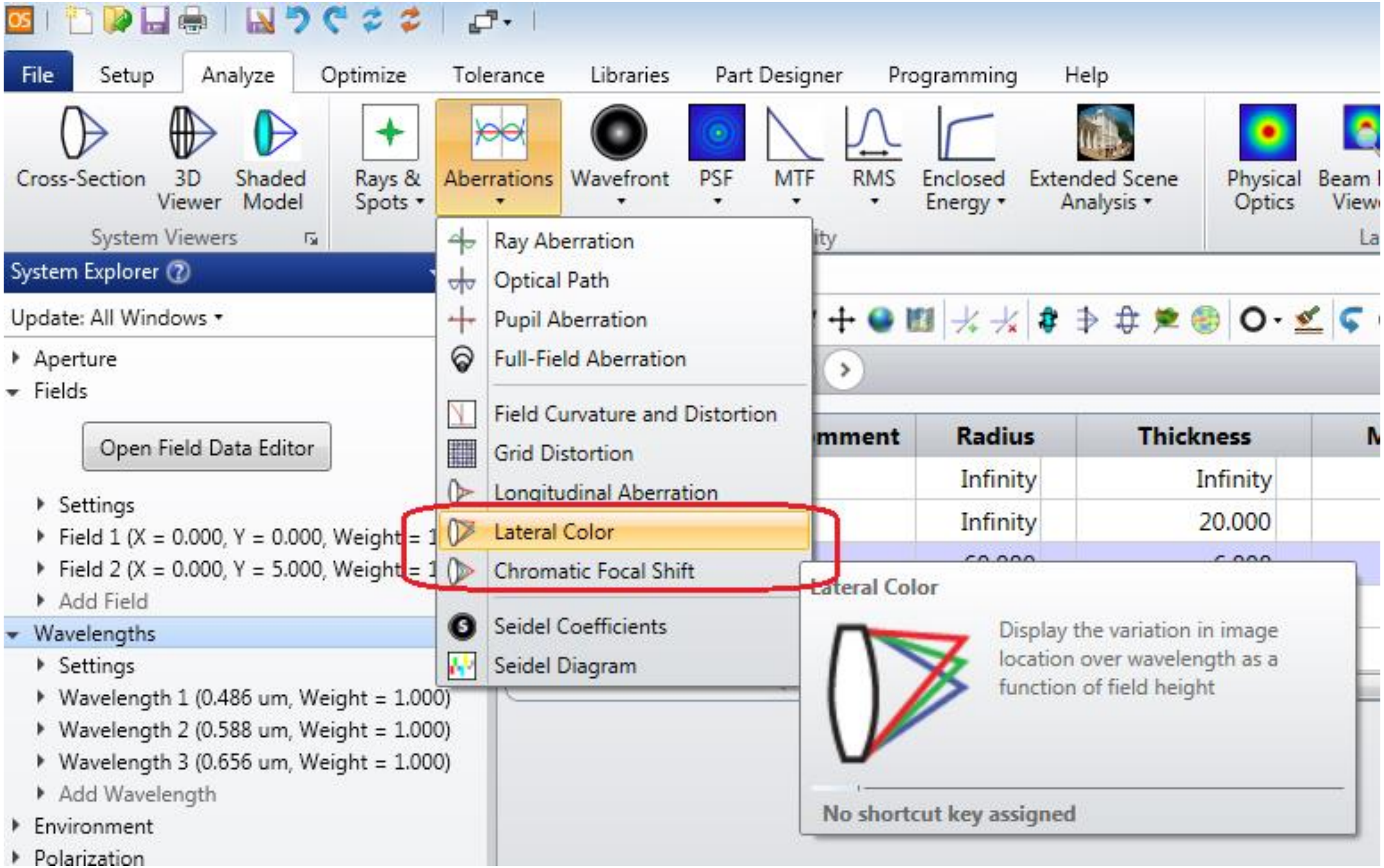
1: Layout



2: Spot Diagram



Aberration Plots

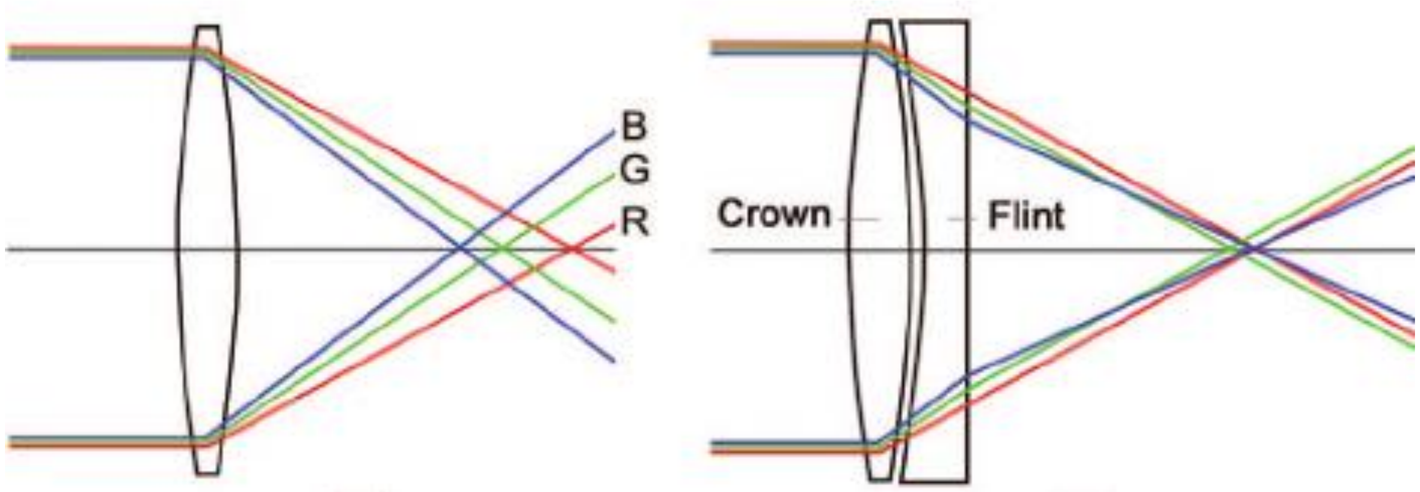


How to Correct Chromatic Aberration

- One way to minimize this aberration is to use glasses of different dispersion in a doublet or triplet. We will mostly investigate **Achromatic Doublet.**

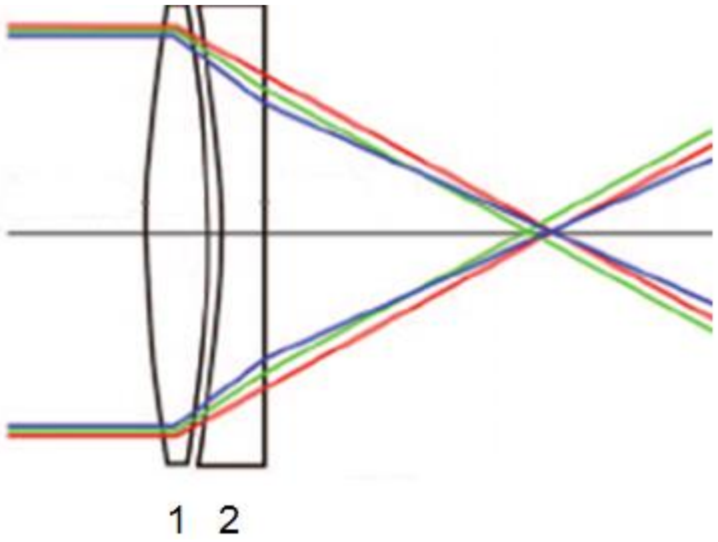
- The use of a strong positive lens made from a low dispersion glass like crown glass (like BK7) coupled with a weaker high dispersion glass like flint glass (like SF2) can correct the chromatic aberration for two colors; e.g., red and blue.

- Such doublets are often cemented together and called achromatic lens.

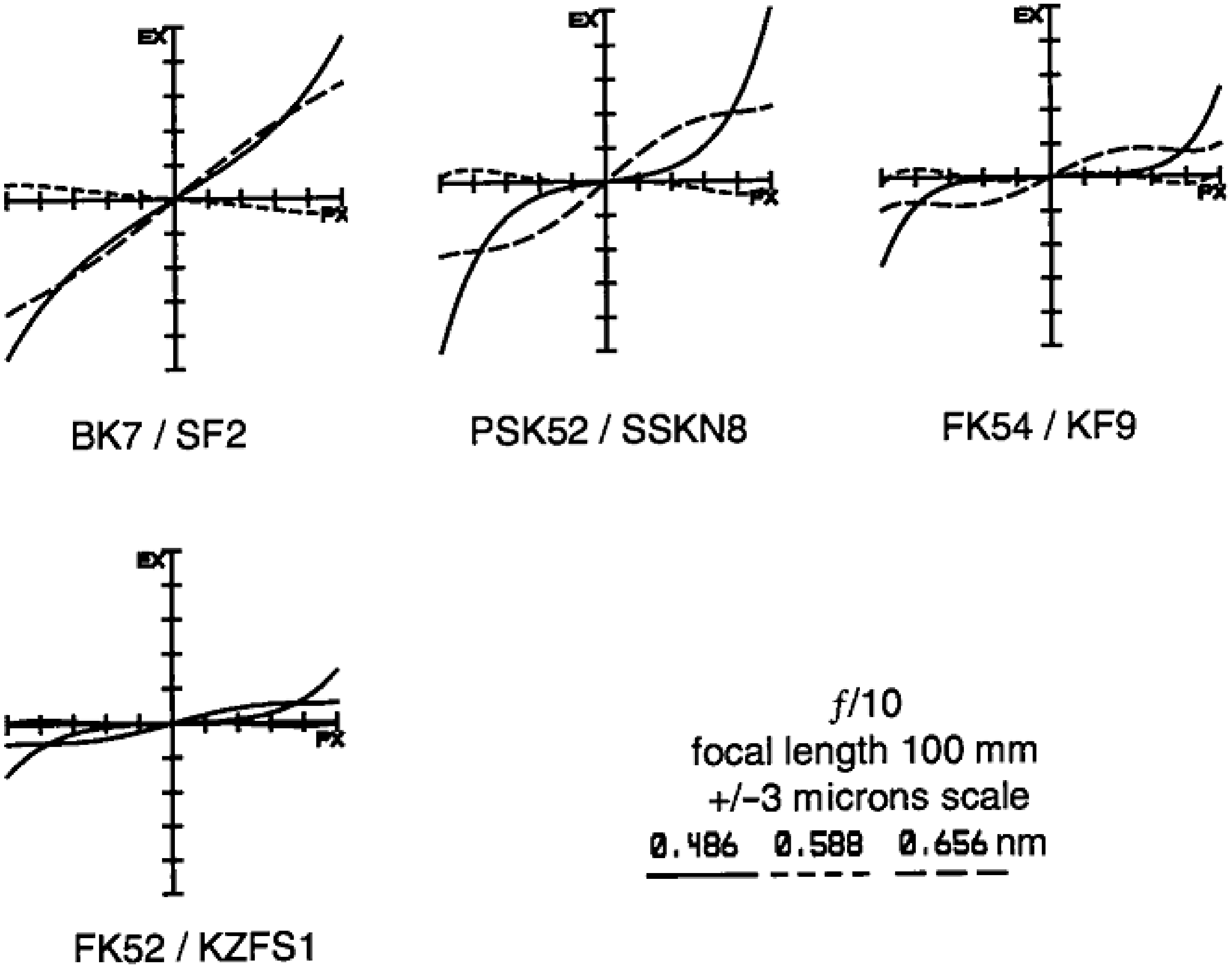


Suggested Glass Pairs for Achoromatic Lens

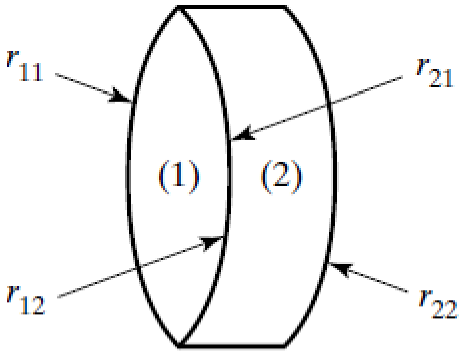
Glass1	**Glass2**
BK7	SF2
PSK52	SSKN8
FK54	KF9
FK52	KZFS1



Ray Fan Plots fot Glass Pairs



Achromatic Doublet Design



- Consider <u>two thin lenses</u> cemented as shown.
- For d-line (λ = 587.6 nm)
  Let P_1, P_2, V_1 and V_2 be powers and Abbe values of glasses, repectively.

Best correction occurs for the condition:

$$\boxed{P_1 V_2 + P_2 V_1 = 0} \text{ here } P_i = 1/f_i$$

$$P_1 = P \frac{-V_1}{V_2 - V_1} \qquad P_2 = P \frac{V_2}{V_2 - V_1}$$

$$P = P_1 + P_2$$

$$K_1 = \frac{P_1}{n_1 - 1} \qquad K_2 = \frac{P_2}{n_2 - 1}$$

Suggested of radius of curvatures:

r_{11} = system focal length / 2

$$r_{12} = -r_{11}$$

$$r_{21} = -r_{11}$$

$$r_{22} = \frac{r_{12}}{1 - K_2 r_{12}}$$

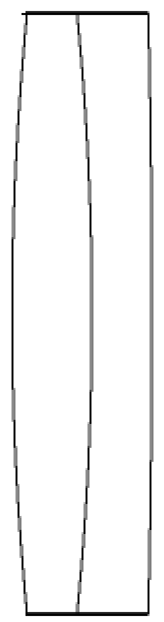
Download `achromate.m` in course web page for implementation of the solution.

Achromatic Doublet Design

Procedure to obtain best acromatic lens for F, d, C (visible) in Zemax.

- Determine the glass pairs.
- Calculate radii of curvatures of lenses to get their initial values using the equations in the previous page.
- Insert these radii to LDE in Zemax.
- Set one, two or all radius of curvatures as variable in LDE.
- In MFE, Set EFFL as desired for d-line. (if necsessary set AXCL = 0 for F and C lines)
- Use Zemax Optimization Tool to get smallest RMS radius for d-line.
- Investigate the optical performance of your design.

Example 2: 300mm-Doublet Design



Design an achromatic doublet to satisfy the following specifications:

EFFL = 300 mm

ENPD = 30 mm

Wavelengths = F, d, C (visible)

Lens1: N-BK7, ct = 4 mm

Lens2: N-SF2, ct = 3 mm

Optimize doublet to get minimum spot size and minimum axial color error in the image plane. [Hint: start with R_{11} = EFFL / 2 = 150 mm]

Using thin lens equations, we can obtain radii of curvatures as follows:

R_{11} = +150.000

R_{12} = -150.000

R_{21} = -150.000

R_{22} = -602.307

Before optimization

Lens Data

Update: All Windows

Surface 5 Properties — Configuration 1/1

	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Ch
0	OBJE(Standard		Infinity	Infinity			0.000	
1	STOP Standard		Infinity	0.000			15.000	
2	(aper) Standard	R11	150.000	4.000	N-BK7		15.000 U	
3	(aper) Standard	R12 & R21	-150.000	3.000	N-SF2		15.000 U	
4	(aper) Standard	R22	-602.307 V	90.000 V			15.000 U	
5	IMAG Standard		Infinity	-			9.896	

Merit Function Editor

Wizards and Operands — Merit Function: 9.81291470515264

	Type	Wave1	Wave2	Zone						Target	Weight	Value	% Contrib
1	DMFS												
2	EFFL		2							300.000	1.000	274.636	80.660
3	AXCL	1	3	0.000						0.000	1.000	0.880	0.097
4	BLNK	Operands for field 1.											
5	TRCX		1	0.000	0.000	0.336	0.000			0.000	0.291	3.313	0.400

After optimization

Lens Data

Update: All Windows

Surface 5 Properties — Configuration 1/1

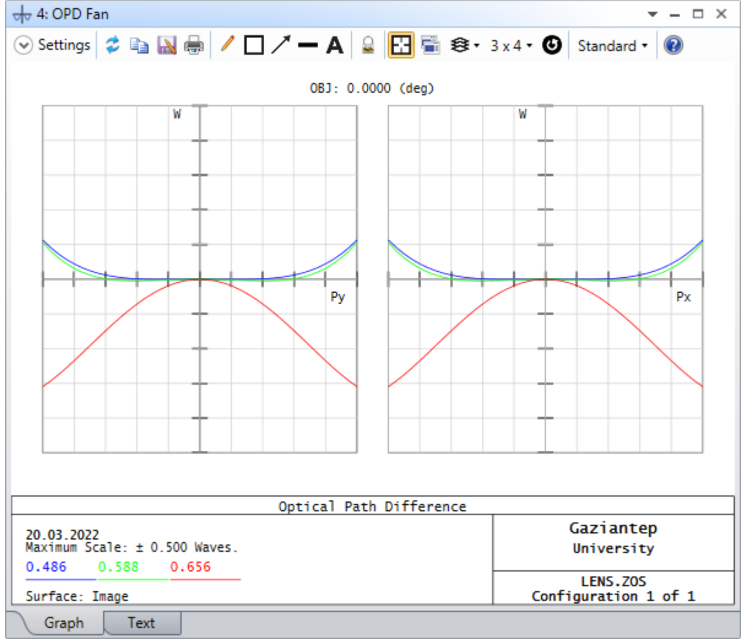
	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chi
0	OBJE(Standard		Infinity	Infinity			0.000	
1	STOP Standard		Infinity	0.000			15.000	
2	(aper) Standard	R11	150.000	4.000	N-BK7		15.000 U	
3	(aper) Standard	R12 & R21	-150.000	3.000	N-SF2		15.000 U	
4	(aper) Standard	R22	-848.745 V	295.845 V			15.000 U	
5	IMAG Standard		Infinity	-			6.105E-03	

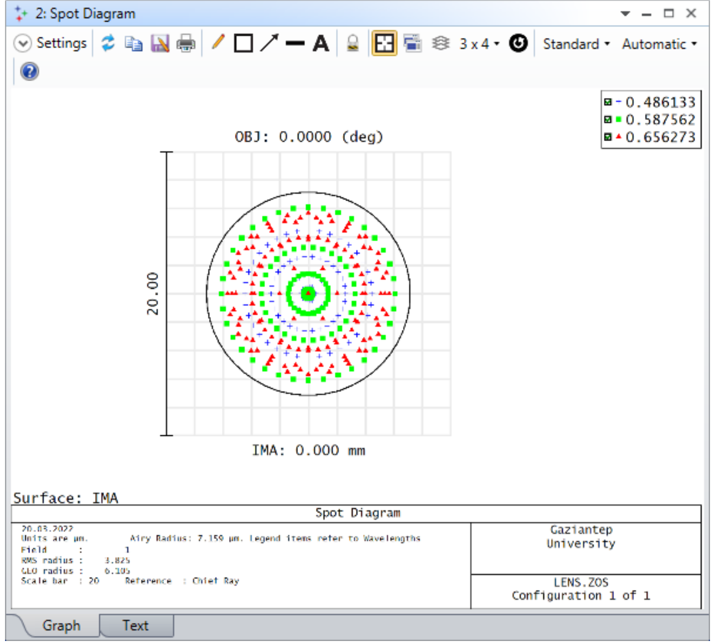
Merit Function Editor

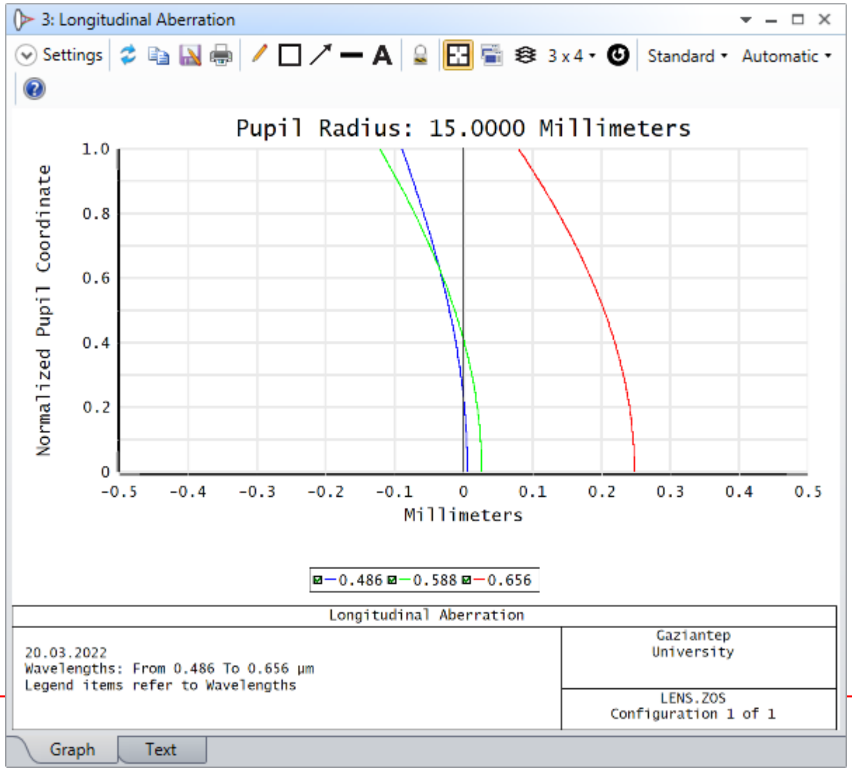
Wizards and Operands — Merit Function: 0.0843456571358175

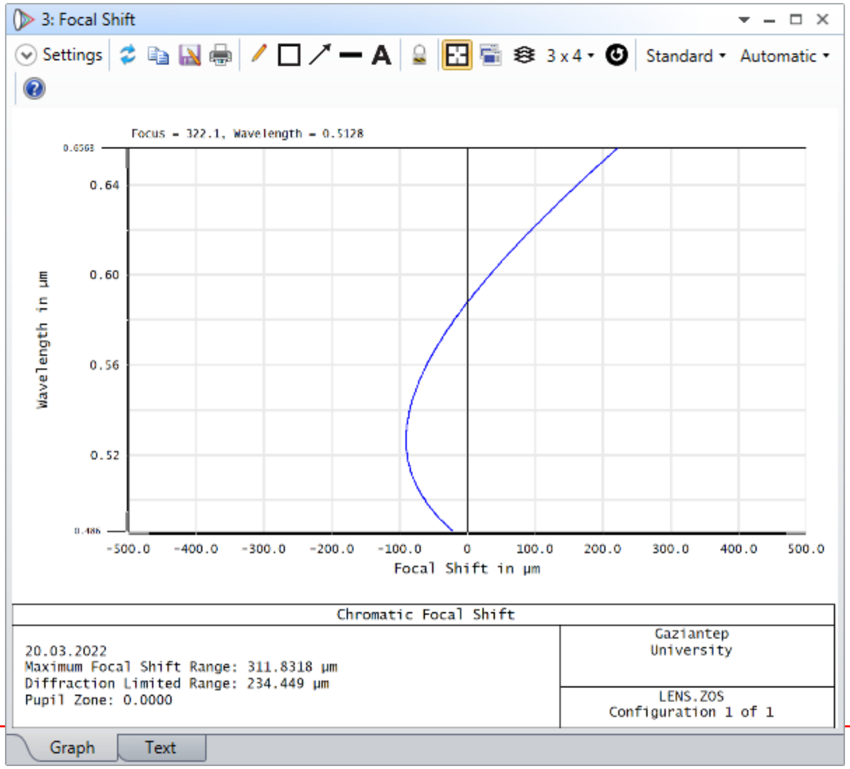
	Type		Wave	Hx	Hy	Px	Py			Target	Weight	Value	% Contrib
1	DMFS												
2	EFFL		2							300.000	1.000	300.007	0.076
3	AXCL	1	3	0.000						0.000	1.000	0.243	99.857
4	BLNK	Operands for field 1.											
5	TRCX		1	0.000	0.000	0.336	0.000			0.000	0.291	-1.021E-04	5.143E-06

final optimization









Apochromatic Lenses (Triplet)

If we use thin lenses, Achromatic Doublet must satisfy:

$$\frac{1}{f_1} + \frac{1}{f_2} = \frac{1}{f}$$

$$f_1 V_1 + f_2 V_2 = 0$$

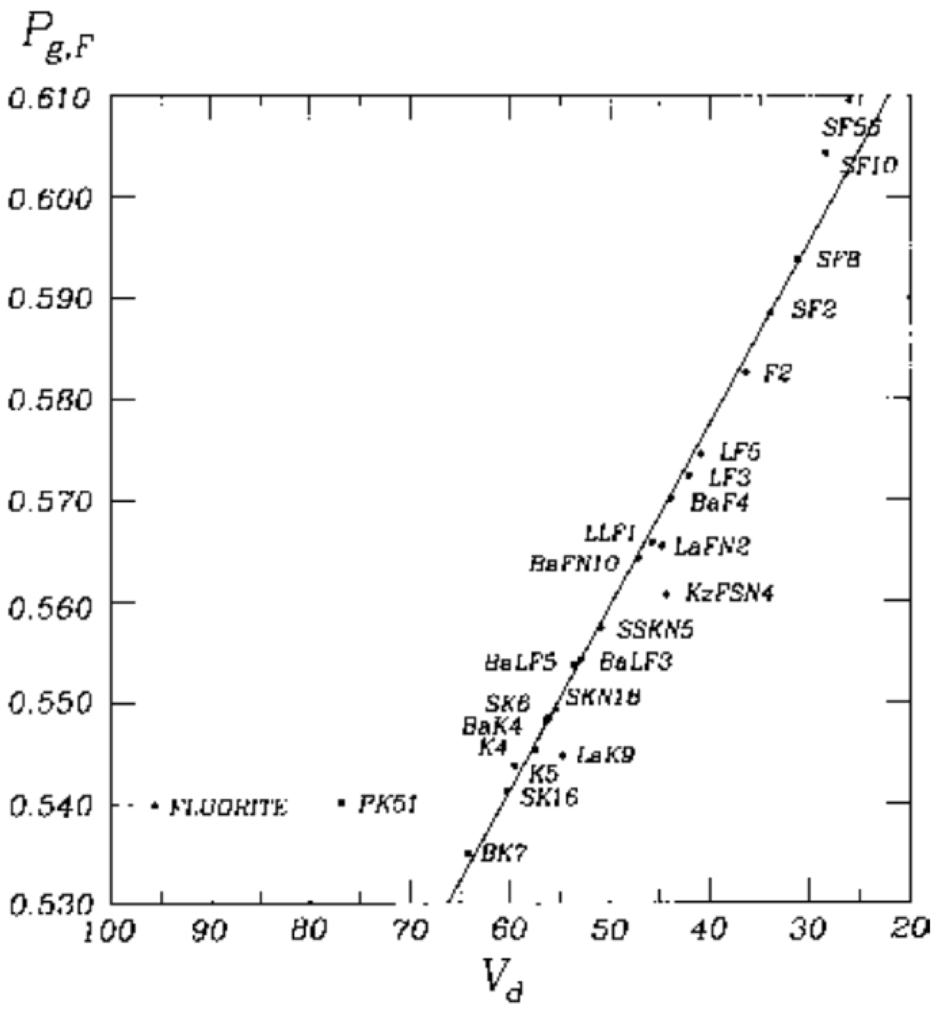
In order to achieve Apochromatic Correction,
a lens system with <u>three elements</u> and
overall focal length of f must satisfy the following
conditions chromatic lens must satisfy:

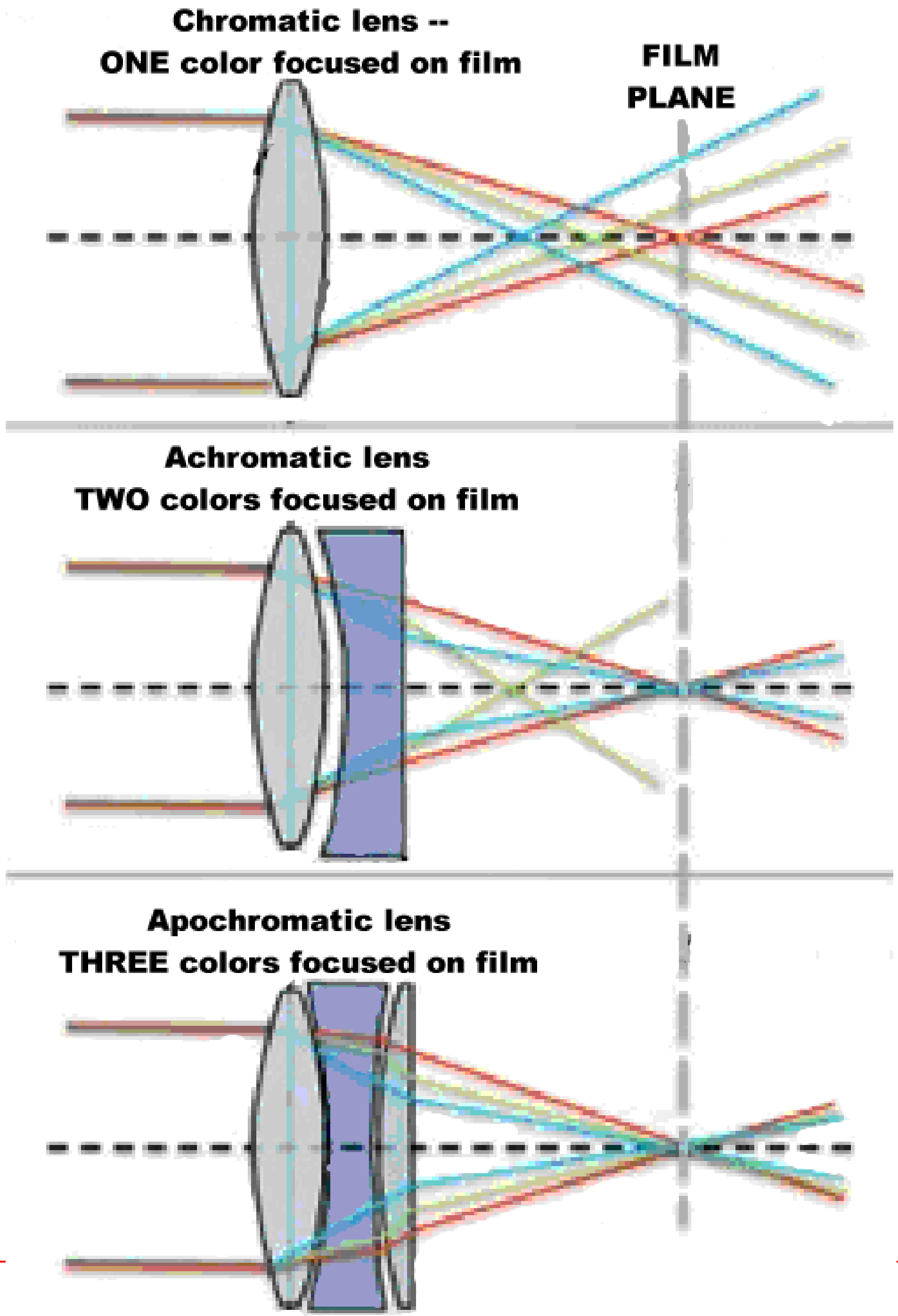
$$\frac{1}{f_1} + \frac{1}{f_2} + \frac{1}{f_3} = \frac{1}{f}$$

$$\frac{1}{f_1 V_1} + \frac{1}{f_2 V_2} + \frac{1}{f_3 V_3} = 0$$

$$\frac{P_1}{f_1 V_1} + \frac{1}{f_2 V_2} + \frac{1}{f_3 V_3} = 0$$

- *P is partial dispersion and it is a linear function of Abbe Value:* $P = aV + b$
- Suggested sturcture: PNP
- Suggested glasses:
  (PK51, KZFS4, SF15)
  (PK51, LAF21, SF15)

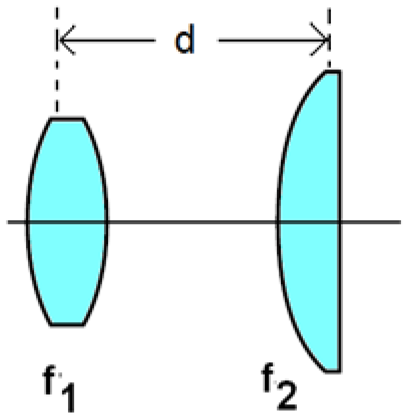



Chromatic lens --
ONE color focused on film
FILM
PLANE
Achromatic lens
TWO colors focused on film
Apochromatic lens
THREE colors focused on film

Spaced Doublet

Another method of making a system achromatic is to use two positive lenses made of same type of glass. Doublet must be separated by a distance equal to one-half the sum of their focal lengths.

$$d = \frac{f_1 + f_2}{2}$$



Effective focal length (f) of the lens system can be found by:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

Subsituting first equation into second one yields:

$$\frac{2}{f} = \frac{1}{f_1} + \frac{1}{f_2}$$

The spaced doublets are mostly used in eyepieces.

Eyepieces

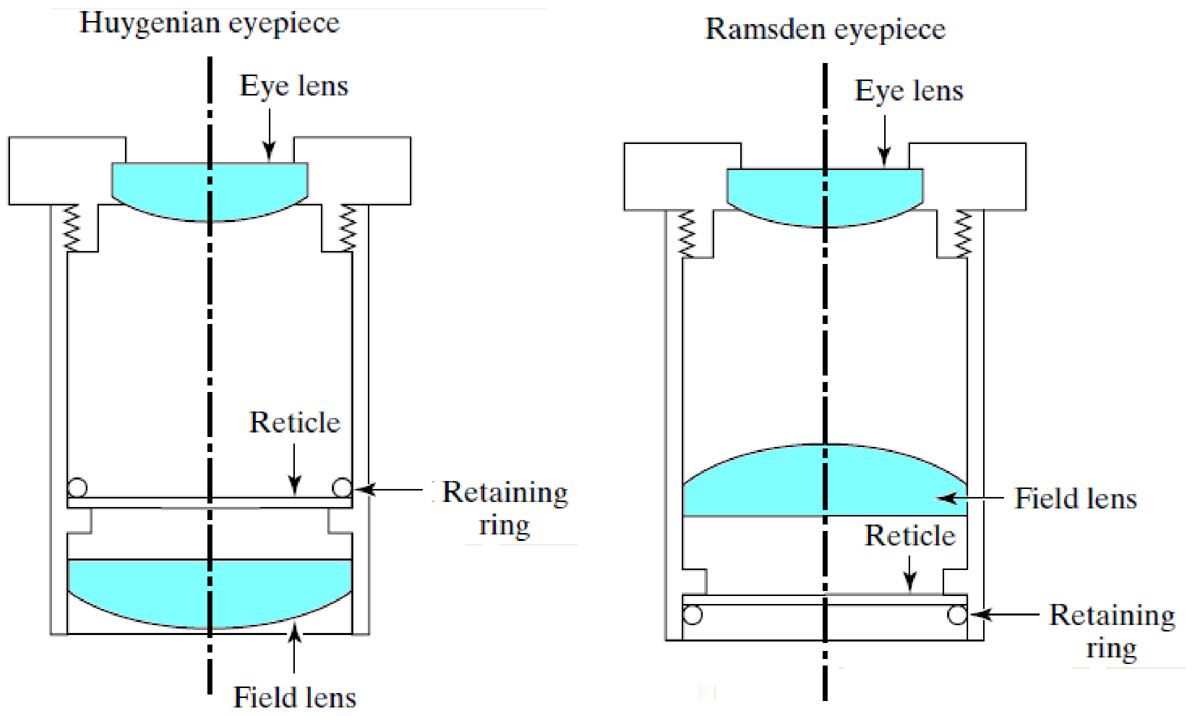
Eyepieces are used in microscpoes, telescopes, and binoculars.
There are simple designs known as Huygenian and Ramsden.
Both designs use two plano-convex lenses.
In Ramsden design, the following relation is suggested:

$$f_1 = \frac{3f_2}{2}$$

Final equations for each focal length become:

$$f_1 = \frac{5f}{4} \qquad f_2 = \frac{5f}{6}$$

where f is the eyepiece focal length.



Eyepieces

- **Reticle:**
  is a pattern of fine markings
  built into the eyepiece.

- **Eye relief (Göz konumu):**
  is exit pupil position where you observe full FOV.

Example 3: Ramsden Eyepiece Design

We want to design f = 28 mm Ramsden Eyepiece using N-BK7 glasses.
ENPD = 3.5 mm, λ = F,d,C, FOV = 10^o, ER = 12 mm, TOTR < 60 mm.

Starting point is to use thin lens equations:

$$f_1 = 5f/4 = 35.0 \text{ mm}$$

$$f_2 = 5f/6 = 23.3 \text{ mm}$$

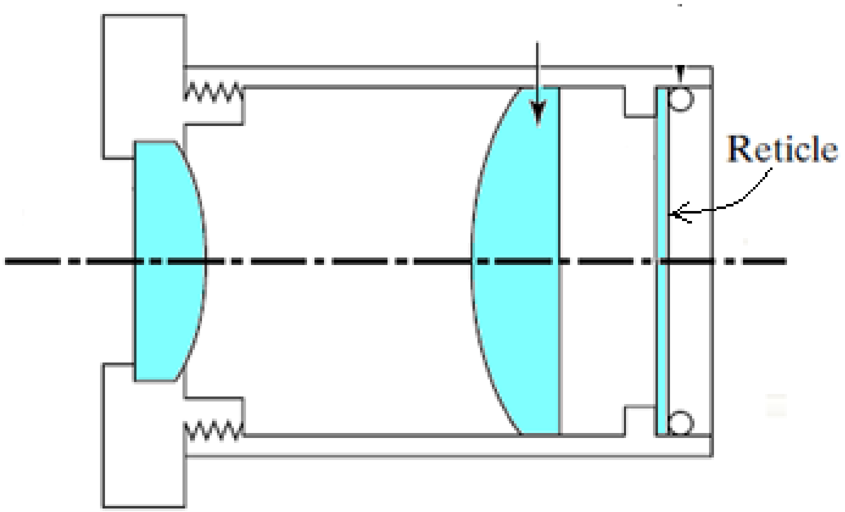
If the lenses are plano-convex, then radius of curvatures for n = 1.52 are as follows:

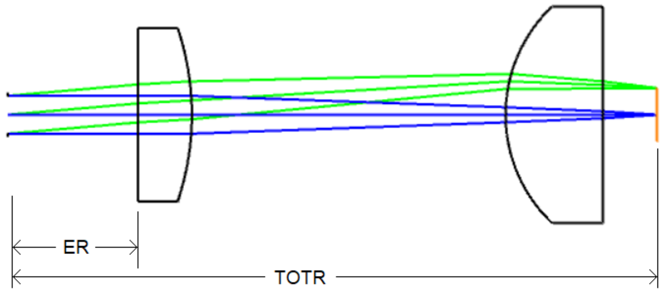
$$|R_1| = (n-1)f_1 = 18.2 \text{ mm}$$

$$|R_2| = (n-1)f_2 = 12.1 \text{ mm}$$

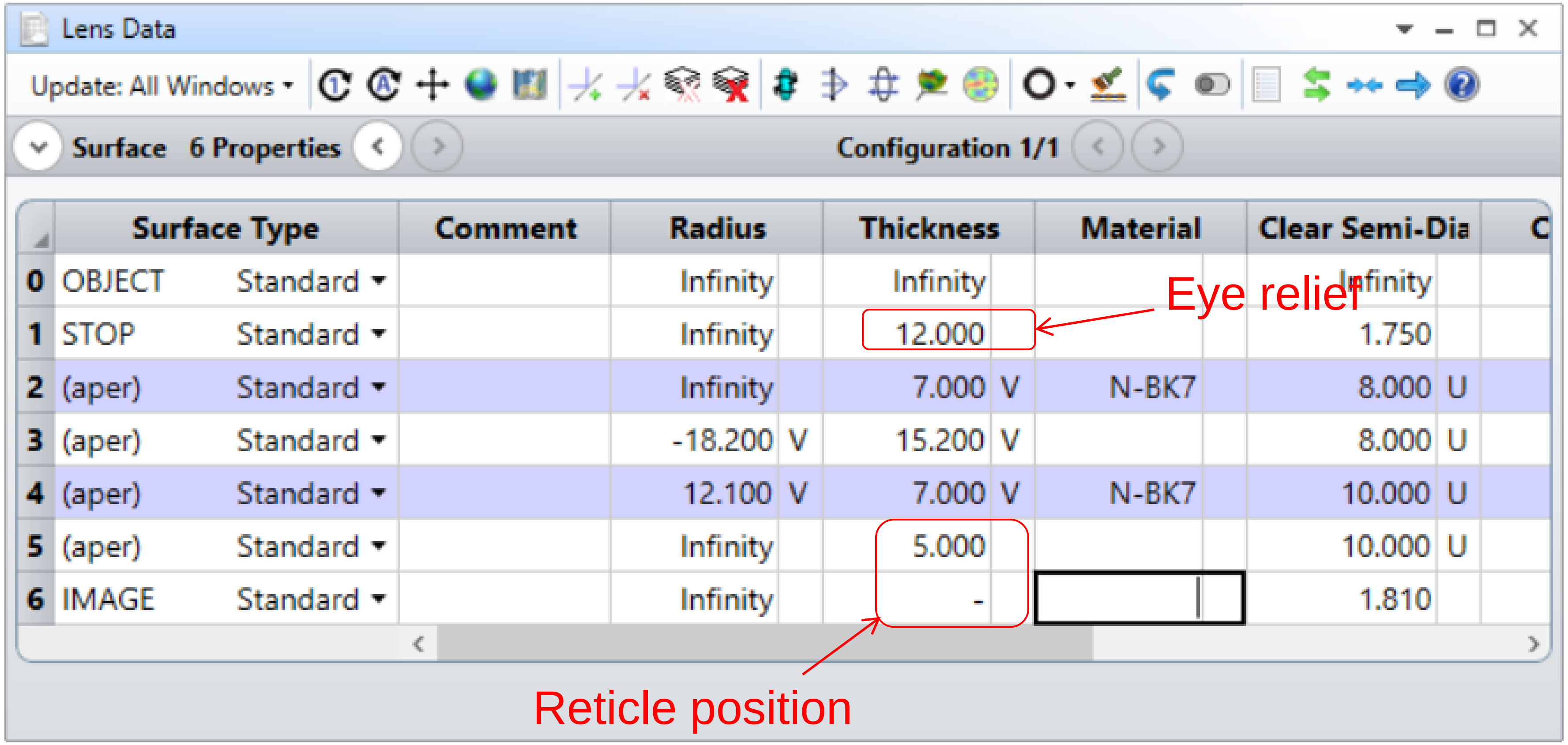
Distance between lenses:

$$d = (f_1 + f_2)/2 = 15.2 \text{ mm}$$

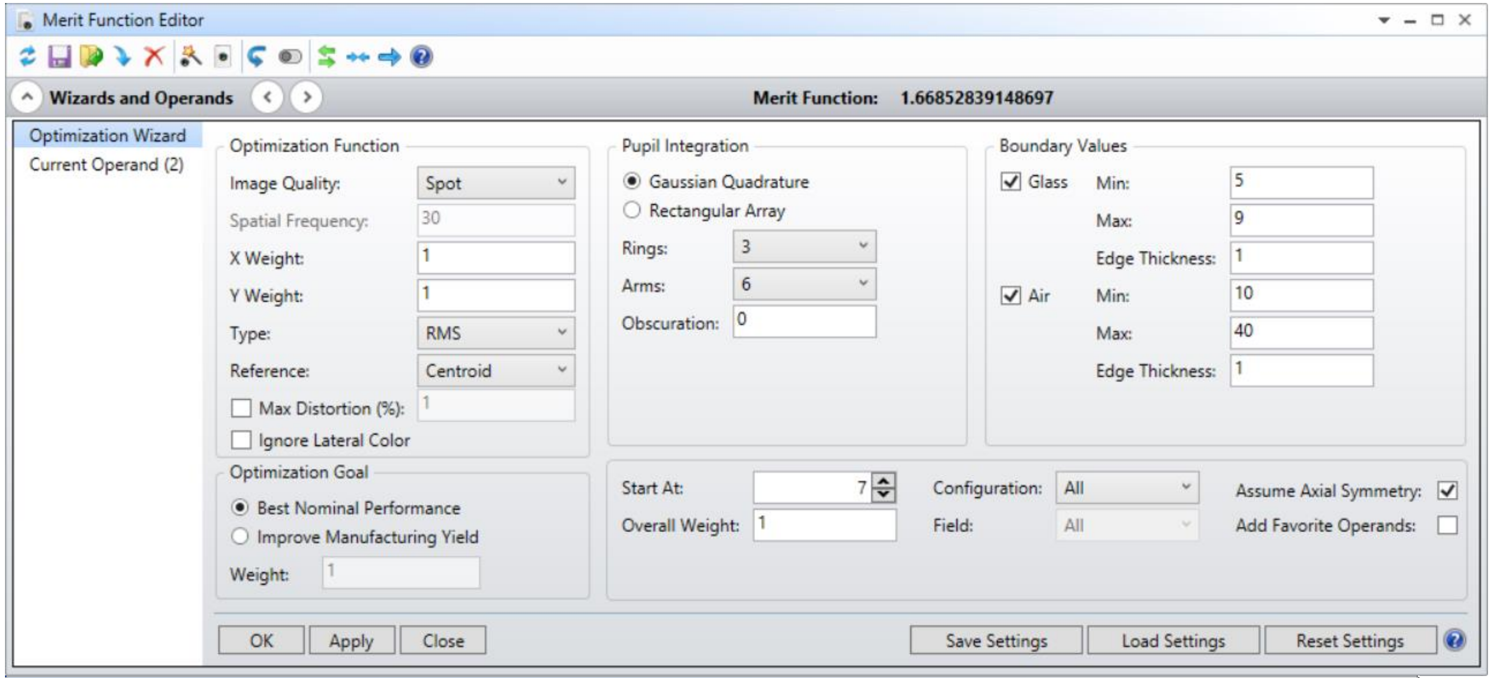




Before Optimization:



Optimization:



Merit Function Editor

Wizards and Operands — Merit Function: 1.66852839148697

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1	EFFL		2							28.000	1.000	18.985	76.433
2	AXCL	1	3	0.000						0.000	1.000	0.211	0.042
3	LACL	1	3							0.000	1.000	0.025	5.742E-04
4	TOTR									0.000	0.000	46.200	0.000
5	OPLT	4								60.000	1.000	60.000	0.000
6	DMFS												
7	BLNK	Sequential merit function: RMS spot x+y centroid X Wgt = 1.0000 Y Wgt = 1.0000 GQ 3 rings 6 ar											
8	BLNK	Default individual air and glass thickness boundary constraints.											

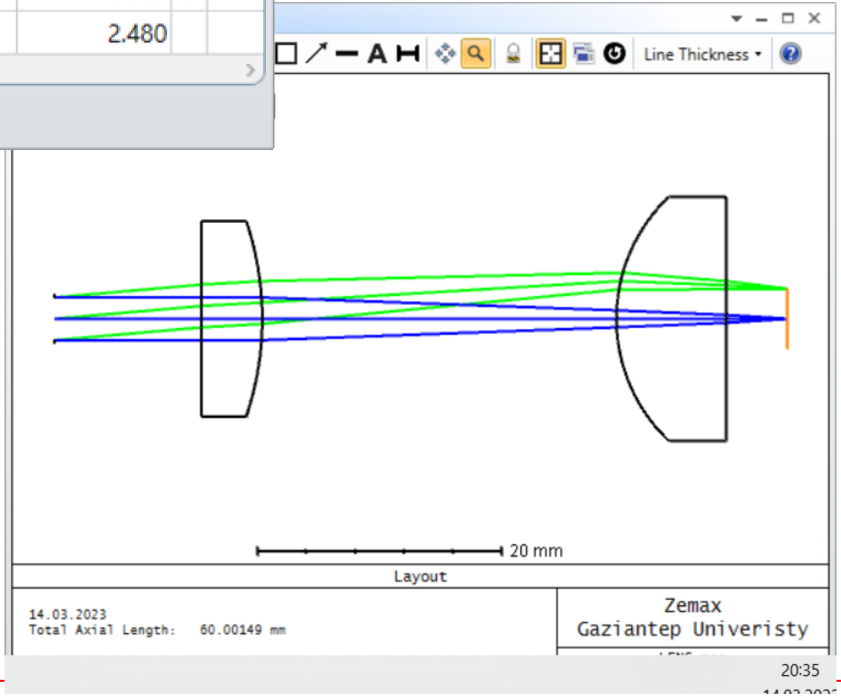
After Optimization:

Lens Data

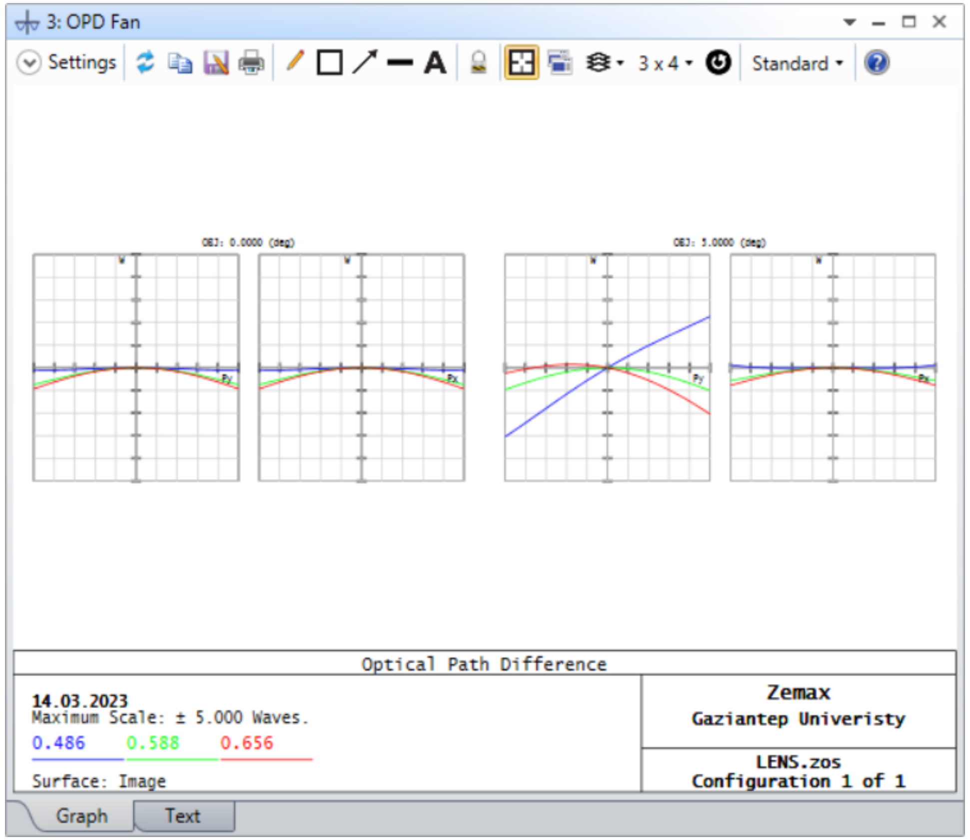
Update: All Windows

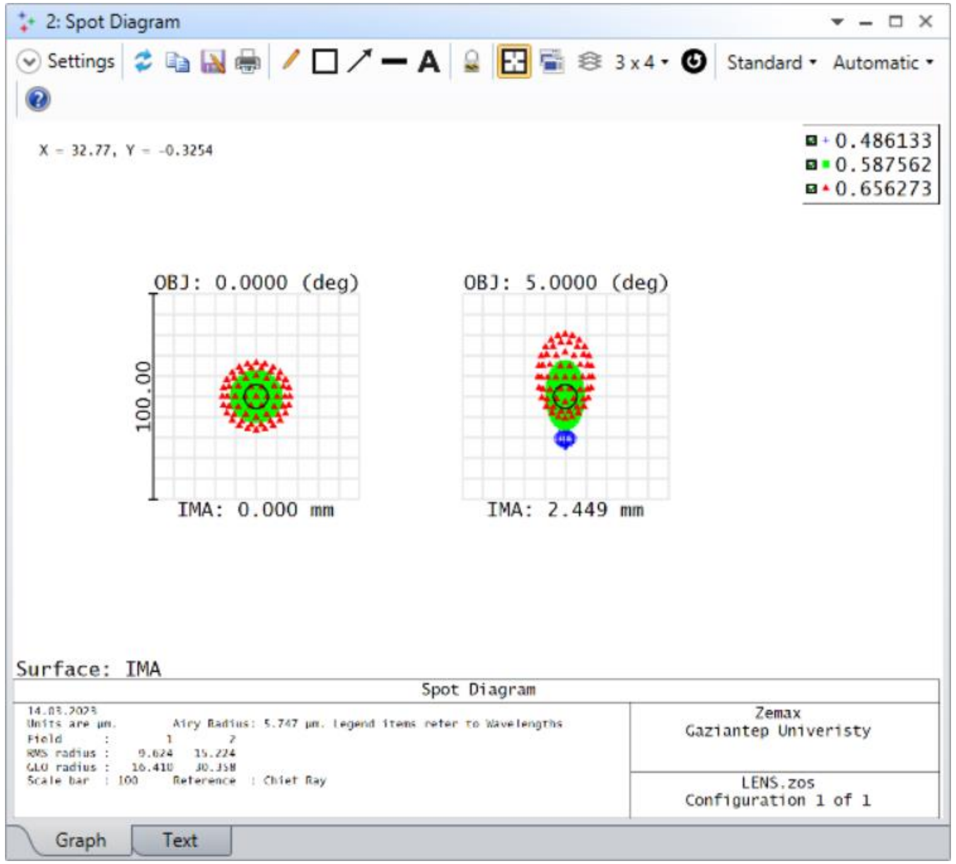
Surface 6 Properties — Configuration 1/1

	Surface Type		Comment	Radius		Thickness		Material	Clear Semi-Dia	
0	OBJECT	Standard		Infinity		Infinity			Infinity	
1	STOP	Standard		Infinity		12.000			1.750	
2	(aper)	Standard		Infinity		4.998	V	N-BK7	8.000	U
3	(aper)	Standard		-24.996	V	29.003	V		8.000	U
4	(aper)	Standard		13.752	V	9.000	V	N-BK7	10.000	U
5	(aper)	Standard		Infinity		5.000			10.000	U
6	IMAGE	Standard		Infinity		-			2.480	



After Optimization:





Cassegrain Design with Field Corrector Lenses

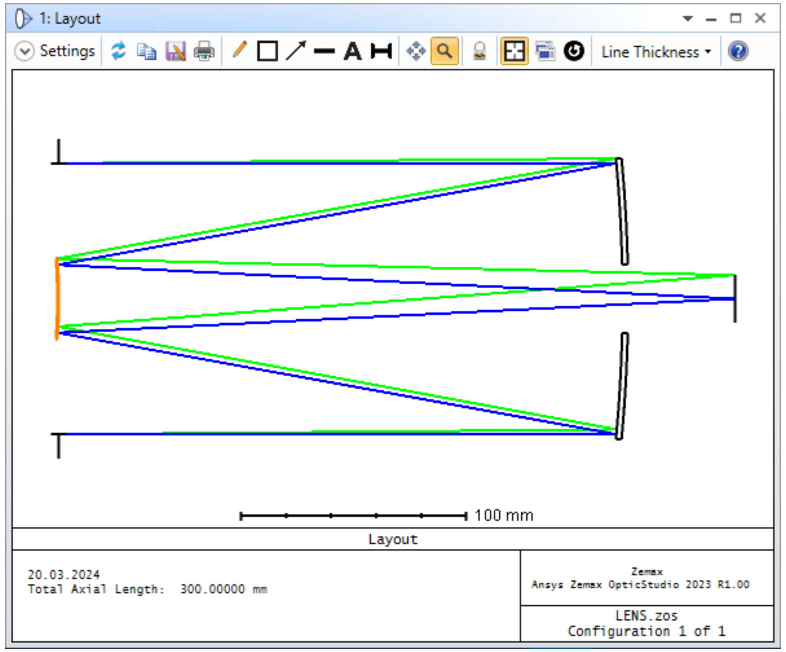
The typical Cassegrain design is known for its excellent on-axis optical performance but tends to perform poorly in off-axis applications.

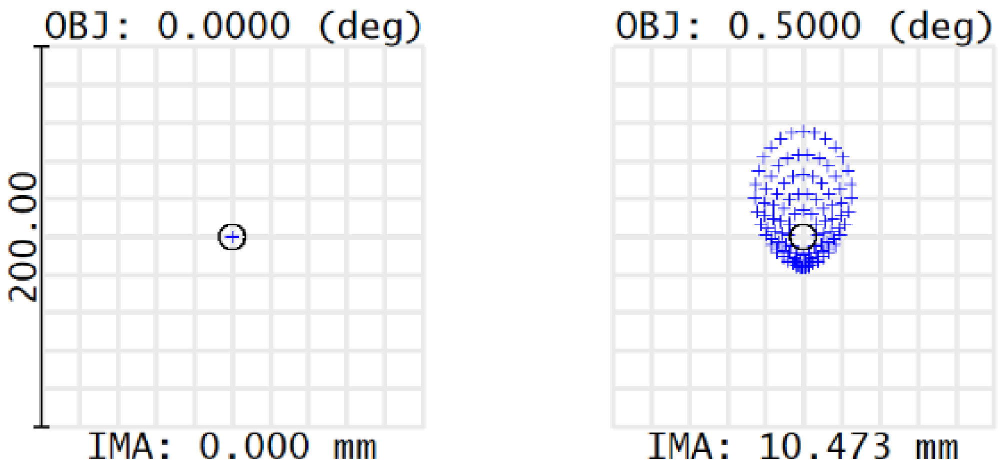
For parabolic mirror, third order angular aberration is given by:

$$AA3 = 3a_1 y^2 \theta / R^2 + 2a_2 y \theta^2 / R + a_3 \theta^3$$

coma + asti + dist

E.g. Cassegrain design with f/10, D= 120 mm, and FOV = 1º.





Cassegrain Design with Field Corrector Lenses

To improve off-axis performance usually a field corrector lens system is added to the mirror system before image sensor.

Note:
If we want to design Cassegrain Telescope whose target (final) focal length F with a corrector lens,

1. Design Cassegrain mirror system with focal length a bit grater or smaller than the target F. Namely, two-mirror focal length should be:
   $F' = F + \Delta F$ or $F' = F - \Delta F$
2. Add corrector lenses and optimize full system to reach target focal length, F.

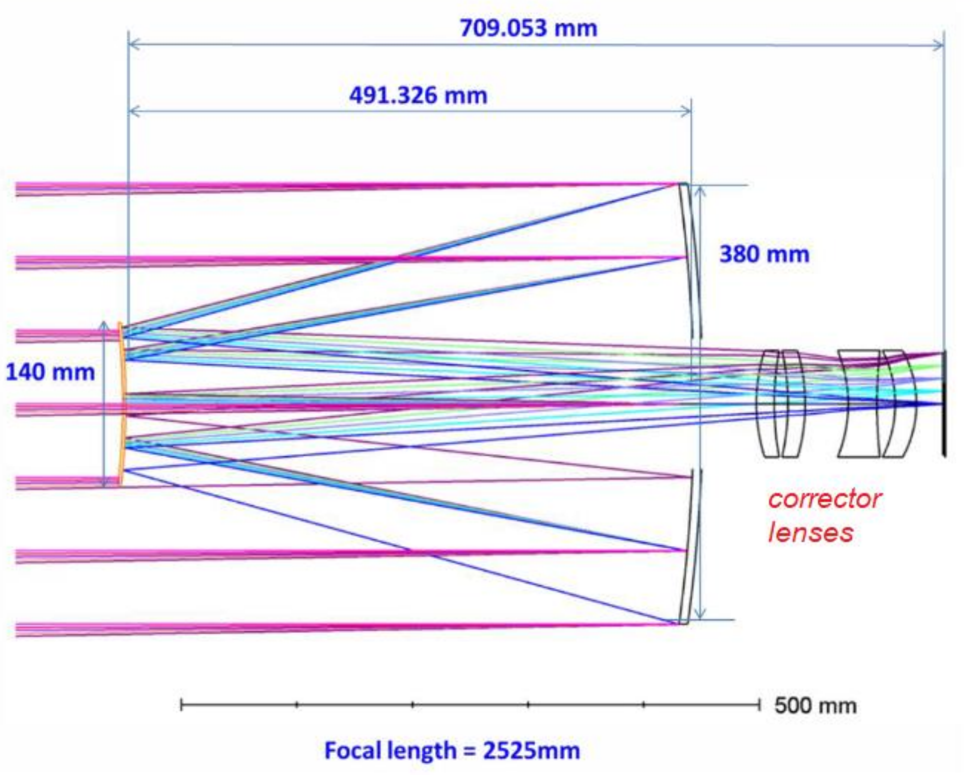


Figure 1: Optical design layout of the Micro-satellite telescope.

Int J Nano Rech 2019 V2:1, ISSN: 2581-6608

Example 4: Cassegrain Telescope with Corrector Design

Design a Cassegrain Telescope with corrector to satisfy the following specifications:

EFFL = 1000 mm

F/# = 10

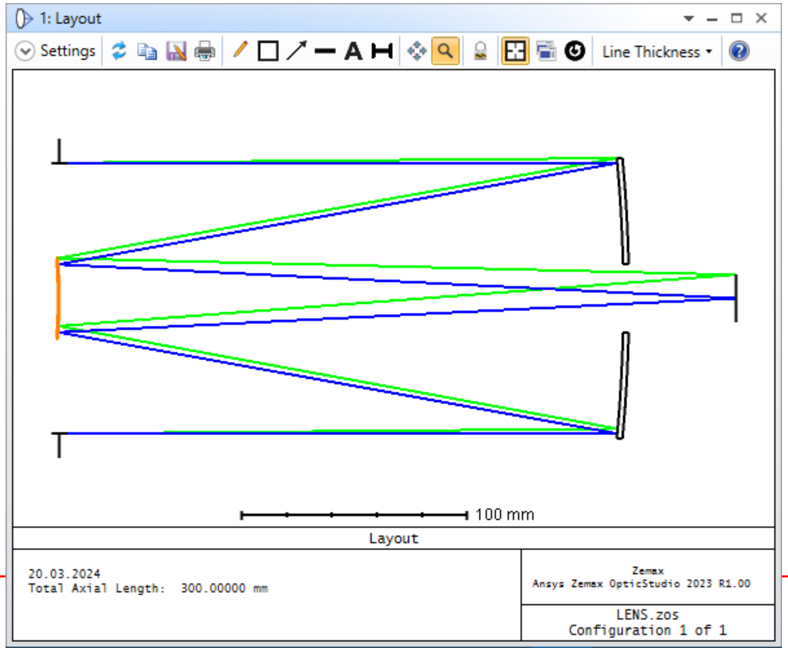
WAVE = F, d, C (visible)

FOV = 1^o

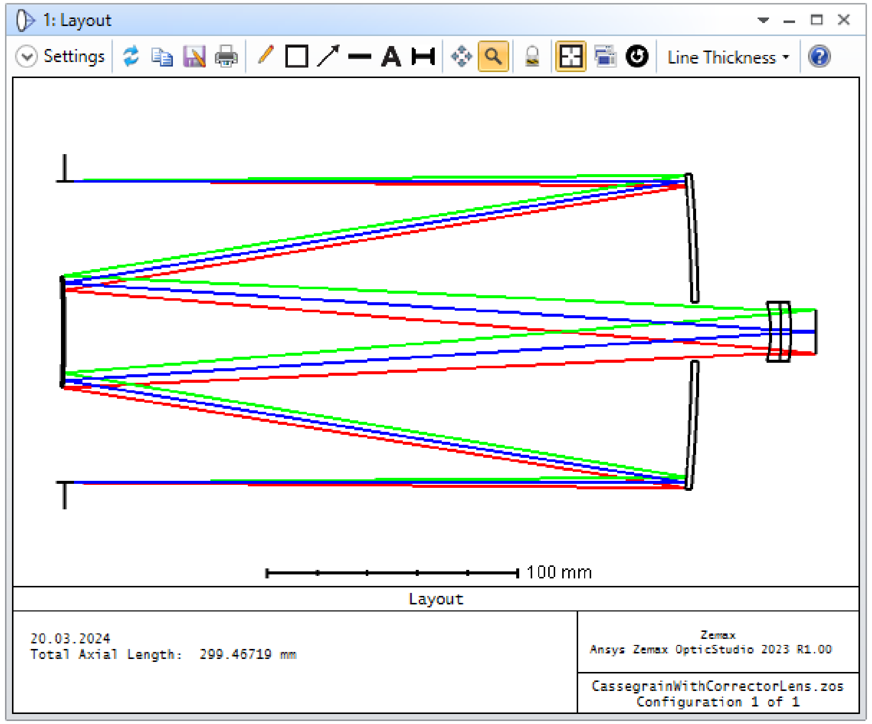
TOTR < 300 mm

Step 1: Design Cassegrain mirrors such that system focal length is F' = 1200 mm as follows:

	Surface Type		Comn	Radius	Thickness	Material	Semi-Diame	Chip Zone	Mech Semi-Dia	Conic
0	OBJECT	Standard		Infinity	Infinity		Infinity	0.000	Infinity	0.000
1	STOP	Standard		Infinity	250.000		60.000	0.000	60.000	0.000
2	(aper)	Standard		-666.667	-250.000	MIRROR	62.156	0.000	62.156	-1.000
3		Standard		-230.769	300.000	MIRROR	17.782	0.000	17.782	-3.130
4	IMAGE	Standard		Infinity	-		10.528	0.000	10.528	0.000



Step2: Add a doublet lens and optimize the system as follows. Notice F = 1000 mm.



Merit Function Editor

Wizards and Operands — Merit Function: 0.000351778933714607

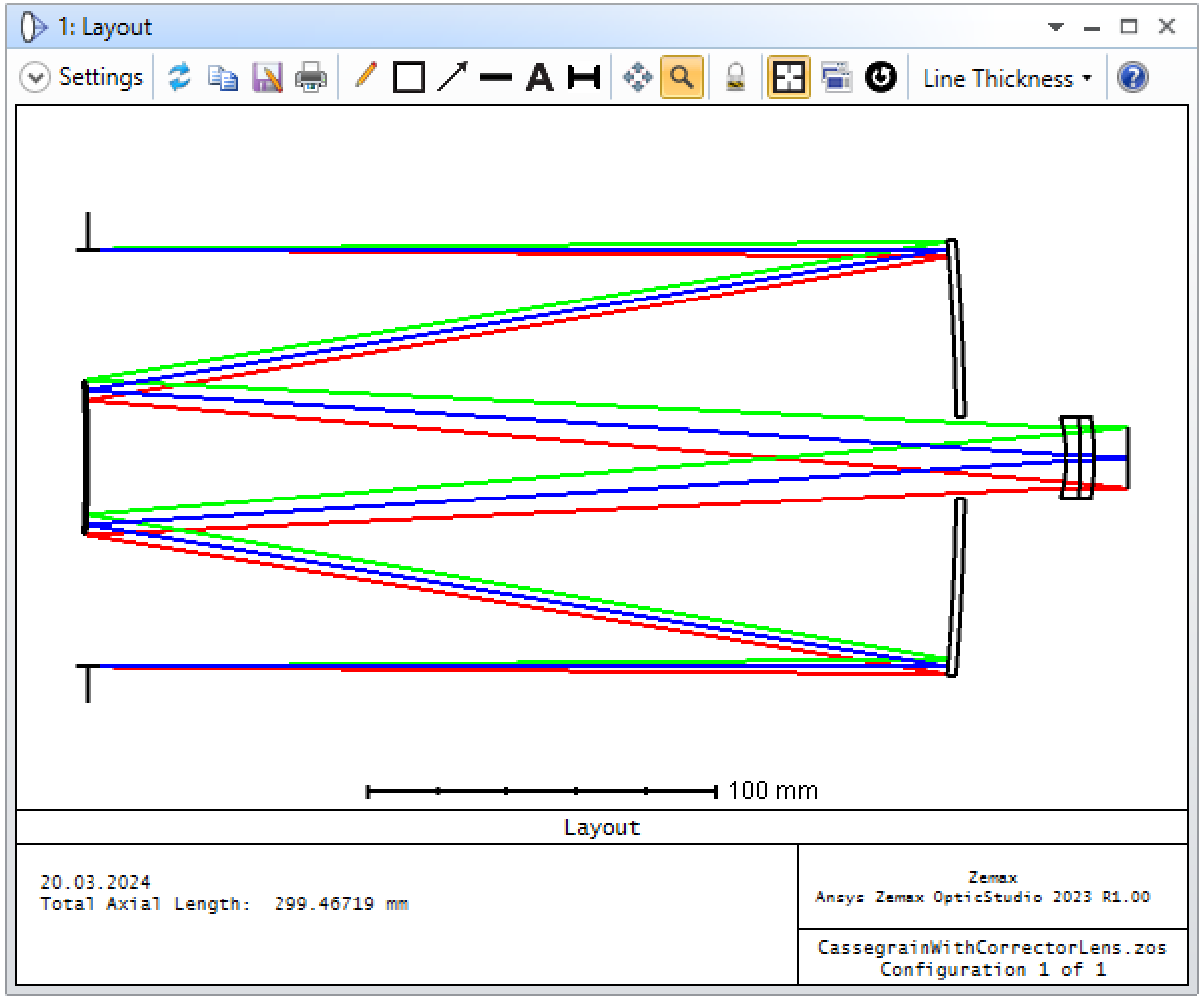
	Type	Surf1	Surf2						Target	Weight	Value	% Contrib
1	EFFL		1						1000.000	1.000	1000.000	5.176E-10
2	TOTR								0.000	0.000	299.467	0.000
3	OPLT	2							300.000	1.000	300.000	0.000
4	DMFS											
5	BLNK	Sequential merit function: RMS spot x+y centroid X Wgt = 1.0000 Y Wgt = 1.0000 GQ 3 rings 6 arms										

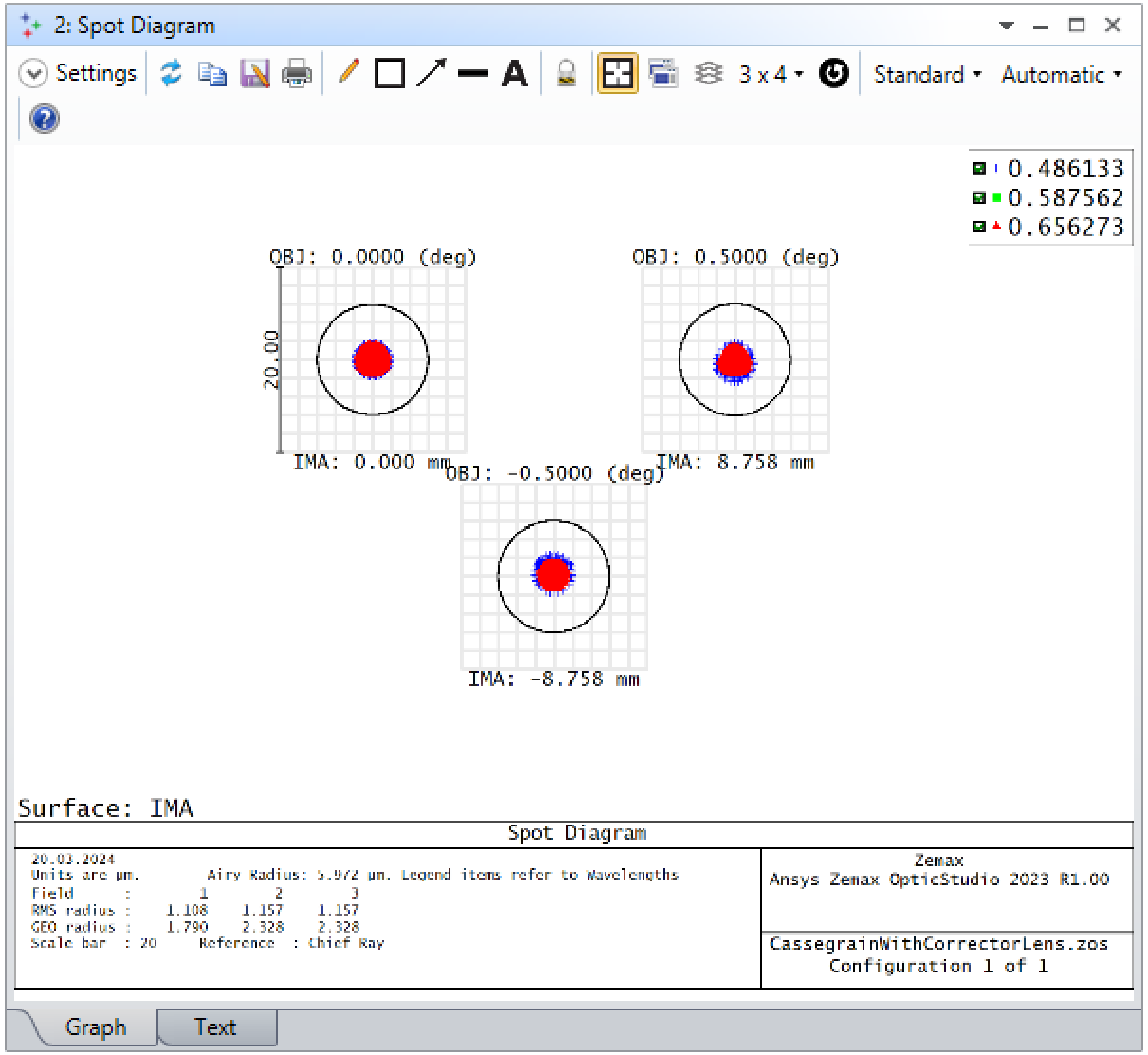
Lens Data

Update: All Windows

Surface 1 Properties — Configuration 1/1

	Surface Type		Comn	Radius		Thickness		Material	Clear Semi-		Chip Zone	Mech Semi-Dia	Conic	
0	OBJECT	Standard		Infinity		Infinity			Infinity		0.000	Infinity	0.000	
1	STOP	Standard		Infinity		250.000			60.000		0.000	60.000	0.000	
2	(aper)	Standard		-736.836	V	-250.000		MIRROR	62.159		0.000	62.594	-1.205	V
3		Standard		-395.780	V	281.467	V	MIRROR	22.271		0.000	22.271	-8.518	V
4	(aper)	Standard		-42.971	V	4.000		N-BK7	12.000	U	0.000	12.000	0.000	
5	(aper)	Standard		-168.166	V	4.000		N-SF2	12.000	U	0.000	12.000	0.000	
6	(aper)	Standard		-68.005	V	10.000			12.000	U	0.000	12.000	0.000	
7	IMAGE	Standard		Infinity		-			8.759		0.000	8.759	0.000	


1: Layout
Settings
Line Thickness
100 mm
Layout
20.03.2024
Total Axial Length: 299.46719 mm
Zemax
Ansys Zemax OpticStudio 2023 R1.00
CassegrainWithCorrectorLens.zos
Configuration 1 of 1


2: Spot Diagram
Settings
3 x 4
Standard
Automatic
0.486133
0.587562
0.656273
OBJ: 0.0000 (deg)
20.00
IMA: 0.000 mm
OBJ: 0.5000 (deg)
IMA: 8.758 mm
OBJ: -0.5000 (deg)
IMA: -8.758 mm
Surface: IMA
Spot Diagram
20.03.2024
Units are µm. Airy Radius: 5.972 µm. Legend items refer to Wavelengths
Field : 1 2 3
RMS radius : 1.108 1.157 1.157
GEO radius : 1.790 2.328 2.328
Scale bar : 20 Reference : Chief Ray
Zemax
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CassegrainWithCorrectorLens.zos
Configuration 1 of 1
Graph
Text