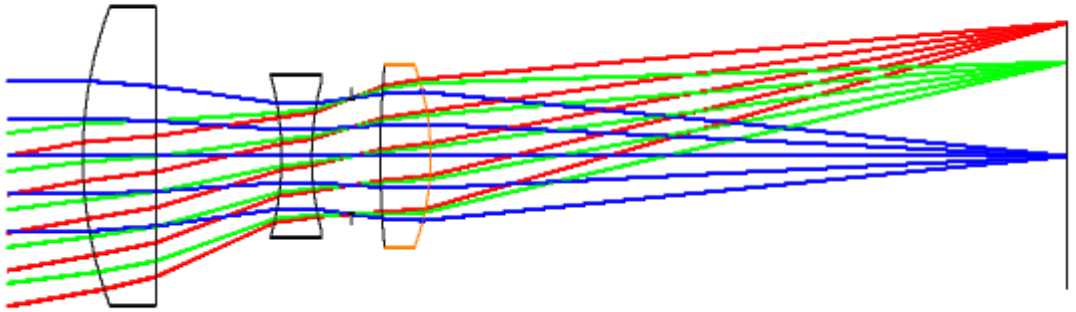
Lectures Notes on Optical Design using Zemax OpticStudio

Lecture 13

Cooke Triplet



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Cooke Triplet

- The Cooke triplet is a photographic lens designed and patented (patent number GB 22,607) in 1893 by Dennis Taylor.
- It was the first lens system that allowed elimination of most of the optical distortion or aberration at the outer edge of the image.

- A Cooke triplet comprises a negative flint glass element in the center with a crown glass element on each side.

- See for more info: https://en.wikipedia.org/wiki/Cooke_triplet

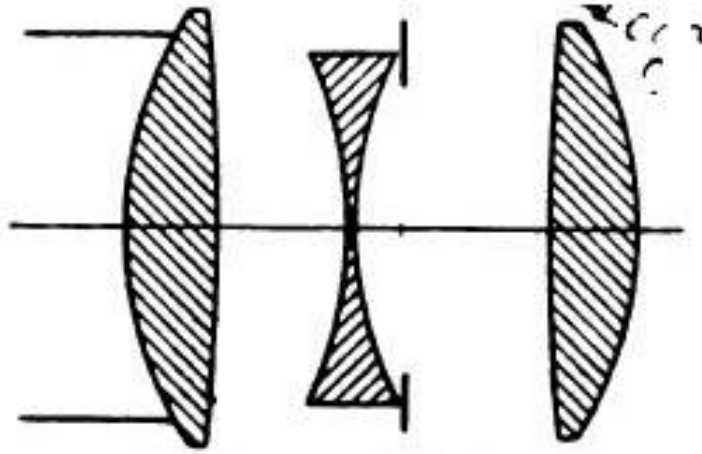


Fig. 94, s. Taf. I.

H. D. TAYLOR: Portraitobjektiv.
Quelle: H. D. TAYLOR. 1.

Reducirt auf $f_D = 100$ mm.
Durchgerechnet für 1 : 4 und $\omega = 13°$.
Radien r_ν, Dicken d_ν und Abstände b_ν in Millimetern auf der Axe gemessen.

$r_1 = 26.4$
$d_1 = 5.9$
$r_2 = 150.7$
$b_1 = 10.9$
$r_3 = 29.8$
$d_2 = 0.2$
$r_4 = 24.2$
$b_2^{1}) = 3.1$
$b_2^{2}) = 9.4$
$r_5 = 150.7$
$d_3 = 5.9$
$r_6 = 26.4$

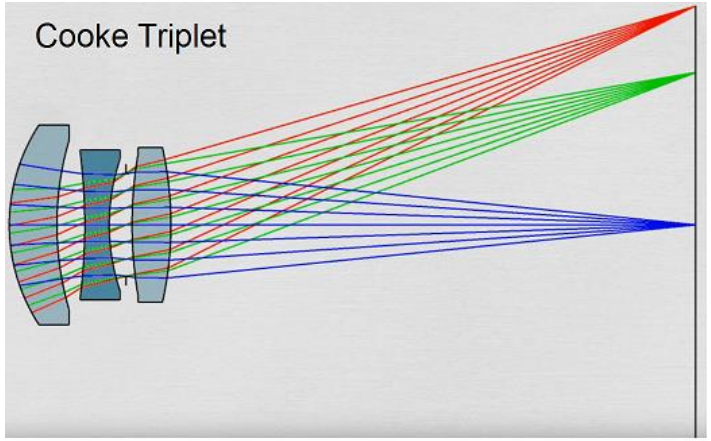
Glasarten n_D.
$L_1 = L_3 = 1.5108$
$L_2 = 1.6042$

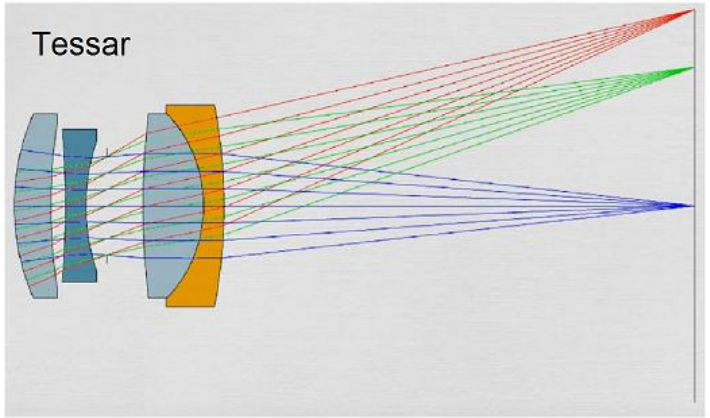
Cooke Triplet

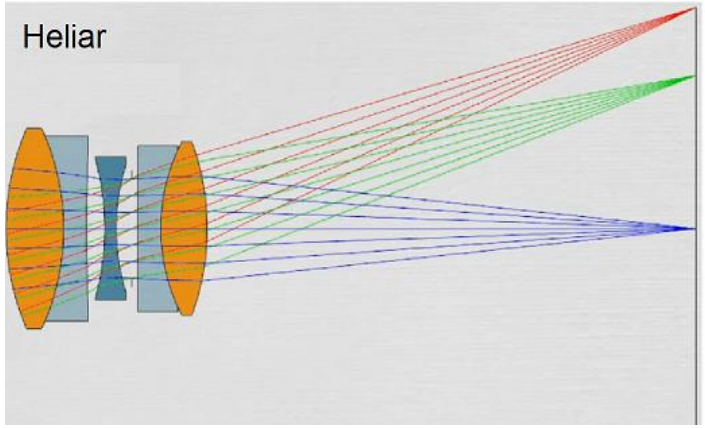
- It is widely used.
- **f/3** or slower
- **FOV < ±20º**

- Structure is PNP.
  Negative lens is used to control FOV.
- AS is in between lenses.

- This triplet can be converted to tessar or heliar to obtain better imaging performance.

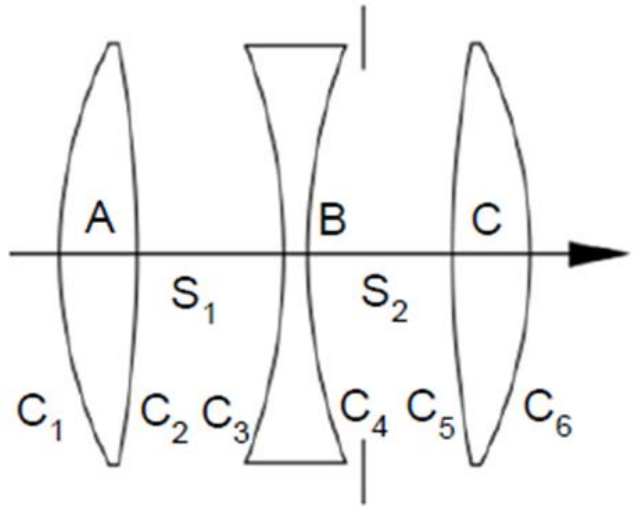






Optimization

- The Cooke triplet can correct, with only three elements, for one wavelength
  - spherical aberration
  - coma
  - astigmatism
  - field curvature
  - distortion
- We have totally 16 parameters to optimize the triplet.
  - **3** glass types
  - **6** Radius of curvatures
  - **3** glass thicknesses
  - **4** air thicknesses



Example 1: f/5 Cooke Triplet Design in Zemax

The specifications are as follows:

- F/# : 5
- EFL : 50 mm
- FOV : 20^{o}
- Wavelength : F, d, C (visible)
- Glasses : Schott

System Explorer

Update: All Windows

- Aperture
  - Aperture Type: Entrance Pupil Diameter
  - Aperture Value: 10.0
  - Apodization Type: Uniform
  - Clear Semi Diameter Margin Millimeters: 1.0
  - Clear Semi Diameter Margin %: 0.0
  - Global Coordinate Reference Surface: 6
  - Telecentric Object Space
  - Afocal Image Space
  - Iterate Solves When Updating
  - Fast Semi-Diameters
  - Check GRIN Apertures
- Fields
- Wavelengths
- Environment
- Polarization
- Advanced
- Ray Aiming
  - Ray Aiming: Paraxial
  - Use Ray Aiming Cache

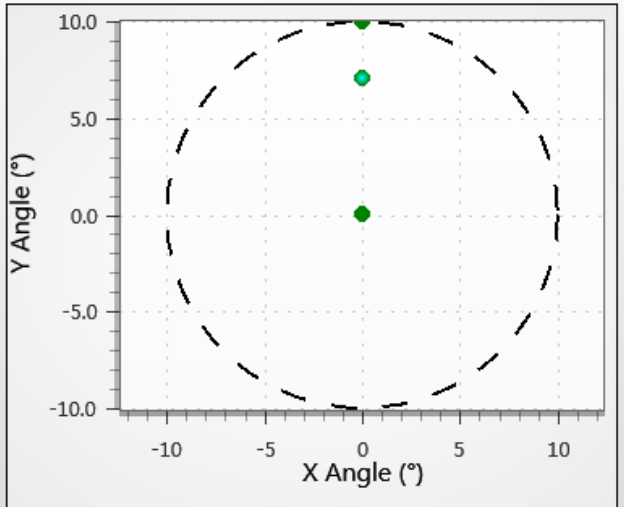
Field Data Editor

Update: All Windows

Field 2 Properties | Configuration 1/1 | Field Type: Angle

	Comment	X Angle (°)	Y Angle (°)	Weight	VDX
1	On-axis Field	0.000	0.000	1.000	0.000
2		0.000	7.071	1.000	0.000
3	Max Field Y	0.000	10.000	1.000	0.000

Field Plot



Wavelength Data

		Wavelength (µm)	Weight	Primary		Wavelength (µm)	Weight	Primary
☑	1	0.486	1.000	○	☐ 13	0.550	1.000	○
☑	2	0.588	1.000	◉	☐ 14	0.550	1.000	○
☑	3	0.656	1.000	○	☐ 15	0.550	1.000	○
☐	4	0.550	1.000	○	☐ 16	0.550	1.000	○
☐	5	0.550	1.000	○	☐ 17	0.550	1.000	○
☐	6	0.550	1.000	○	☐ 18	0.550	1.000	○
☐	7	0.550	1.000	○	☐ 19	0.550	1.000	○
☐	8	0.550	1.000	○	☐ 20	0.550	1.000	○
☐	9	0.550	1.000	○	☐ 21	0.550	1.000	○
☐	10	0.550	1.000	○	☐ 22	0.550	1.000	○
☐	11	0.550	1.000	○	☐ 23	0.550	1.000	○
☐	12	0.550	1.000	○	☐ 24	0.550	1.000	○

F, d, C (Visible) | Select Preset | Decimals: Use Editor Preference

Minimum Wave: 0.486 | Maximum Wave: 0.656 | Steps: 4 | Gaussian Quadrature

Close | Save | Load | Sort

Example 1: LDE at time t = 0

Start with predefined design form.

Lens Data

Update: All Windows

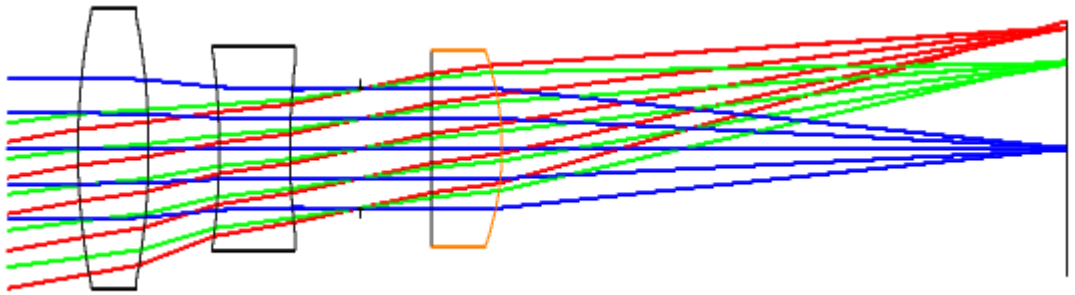
Surface 8 Properties | Configuration 1/1

	Surface Type	Comment	Radius	Thickness	Material	Clear Semi-Dia
0	OBJECT Standard		Infinity	Infinity		Infinity
1	Standard		Infinity	5.000		0.000 U
2	Standard		50.000 V	5.000 V	N-BK7 S	9.857
3	Standard		-50.000 V	5.000 V		9.231
4	Standard		-50.000 V	5.000 V	N-F2 S	7.192
5	Standard		50.000 V	5.000 V		6.213
6	STOP Standard		Infinity	5.000 V		4.192
7	Standard		Infinity V	5.000 V	N-BK7 S	6.281
8	Standard		-21.037 F	39.983 V		6.868
9	IMAGE Standard		Infinity			8.998

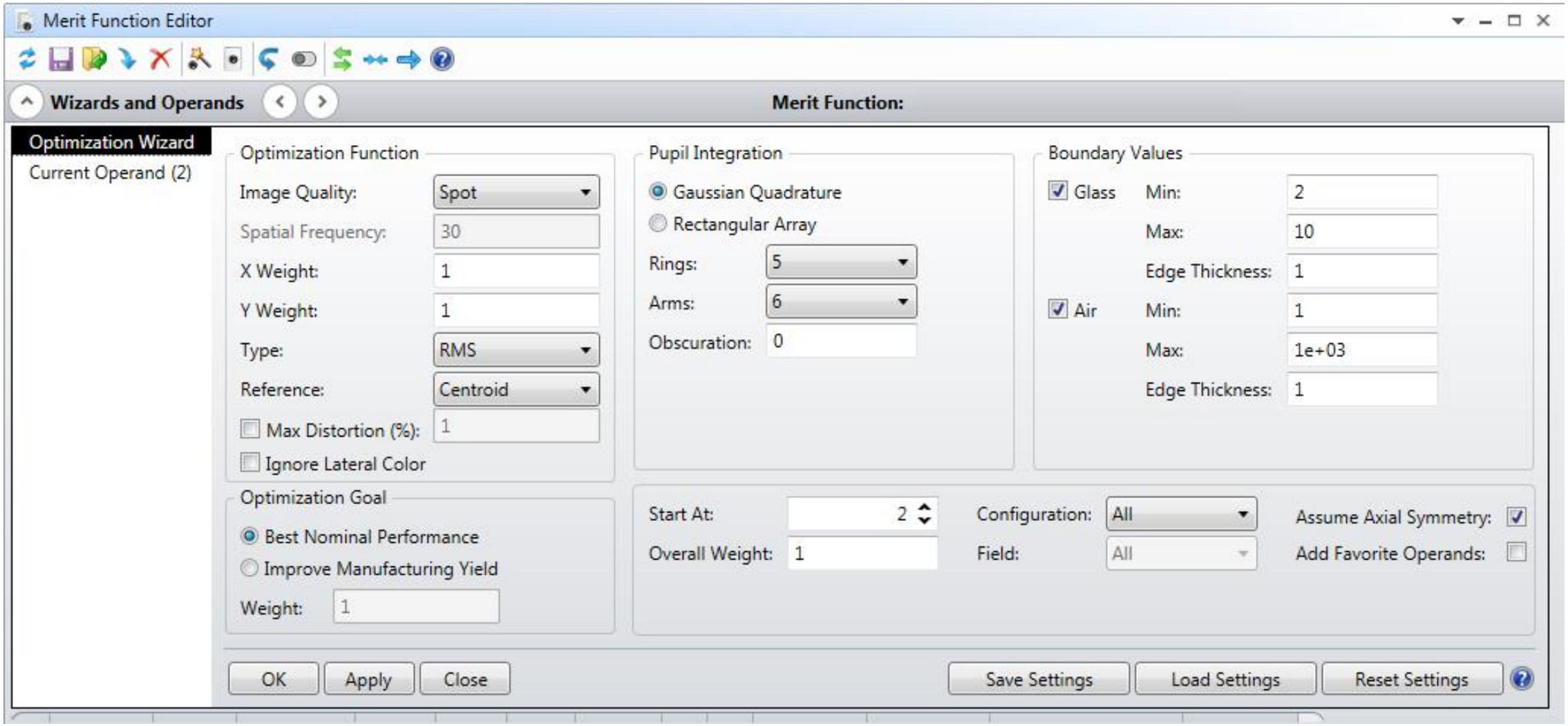
Curvature solve on surface 8

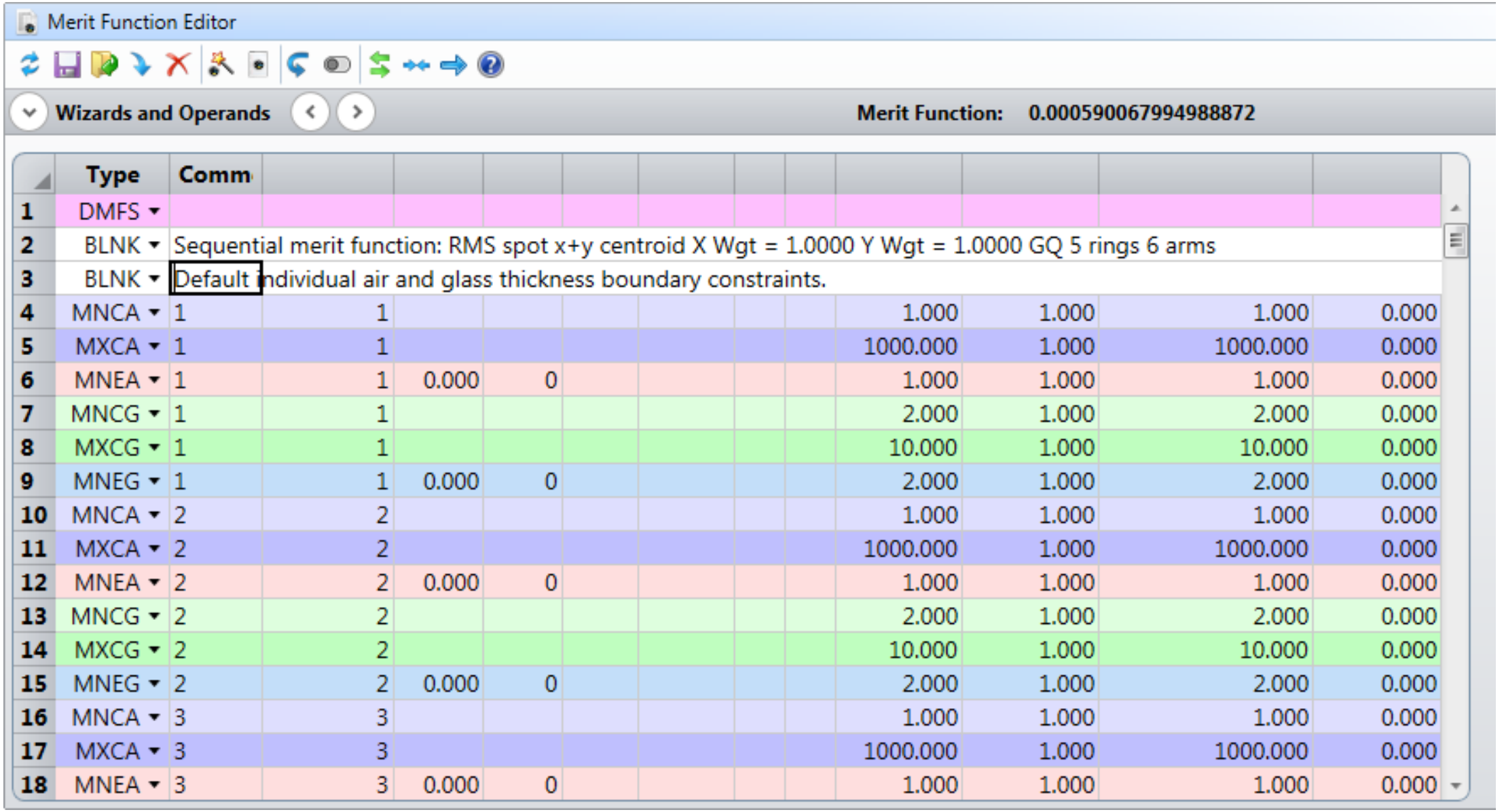
Solve Type: F Number

F/#: 5



Example 1: MFE

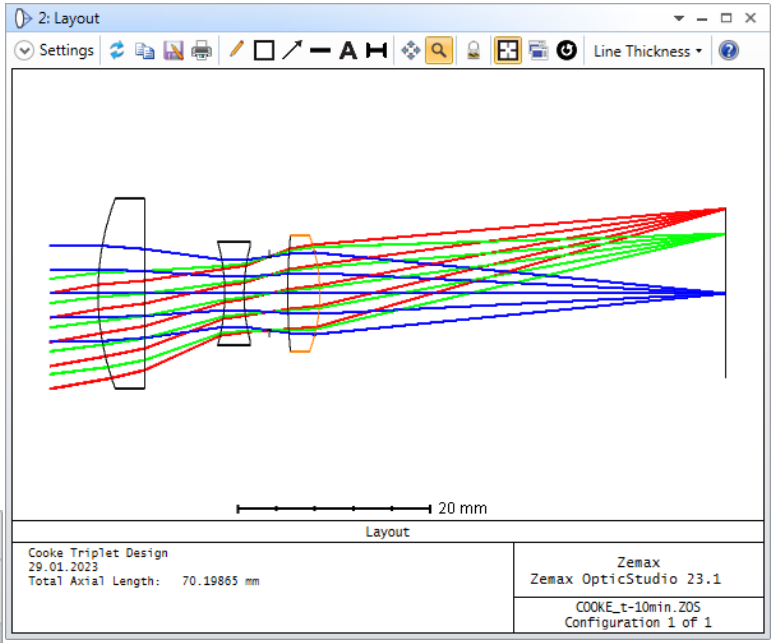




	Type	Comm										
1	DMFS											
2	BLNK	Sequential merit function: RMS spot x+y centroid X Wgt = 1.0000 Y Wgt = 1.0000 GQ 5 rings 6 arms										
3	BLNK	Default individual air and glass thickness boundary constraints.										
4	MNCA	1	1						1.000	1.000	1.000	0.000
5	MXCA	1	1						1000.000	1.000	1000.000	0.000
6	MNEA	1	1	0.000	0				1.000	1.000	1.000	0.000
7	MNCG	1	1						2.000	1.000	2.000	0.000
8	MXCG	1	1						10.000	1.000	10.000	0.000
9	MNEG	1	1	0.000	0				2.000	1.000	2.000	0.000
10	MNCA	2	2						1.000	1.000	1.000	0.000
11	MXCA	2	2						1000.000	1.000	1000.000	0.000
12	MNEA	2	2	0.000	0				1.000	1.000	1.000	0.000
13	MNCG	2	2						2.000	1.000	2.000	0.000
14	MXCG	2	2						10.000	1.000	10.000	0.000
15	MNEG	2	2	0.000	0				2.000	1.000	2.000	0.000
16	MNCA	3	3						1.000	1.000	1.000	0.000
17	MXCA	3	3						1000.000	1.000	1000.000	0.000
18	MNEA	3	3	0.000	0				1.000	1.000	1.000	0.000

Example 1: LDE at t = 10 min

- Stop the **hammer** optimization.
- Can you change the design to reduce manufacturing cost?



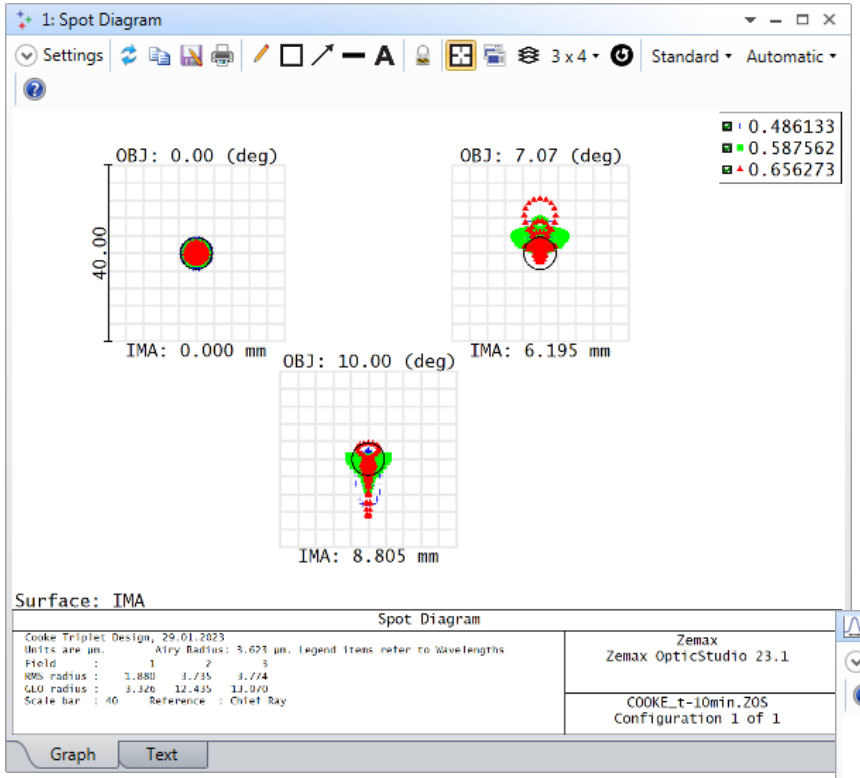
Lens Data

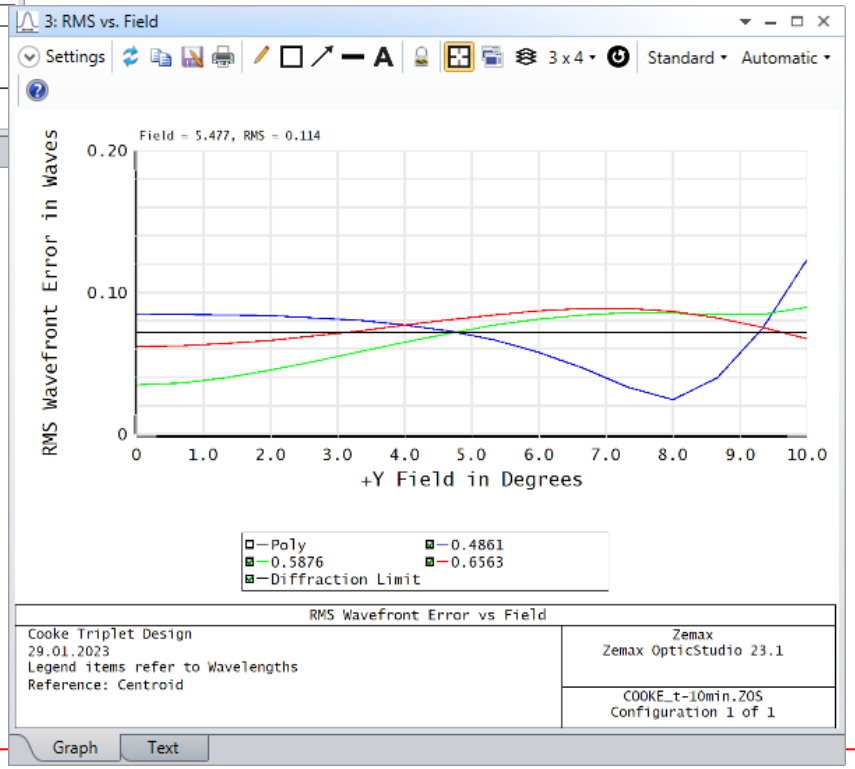
Update: All Windows

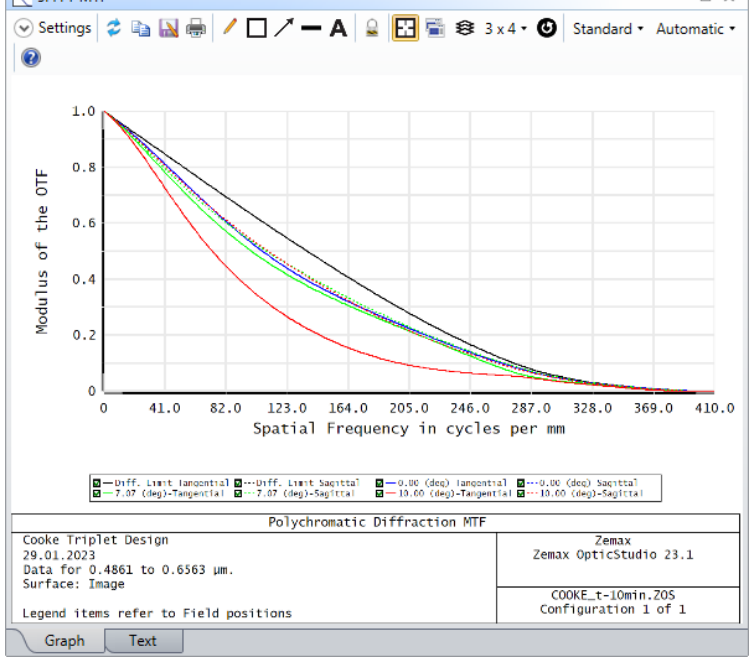
Surface 8 Properties

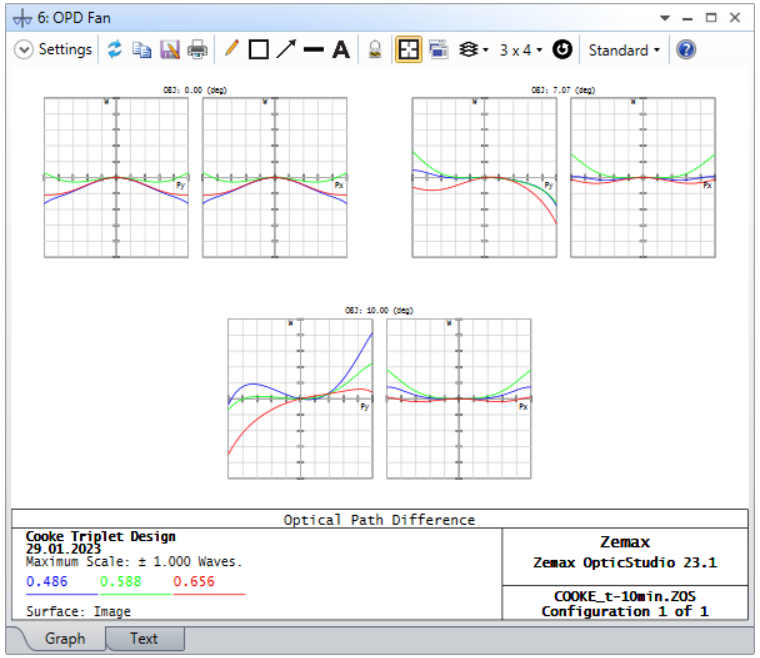
Configuration 1/1

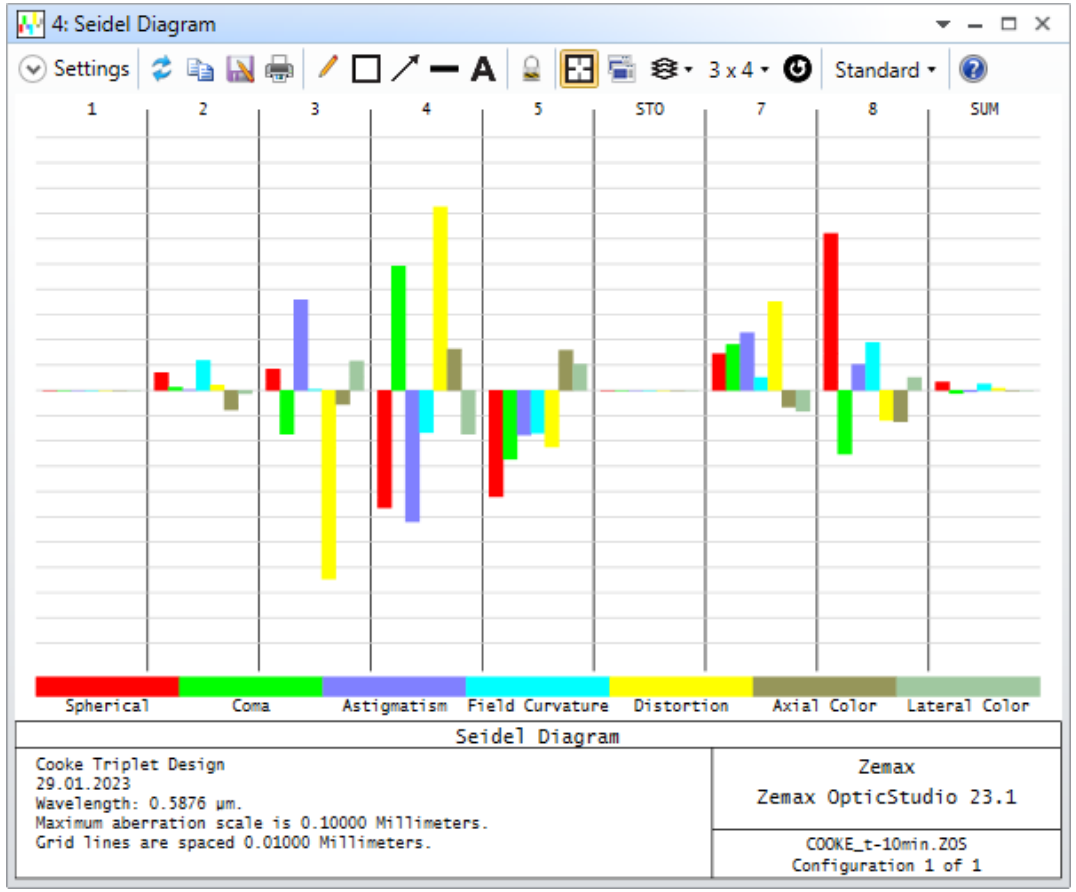
	Surface Type	Comment	Radius		Thickness		Material		Clear Semi-Dia		Chi
0	OBJECT Standard		Infinity		Infinity				Infinity		
1	Standard		Infinity		5.000				0.000	U	
2	Standard		27.987	V	4.896	V	N-LAF35	S	9.806		
3	Standard		-1112.760	V	8.277	V			8.973		
4	Standard		-19.586	V	2.000	V	SF10	S	5.396		
5	Standard		19.343	V	2.642	V			5.004		
6	STOP Standard		Infinity		1.899	V			3.829		
7	Standard		65.065	V	3.332	V	N-LAF35	S	5.637		
8	Standard		-17.475	F	42.153	V			6.068		
9	IMAGE Standard		Infinity		-				8.809		


1: Spot Diagram
Settings
3 x 4
Standard
Automatic
0.486133
0.587562
0.656273
OBJ: 0.00 (deg)
OBJ: 7.07 (deg)
40.00
IMA: 0.000 mm
IMA: 6.195 mm
OBJ: 10.00 (deg)
IMA: 8.805 mm
Surface: IMA
Spot Diagram
Cooke Triplet Design, 29.01.2023
Units are µm.
Airy Radius: 5.623 µm. Legend items refer to Wavelengths
Field : 1 2 3
RMS radius : 1.880 3.735 3.774
GLO radius : 3.326 12.435 13.070
Scale bar : 40 Reference : Chief Ray
Zemax
Zemax OpticStudio 23.1
COOKE_t-10min.ZOS
Configuration 1 of 1
Graph
Text


3: RMS vs. Field
Settings
3 x 4
Standard
Automatic
Field = 5.477, RMS = 0.114
RMS Wavefront Error in Waves
0.20
0.10
0
0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0
+Y Field in Degrees
Poly
0.4861
0.5876
0.6563
Diffraction Limit
RMS Wavefront Error vs Field
Cooke Triplet Design
29.01.2023
Legend items refer to Wavelengths
Reference: Centroid
Zemax
Zemax OpticStudio 23.1
COOKE_t-10min.ZOS
Configuration 1 of 1
Graph
Text


Settings
3 x 4
Standard
Automatic
Modulus of the OTF
1.0
0.8
0.6
0.4
0.2
0
0 41.0 82.0 123.0 164.0 205.0 246.0 287.0 328.0 369.0 410.0
Spatial Frequency in cycles per mm
Diff. Limit Tangential
Diff. Limit Sagittal
0.00 (deg) Tangential
0.00 (deg) Sagittal
7.07 (deg)-Tangential
7.07 (deg)-Sagittal
10.00 (deg)-Tangential
10.00 (deg)-Sagittal
Polychromatic Diffraction MTF
Cooke Triplet Design
29.01.2023
Data for 0.4861 to 0.6563 µm.
Surface: Image
Legend items refer to Field positions
Zemax
Zemax OpticStudio 23.1
COOKE_t-10min.ZOS
Configuration 1 of 1
Graph
Text

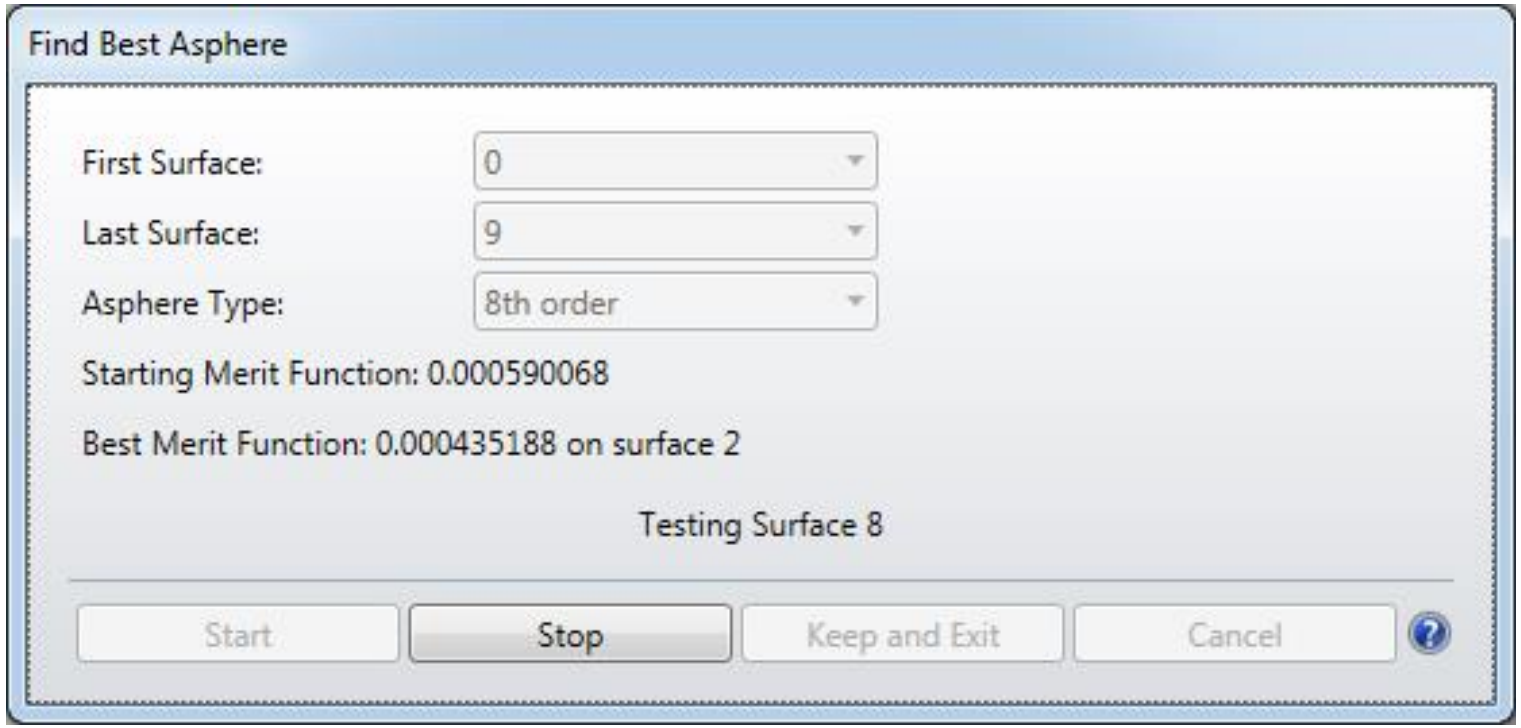

6: OPD Fan
Settings
3 x 4
Standard
OBJ: 0.00 (deg)
OBJ: 7.07 (deg)
OBJ: 10.00 (deg)
Optical Path Difference
Cooke Triplet Design
29.01.2023
Maximum Scale: ± 1.000 Waves.
0.486 0.588 0.656
Surface: Image
Zemax
Zemax OpticStudio 23.1
COOKE_t-10min.ZOS
Configuration 1 of 1
Graph
Text


4: Seidel Diagram
Settings
3 x 4
Standard
1
2
3
4
5
STO
7
8
SUM
Spherical
Coma
Astigmatism
Field Curvature
Distortion
Axial Color
Lateral Color
Seidel Diagram
Cooke Triplet Design
29.01.2023
Wavelength: 0.5876 µm.
Maximum aberration scale is 0.10000 Millimeters.
Grid lines are spaced 0.01000 Millimeters.
Zemax
Zemax OpticStudio 23.1
COOKE_t-10min.ZOS
Configuration 1 of 1

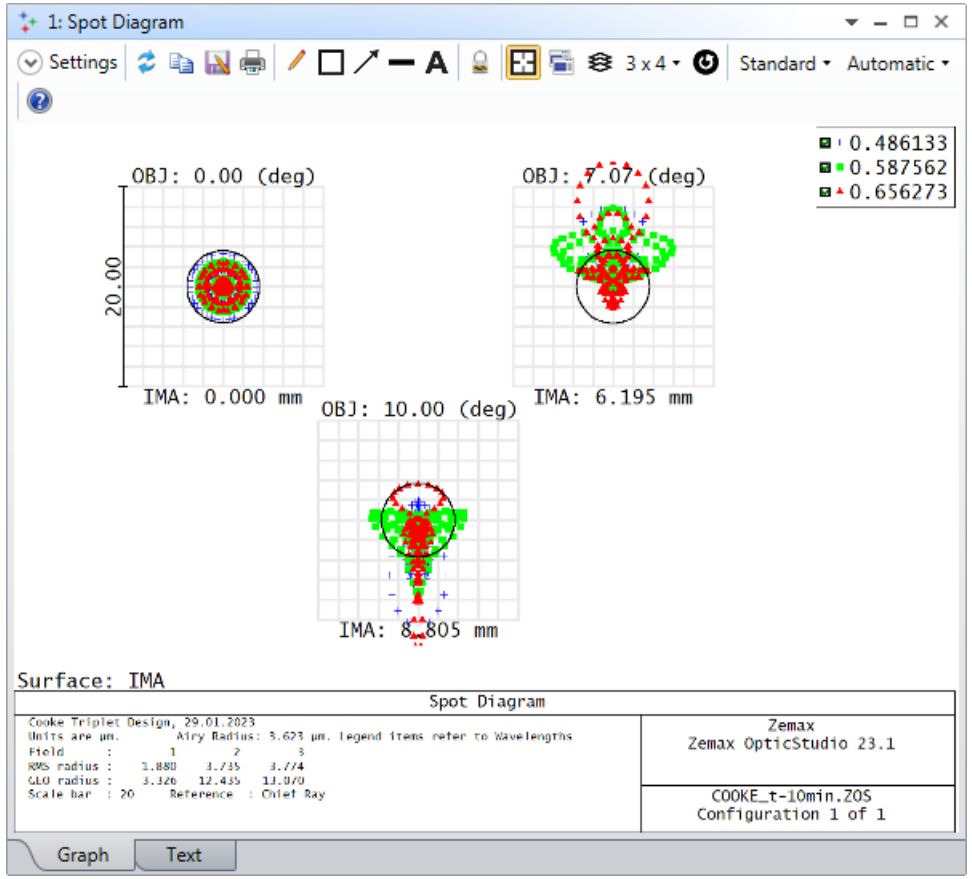

7: Image Simulation
Settings
3 x 4
Standard
Consider changing the field type to object height for improved accuracy. See Help Files for more details.
Image Simulation: Geometric Aberrations
Cooke Triplet Design
29.01.2023
Object height is 14.1421 degrees.
Field position: 0.00 (deg)
Center: chief ray
Image size is 16.4400 W x 12.3300 H (Millimeters)
Zemax
Zemax OpticStudio 23.1
COOKE_t-10min.ZOS
Configuration 1 of 1

Example 1: Improve Performance

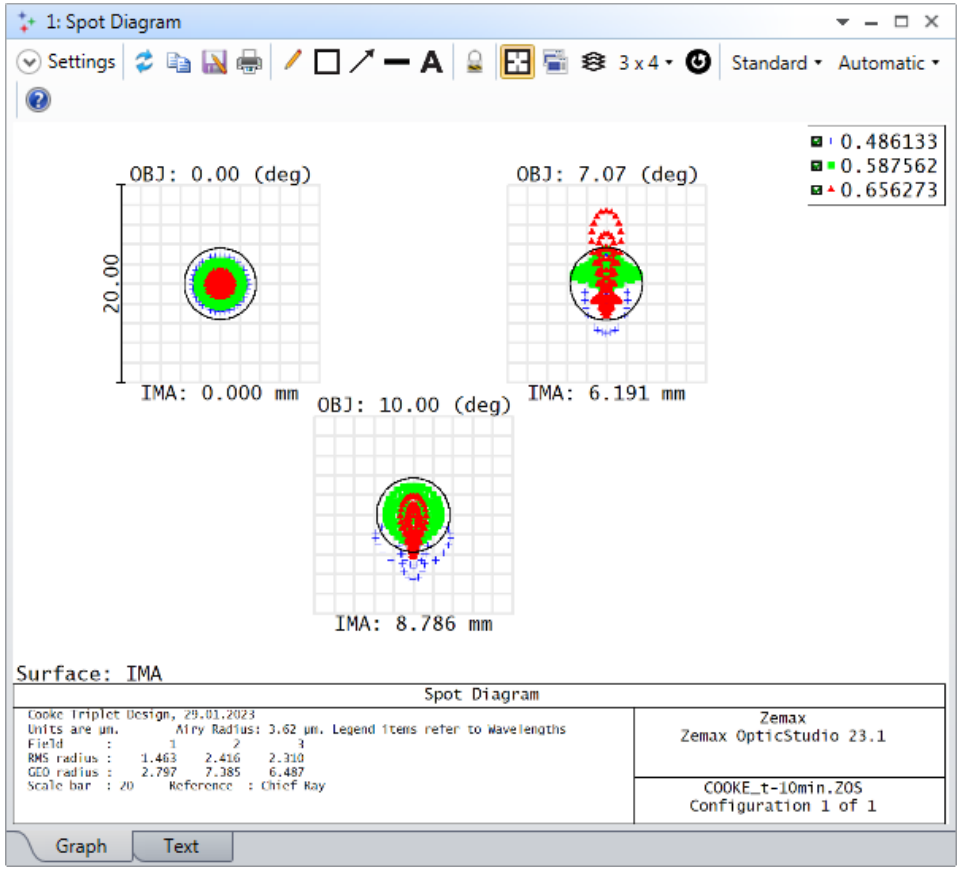
- We may use aspheric surface
- In the Optimize section you can click on **Find Best Asphere** to obtain better performance.



Before using aspherical surface



After using aspherical surface



Example 2: LWIR Objective

Design the following objective using two and three lenses.

Spectral range	8-12 μm
Focal length	75 mm
f/#	3
SFOV	3^o (FOV = 6^o)
Materials	Germanium – ZnSe pair
ct1 = ct2	5 mm
Distance between lenses	5-15 mm variable
Radius of curvatures	All variable

Perform optimization to obtain minimum spot radius averaged over FOV.

Starting values are given below. In MFE set only EFFL = 75 mm.

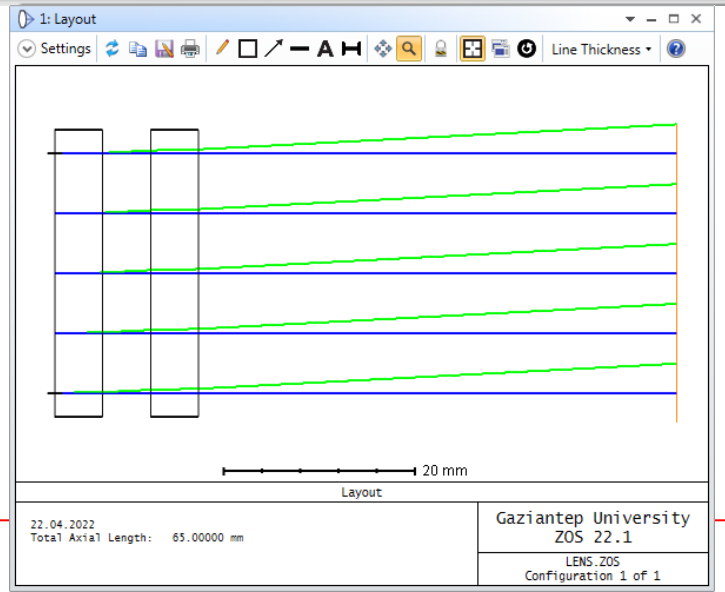
Lens Data

Update: All Windows

Surface 6 Properties

Configuration 1/1

	Surface Type	Comment	Radius		Thickness		Material	Coating	Clear Semi-Dia	
0	OBJE(Standard		Infinity		Infinity				Infinity	
1	STOP Standard		Infinity		0.000				12.500	
2	(aper) Standard		Infinity	V	5.000		GERMANIUM		15.000	U
3	(aper) Standard		Infinity	V	5.000				15.000	U
4	(aper) Standard		Infinity	V	5.000		ZNSE		15.000	U
5	(aper) Standard		Infinity	V	50.000	V			15.000	U
6	IMAG Standard		Infinity		-				15.557	



After optimization (just use EFFL operand)

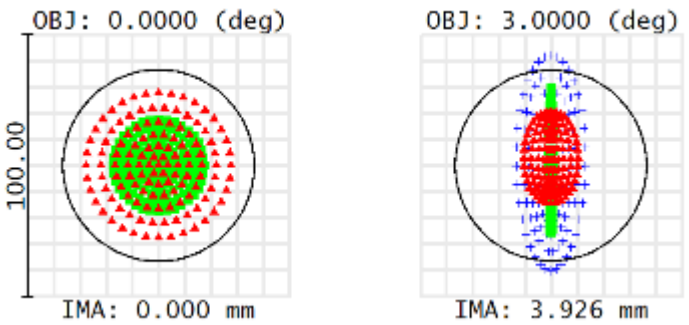
Lens Data

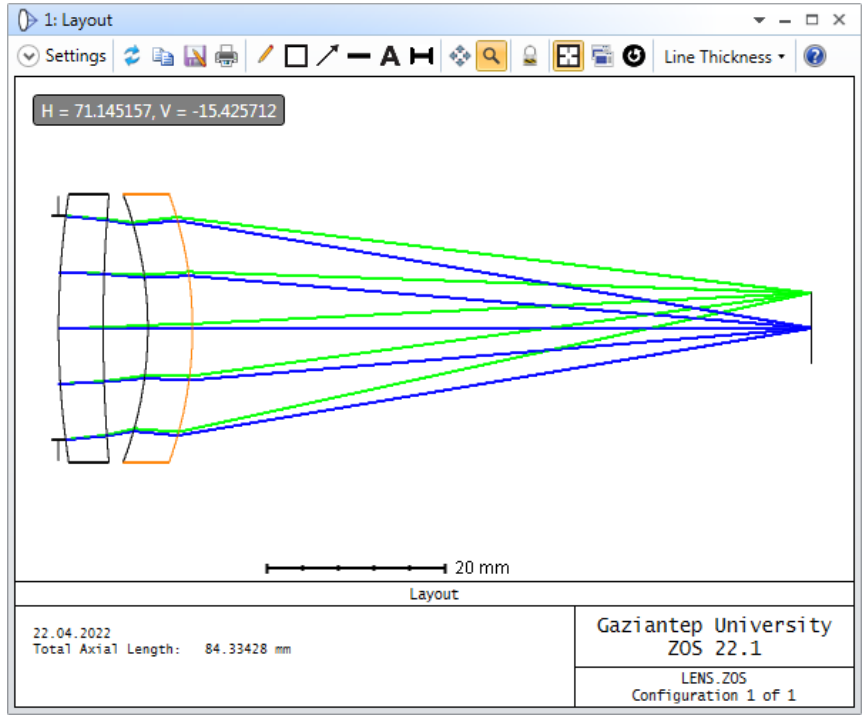
Update: All Windows

Surface 6 Properties

Configuration 1/1

	Surface Type	Comment	Radius		Thickness		Material
0	OBJE(Standard		Infinity		Infinity		
1	STOP Standard		Infinity		0.000		
2	(aper) Standard		98.693	V	5.000		GERMANIUM
3	(aper) Standard		175.250	V	5.000		
4	(aper) Standard		-41.835	V	5.000		ZNSE
5	(aper) Standard		-44.309	V	69.334	V	
6	IMAG Standard		Infinity		-		





Try a triplet solution (F/3, EFFL = 75 mm, TOTR=70 mm). Here is an example:

Lens Data

Update: All Windows

Surface 8 Properties | Configuration 1/1

	Surface Type	Comment	Radius		Thickness		Material	Coating	Clear Semi-Dia		Chip Zon
0	OBJE(Standard		Infinity		Infinity				Infinity		0.00
1	STOP Standard		Infinity		0.000				12.500		0.00
2	(aper) Standard		33.170	V	4.000		GERMANIUM		15.000	U	0.00
3	(aper) Standard		37.614	V	34.637	V			15.000	U	0.00
4	(aper) Standard		-14.806	V	4.000		ZNSE		10.000	U	0.00
5	(aper) Standard		-20.048	V	16.440	V			10.000	U	0.00
6	(aper) Standard		100.042	V	4.000		GERMANIUM		10.000	U	0.00
7	(aper) Standard		155.803	V	6.923	V			10.000	U	0.00
8	IMAG Standard		Infinity		-				4.000	U	0.00