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Solution of Exercises
Lecture Optical design with Zemax– Part 6

6 Correction

6.1 Triplet

A classical Cooke triplet with object in infinity, entrance pupil diameter 20 mm, spectal sampling lines d, F, C and the data

Surf	Type	Radius	Thickness	Glass	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity		0	0
1	STANDARD	22.01359	3.258956	SK16	19	0
2	STANDARD	-435.7604	6.007551		19	0
3	STANDARD	-22.21328	0.9999746	F2	10	0
STO	STANDARD	20.29192	4.750409		10	0
5	STANDARD	79.6836	2.952076	SK16	15	0
6	STANDARD	-18.39533	42.20778		15	0
IMA	STANDARD	Infinity			36.34532	0

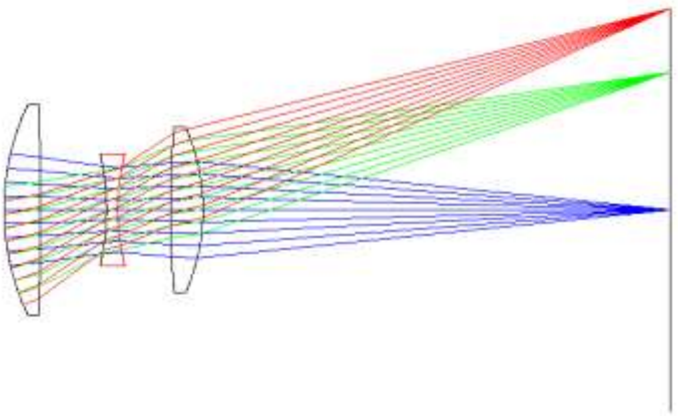
is given.
a) Optimize the system with the required data:

- finite object distance 150 mm
- entrance pupil diameter 6 mm
- wavelengths: 450 , 550 , 650 nm
- field height 12.5 mm
- overall site (total track) from first surface until image plane: 210 mm
- performance diffraction limited

b) Increase the numerical aperture until the diffraction limit is violated.

Solution

a) Layout of the starting system:

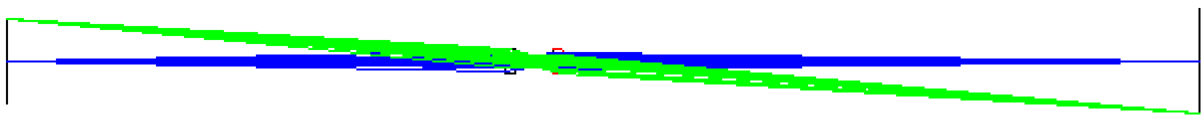


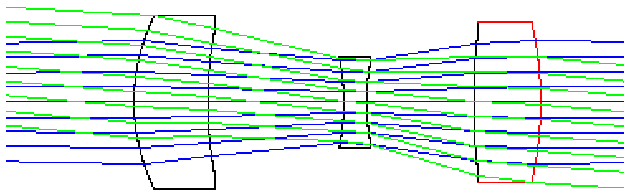
After changing the data to the required numbers and establishing the merit function with TOTR 210 we get after optimization of only the radii and the image distance the result. The performance is near to the diffraction limit.

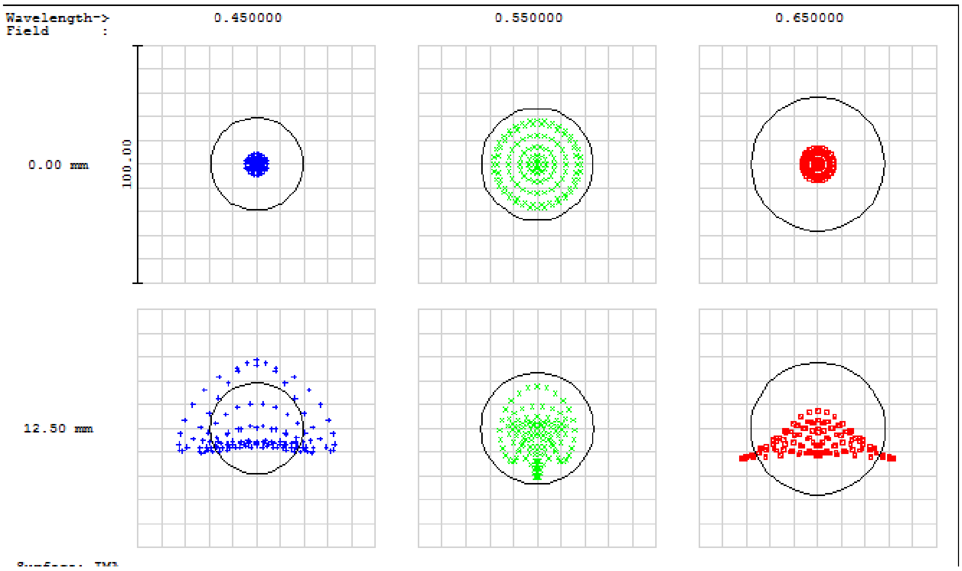
Lens Data Editor

Edit Solves View Help

	Surf:Type	Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		150.00000				12.500000	
1	Standard		8.6789496	V	3.2589558		SK16		3.8303465	
2	Standard		16.647027	V	6.0075511				3.2459149	
3	Standard		-11.22288	V	0.9999746		F2		1.9834721	
STO	Standard		8.4222517	V	4.7504089				1.8894660	
5	Standard		26.326047	V	2.9520756		SK16		3.2413931	
6	Standard		-16.33795	V	192.03103	V			3.5362524	
IMA	Standard		Infinity		-				15.959332	





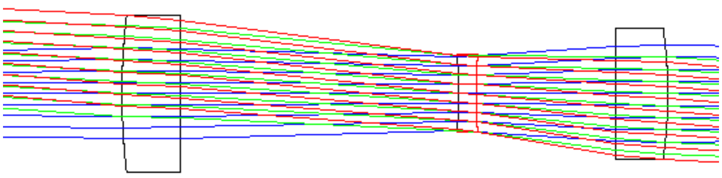


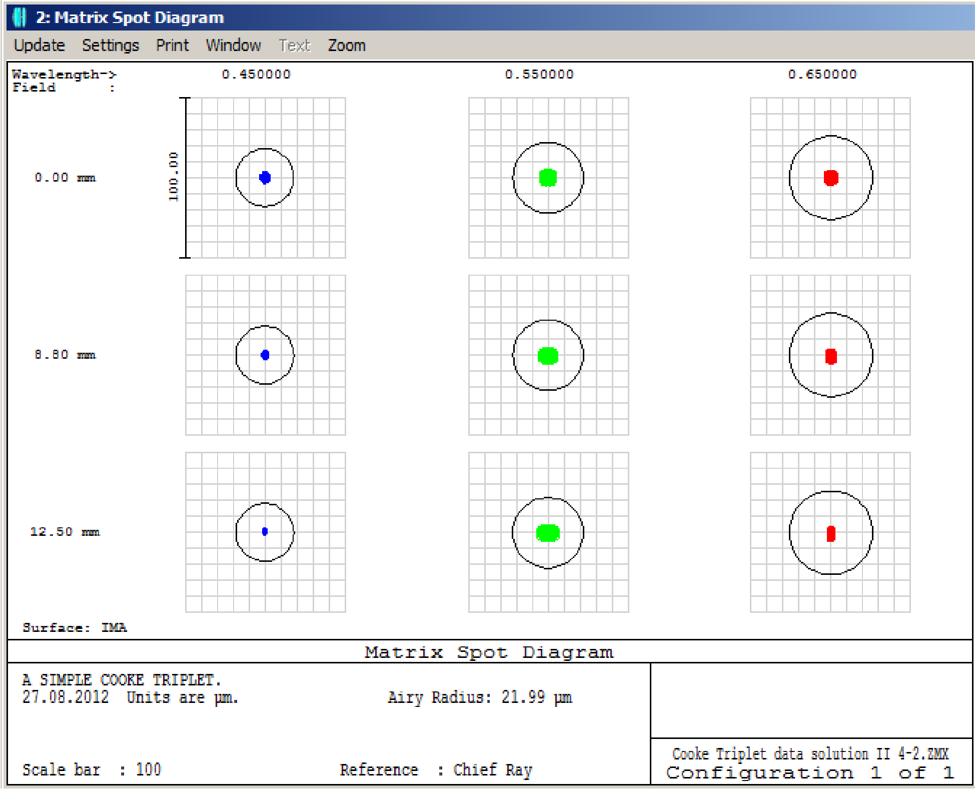
Now in a second step, also the distances between the lenses are allowed to be changed. To get reliable results, the minimum air thickness is set to be 0,5 mm in the merit function. An additional field points in the zone with y = 8.8 mm is introduced to control the correction in the intermediate field size. The result is now quite good.

Lens Data Editor

Edit Solves View Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		150.00000				12.500000	
1	Standard		37.269115	V	3.2589558		SK16		4.3953405	
2	Standard		1688.8291	V	15.670985	V			4.1591640	
3	Standard		-27.08787	V	0.9999746		F2		2.1926301	
STO	Standard		32.195805	V	7.8170258	V			2.1423506	
5	Standard		108.81868	V	2.9520756		SK16		3.4518964	
6	Standard		-26.00624	V	179.30098	V			3.6900695	
IMA	Standard		Infinity		-				13.966735	



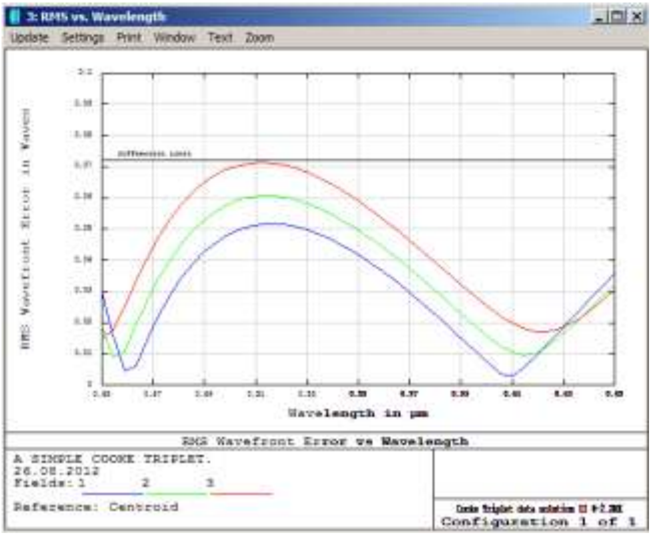


b) If the rms value of the wave aberration is taken as a criterion for the diffraction limit with the limiting value 0.072, we find a maximum entrance pupil diameter of D = 10.3 . This value is obtained for the wavelength λ = 510 nm in the maximumfield. This result is found, if the aperture is increase step by step and the rms-value over the wavelength is considered to control the rms value.

Lens Data Editor

Edit Solves View Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter		Conic
OBJ	Standard		Infinity		150.00000				12.500000		0.0000000
1	Standard		38.138319	V	3.2589558		SK16		6.2190625		0.0000000
2	Standard		-7067.294	V	15.676738	V			5.9755935		0.0000000
3	Standard		-27.15610	V	0.9999746		F2		3.7415199		0.0000000
STO	Standard		33.338140	V	7.9247624	V			3.6941376		0.0000000
5	Standard		116.31798	V	2.9520756		SK16		5.3660674		0.0000000
6	Standard		-26.23056	V	179.18749	V			5.6166401		0.0000000
IMA	Standard		Infinity		-				14.010488		0.0000000



6.2 Schmidt telescope

Setup a system with a focussing spherical mirror with focal length f = 25 mm, an incoming beam with diameter D = 20 mm at the wavelength λ = 632.8 nm.

a) The system is far from beeing diffraction limited. In the so called Schmidt telecope, an aspherical plate is located in front of the mirror to correct the spherical aberration. Optimize a Schmidt corrector, if it is a plate made of N-BK7, has a thickness of 2 mm and is located in the focal plane of the mirror. Only the 4th order of asphericity is allowed. Is the system now diffraction limited ?

b) Determine the maximum field angle of the system, which guarantees a diffraction limited behavior. The pupil should be assumed to be at the corrector plate.

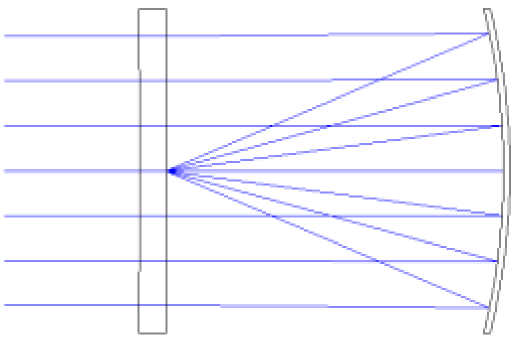
c) Determine the spectral range, for which the system is diffraction limited on axis.

d) If now for the nominal wavelength the mirror and the corrector plate are allowed to be aspherical, what is the largest achievable field angle for a diffraction limited behavior ?

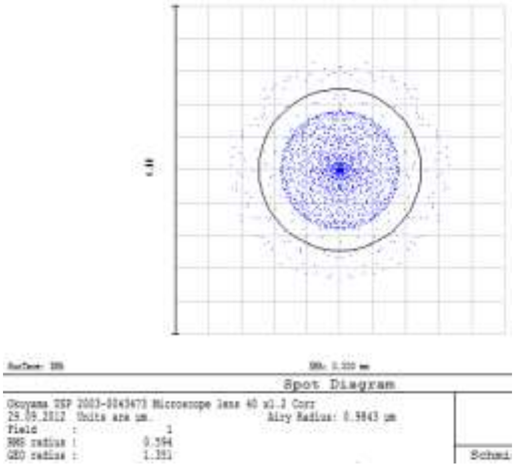
Solution:

a) System data and layout:

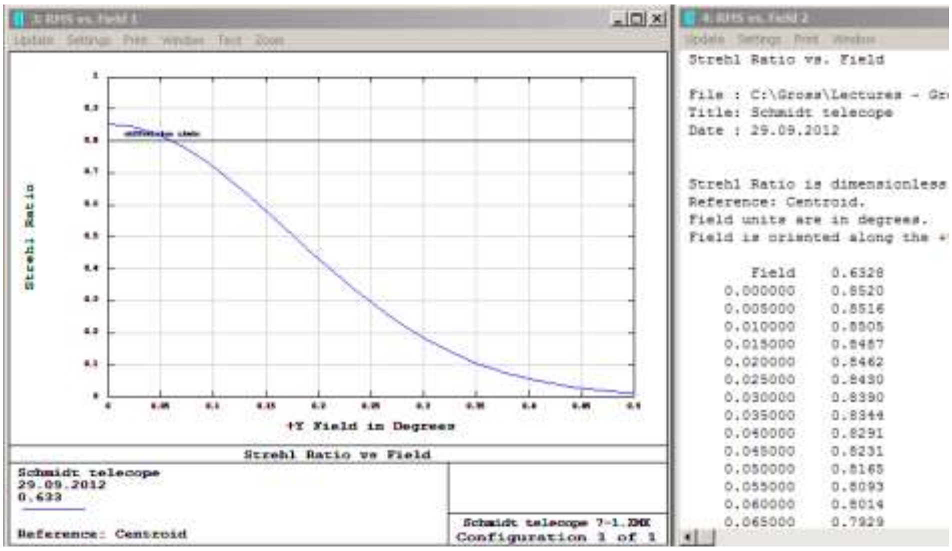
Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0 (unused)	Par 1 (unused)	Par 2 (unused)
OBJ	Standard		Infinity	Infinity		0.0000000	0.0000000			
1	Standard		Infinity	10.0000000		10.0000000	0.0000000			
2*	Even Asp..		Infinity	2.0000000	N-BK7	12.0000000 U	0.0000000		0.0000000	-3.99E-006 V
3*	Standard		Infinity	25.0000000		12.0000000 U	0.0000000			
*	Standard		-50.000000	-25.000000	MIRROR	12.0000000 U	0.0000000			
IMA	Standard		Infinity	-		1.357E-003	0.0000000			



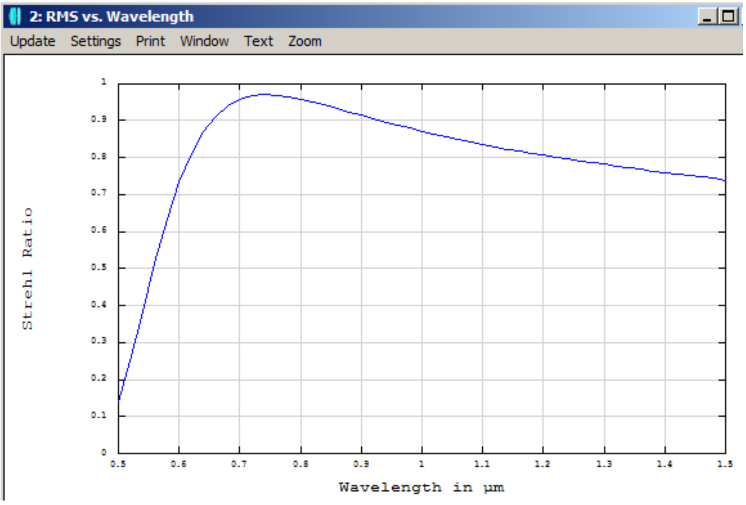
The system is diffraction limited with a Strehl number of 85%. The spot also shows the good performance:



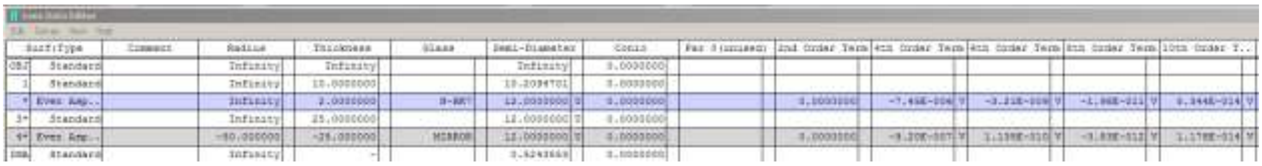
b) If a finite field angle of e.g. 1° is established, the rms-over-field representation with the Strehl ratio shows, that the system is diffraction limited for a field angle of maximal 0.06°.
For this option, a higher ray density of 9 should be taken.



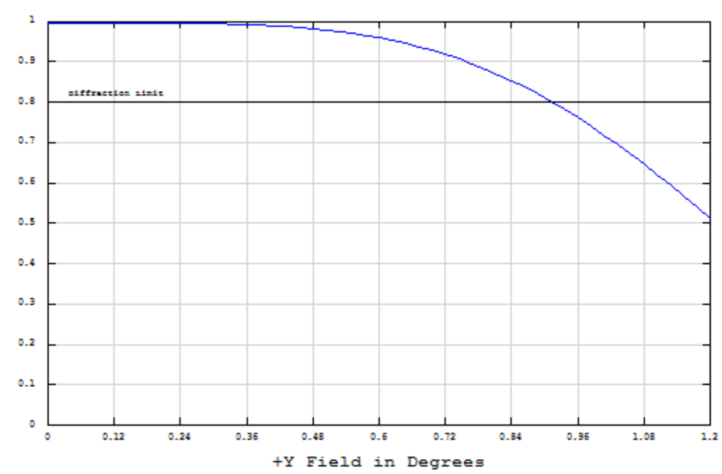
c) If the corresponding option is chosen to show the performance over the wavelength, we get the following curve.
The limits of the diffraction limited performance are between 0.61 µm and 1.22 µm.



d) If the mirror and the corrector plate are allowed to be aspherical until the 10th order, the system is diffraction limited until an field angle of 0.91°.



Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0 (unused)	2nd Order Term	4th Order Term	6th Order Term	8th Order Term	10th Order T...
OBJ Standard		Infinity	Infinity		Infinity	0.0000000						
1 Standard		Infinity	10.0000000		[illegible]	0.0000000						
2* Even Asp..		Infinity	2.0000000	[illegible]	12.0000000 U	0.0000000		0.0000000	-7.46E-006 V	[illegible] V	[illegible] V	[illegible] V
3* Standard		Infinity	25.0000000		12.0000000 U	0.0000000						
4* Even Asp..		-50.000000	-25.000000	MIRROR	12.0000000 U	0.0000000		0.0000000	[illegible] V	[illegible] V	[illegible] V	[illegible] V
IMA Standard		Infinity	-		[illegible]	0.0000000						



0.64800	0.9450
0.67200	0.9368
0.69600	0.9277
0.72000	0.9178
0.74400	0.9069
0.76800	0.8950
0.79200	0.8820
0.81600	0.8681
0.84000	0.8531
0.86400	0.8370
0.88800	0.8198
0.91200	0.8015
0.93600	0.7822
0.96000	0.7618
0.98400	0.7404
1.00800	0.7181
1.03200	0.6948
1.05600	0.6706
1.08000	0.6457
1.10400	0.6200
1.12800	0.5937

6.3 Retrofocus lens

A system which consists of a negative and a stronger positive lens acts as a retrofocus lens, where the focal length is shorter than the free working distance.

a) Setup a retrofocus lens out of ideal lenses for a wavelength of 546.07 nm an incoming collimated beam diameter of 10 mm with a negative lens of f_1 = -50 mm. The positive lens should be determined in a way, that the free working distance is twice the focal length and the numerical aperture in the image space is NA = 0.2.

b) To realize the system, now single lenses of finite thickness are inserted. Optimize the shape of the lenses for the monochromatic radiation on axis, if a heavy flint glass is used. What is the dominant degradation effect for the quality ?

c) If the correction is considered, the positive lens is much more critical than the negative lens, because the ray height is larger and the ray bending angle stronger. Therefore this lens shoud be

splitted into two lenses and the bending of the negative lens is allowed to be changed too. Optimize the corresponding system.
d) It is seen, that the performance is not diffraction limited. Therefore try to find better glasses in the correction. What is the best achievable Strehl ratio ?

Solution:

a) A system with two ideal lenses is established with f_1 = -50. If the numerical aperture should be NA = 0.2 and the incoming beam radius is 10/2 mm = 5 mm, we get a total focal length of f = 5 / 0.2 = 25 mm and an image distance of d' = 50 mm.
To find the focal length of the positive lens and the corresponding distance between the lenses, a merit function with the condition d_{image} = 2 f is constructed.

Lens Data Editor

Edit Solves View Help

	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Focal Length
OBJ	Standard		Infinity	Infinity		0.0000000	0.0000000		
1	Standard		Infinity	20.0000000		5.0000000	0.0000000		
STO	Paraxial			50.0000000 V		5.0000000			-50.000000
3	Paraxial			50.0000000		10.0000000			33.3333333 V
4	Standard		Infinity	0.0000000		1.330E-011	0.0000000		
IMA	Standard		Infinity	-		1.330E-011	0.0000000		

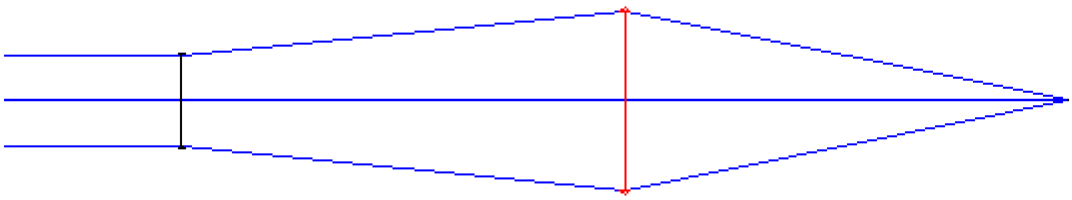
Merit function:

Merit Function Editor: 5.266968E-011

Edit Tools View Help

Oper #	Type			Target	Weight	Value	% Contrib
1: EFFL	EFFL		1	25.0000000	1.0000000	25.0000000	20.3286389
2: TTHI	TTHI	3	4	0.0000000	0.0000000	50.0000000	0.0000000
3: CONS	CONS			2.0000000	0.0000000	2.0000000	0.0000000
4: PROD	PROD	1	3	0.0000000	0.0000000	50.0000000	0.0000000
5: DIFF	DIFF	2	4	0.0000000	1.0000000	-6.6485484E-011	79.6713611

We get the focal length f_2 = 33.3 mm and a distance d_{12} = 50 mm.



b) Now real lenses with high refractive index are inserted, for example of the glass SF6.
First the negative lens is established with a thickness of 2 mm. The back surface is defined as a pick up to give the element power of $F_1 = 1/f_1$ = -0.02. The first surface is taken as a variable. In the merit function, a spot criterion is added with a default option.

Merit Function Editor: [illegible]

Oper #	Type			Target	Weight	Value	% Contrib
1: EFFL	EFFL		1	25.0000000	1.0000000	24.9999998	1.2346194E-007
2: TTHI	TTHI	5	6	0.0000000	0.0000000	50.0000000	0.0000000
3: CONS	CONS			2.0000000	0.0000000	2.0000000	0.0000000
4: PROD	PROD	1	3	0.0000000	0.0000000	49.9999997	0.0000000
5: DIFF	DIFF	2	4	0.0000000	1.0000000	3.0034992E-007	4.9385001E-007
6: BLNK	BLNK						
7: BLNK	BLNK	Operands for field 1.					
8: TRAC	TRAC		1	0.0000000	0.3721639	1.9293531E-003	7.5839885
9: TRAC	TRAC		1	0.0000000	0.7518282	3.0222668E-003	37.5944911
10: TRAC	TRAC		1	0.0000000	0.8936086	1.7174112E-003	14.4289893
11: TRAC	TRAC		1	0.0000000	0.7518282	1.2902731E-003	6.8520719
12: TRAC	TRAC		1	0.0000000	0.3721639	4.0573958E-003	33.5404585

Lens Data Editor

Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0 (unused)	Par 1 (unused)
OBJ	Standard		Infinity	Infinity		0.0000000	0.0000000		
1	Standard		Infinity	20.0000000		5.0000000	0.0000000		
STO	Standard		-36.826333 V	2.0000000	SF6	5.0000000	0.0000000		
3	Standard		-402.71119 X	48.6868785 V		5.1414843	0.0000000		
4	Standard		Infinity	0.0000000		10.0629235	0.0000000		
5	Paraxial			50.0000000		10.0629235			33.3014239 V
6	Standard		Infinity	0.0000000		4.844E-003	0.0000000		
IMA	Standard		Infinity	-		4.844E-003	0.0000000		

In a second step, the same procedure is used for the positive lens with $F_2 = 1/f_2 = 0.033$ and a thickness of 5 mm. Now also the image thickness must be a variable, since the principal plane lies inside the positive lens. The indices of the working distance condition in the merit function (OP 2) must be updated. The radiie of the negative lens are fixed in this second step.

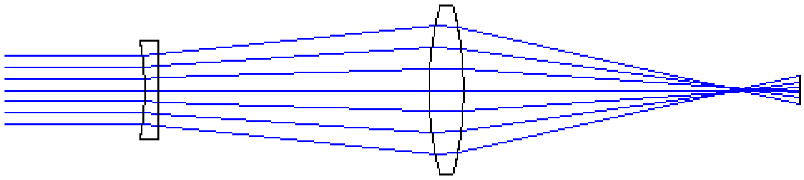
Lens Data Editor

Edit Solves View Help

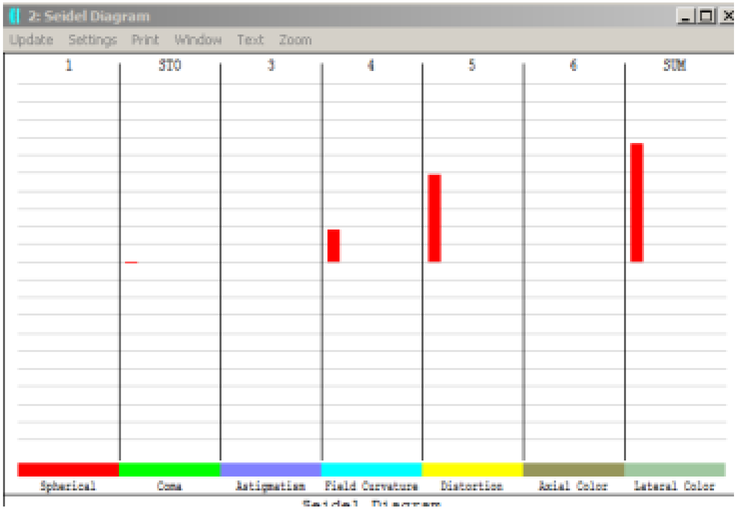
Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter
OBJ	Standard		Infinity	Infinity		0.0000000
1	Standard		Infinity	20.0000000		5.0000000
*	Standard		-36.826000	2.0000000	SF6	7.0000000 U
3*	Standard		-402.67240 X	38.8374420 V		7.0000000 U
4*	Standard		46.3475232 V	5.0000000	SF6	12.0000000 U
5*	Standard		-49.050953 X	48.3203303 V		12.0000000 U
6	Standard		Infinity	0.0000000		2.0967869
IMA	Standard		Infinity	-		2.0967869

Merit Function Editor: [illegible]

Oper #	Type		Wave	Target	Weight	Value	% Contrib
1: EFFL	EFFL		1	25.0000000	1.0000000	24.4555468	5.5292991
2: TTHI	TTHI	5	6	0.0000000	0.0000000	48.3203303	0.0000000
3: CONS	CONS			2.0000000	0.0000000	2.0000000	0.0000000
4: PROD	PROD	1	3	0.0000000	0.0000000	48.9110935	0.0000000
5: DIFF	DIFF	2	4	0.0000000	1.0000000	-0.5907633	6.5099238
6: BLNK	BLNK						
7: BLNK	BLNK	Operands for field 1.					
8: TRAC	TRAC		1	0.0000000	0.3721639	0.2331006	0.3771985
9: TRAC	TRAC		1	0.0000000	0.7518282	0.6004012	5.0553424
10: TRAC	TRAC		1	0.0000000	0.8936086	1.0764866	19.3158346
11: TRAC	TRAC		1	0.0000000	0.7518282	1.5958619	35.7156127
12: TRAC	TRAC		1	0.0000000	0.3721639	1.9902123	27.4967889



It is seen, that the single positive lens can not focus the beam to a good quality. The dominante spherical aberration at this lens is also seen with the Seidel diagram.



c) Now the last lens is splitted into two lenses, a little bit thinner and close together. To get the desired numerical aperture, the pick up can no longer be used. Instead, the corresponding F-number of F# = 1/(2NA) = 2.5 is inserted in the merit function. After optimization, the result is much better, but still far from beeing diffraction limited.

Lens Data Editor

Edit Solves View Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.0000000	
1	Standard		Infinity		20.0000000				5.0000000	
*	Standard		46.5750060	V	2.0000000		SF6		7.0000000	U
3*	Standard		21.2828654	X	54.9282592	V			7.0000000	U
4*	Standard		1476.26846	V	4.0000000		SF6		12.0000000	U
5*	Standard		-60.930263	V	1.0000000				12.0000000	U
6*	Standard		45.6257549	V	4.0000000		SF6		12.0000000	U
7*	Standard		231.594025	V	50.0055785	V			12.0000000	U
8	Standard		Infinity		0.0000000				0.0210001	
IMA	Standard		Infinity		-				0.0210001	

d) With a low refracting negative lens a a higher refractive index in te two positive lenses, we get the following result with a Strehl of 0.26 %.

Lens Data Editor

Edit Solves View Help

Surf	Type	Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.0000000	
1	Standard		Infinity		20.0000000				5.0000000	
*	Standard		120.433348	V	2.0000000		FK5		7.0000000	U
3*	Standard		20.2179678	X	53.7388819	V			7.0000000	U
4*	Standard		-738.55119	V	4.0000000		SF59		12.0000000	U
5*	Standard		-63.653002	V	1.0000000				12.0000000	U
6*	Standard		49.3991908	V	4.0000000		SF59		12.0000000	U
7*	Standard		185.512709	V	50.0031538	V			12.0000000	U
8	Standard		Infinity		0.0000000				8.908E-003	
IMA	Standard		Infinity		-				8.908E-003