Expert system for lens starting point selection. Application examples in lens design practice.

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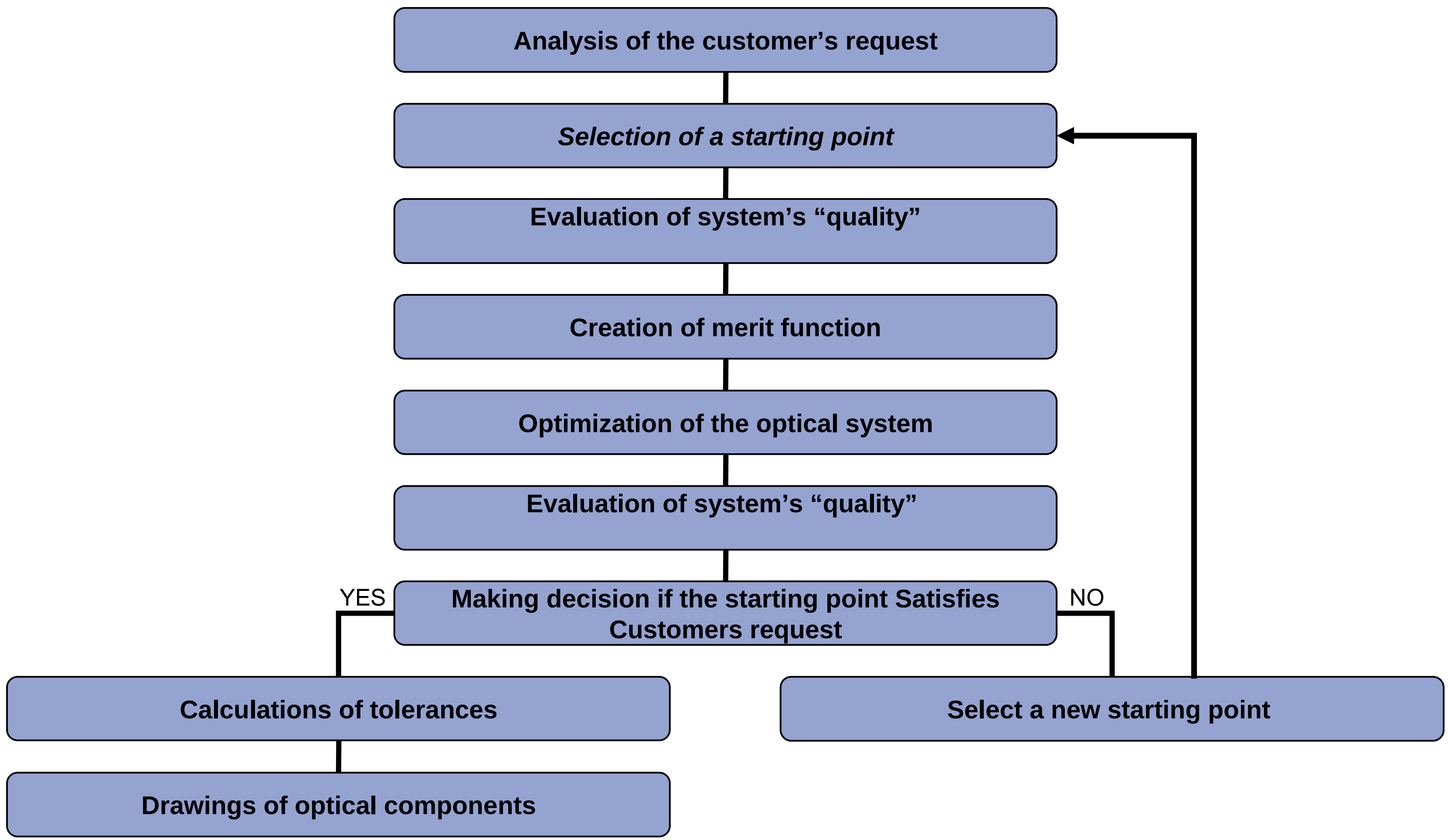
Stages of optical design procedure



Statement

- Creation of starting point is the main stage of the whole design process. If starting point was successfully matched we can get the result very fast.
- Bad starting point leads to failure of the design process after loosing some time for understanding the wrong choice.

Traditional start

- *Improving already known optical schemes received earlier by empirical way;*
- *Analytical search of optical scheme parameters by solving systems of equations in the area of third-order aberrations*
- Both methods solved same problem – studying the influence of different scheme parameters onto the aberrations and searching the optimum parameters, which kept the aberrations inside the permitted limits. So, the question of starting optical scheme was not solved, empirical schemes were improved.

Optical experts knowledge

- Historically there appeared several schemes which correction possibilities were well known, for example, symmetrical schemes which provide absence of odd aberrations: coma, distortion, lateral color.
- Using aplanatic surfaces, for example in front lens of micro-objectives, there were achieved high apertures without appearing of big spherical aberration and coma. Surfaces, concentric to a chief ray, allow to build a lens free from coma, astigmatism, distortion and lateral color for wide field of view.
- These achievements put a base for starting point of optical schemes with *predictable properties*.

Starting design – advanced approaches

- Many programs approach the starting point by supplying a number of standard or sample designs that users can apply as starting points (relying on the user’s knowledge to select or generate a suitable starting design form).
- Smarter approaches are being explored, including expert systems (Donald Dilworth’s ILDC paper, “Expert Systems in Lens Design”).
- Possibility of training neural network to recognize a good starting point (research presented by Scott W.Weller, “Design Selection Using Neural Networks”).
- Some designers use database programs (for example, LensView).

Expert system (general definition)

- Computer-based system designed to respond like a human expert in a given field. Expert systems are built on knowledge gathered from human experts, analogous to a dataase but containing rules that may be applied to solving a specific problem. (Britannica Concise Encyclopedia)

Introduction

- Expert systems take more and more space in the R&D process in different engineering applications and now there appeared a number of attempts to create such system in the field of optical design.
- We propose expert system intended to generate starting points for objectives, which will undertake the preliminary design of optical systems, so called "structural synthesis."
- Teaching students stimulates to explain how to design OS (not a very big difference to whom: computer or student).

*Unique combination of Information technologies and Optics in ITMO allowed to progress in this direction.

*Active team for this research which consists of both experienced and young generations of specialists.

Why we decided to create ExSys

- Teaching students stimulates to explain how to design OS (not a very big difference to whom: computer or student).
- Unique combination of Information technologies and Optics in ITMO allowed to progress in this direction.
- Active optical design team which consists of both experienced and young generations of specialists.

Basics

- Our goal: find starting point for an objective.
- We have a number of optical experts.
- We attracted knowledge engineers to get the knowledge from optical experts and transfer it into expert system for starting points selections.

What is it “starting point” ?

- Starting point we describe as structure (number, location and type of optical elements);
- Parameters and specifications

necessary for input to special optical design SW to start calculations;

Usually we try several starting points
– the number depends on OS complexity

Knowledge engineer’s goal:

- To get from optical expert reply and explanation for two main questions:
- HOW & WHY
- First problem is to establish fruitful contact and “common” language between knowledge engineer (Young Generation) and optical expert (Old generation)
- Instruments to solve this goal are OS classifications, which lead to formalization of the starting point selection process.

Types of classifications

- OS type classification;
- OS “internal” classification: general and technical, link between them;
- Classification of optical elements: basic, correction, fast and wide-angular;
- Classification of optical surfaces;
- Classification of optical modules as starting points;
- Classification OS by its construction.

Most general classification depending on object-image position

Conventional notation of Systems' class	Name of the systems' class
00	Binocular type
01	Photographic type
10	Microobjective type
11	Relay type

Link between general & technical classification for OS “01” type

- J=”0”, OS has low speed, FN>2.8
- J=”1”, OS is called “fast” if 1.5<FN<2.8
- J=”2”, OS is considered to be superfast if FN<1.5
- W=”0”, small angle OS, 2w <15 degr.
- W=”1”, middle angle OS, 15<2w<60
- W=”2”, wide angle OS, 2w>60
- F=”0”, short focal length (FOCL) OS, f’<50 mm
- F=”1”, middle FOCL OS, 50<f’<100
- F=”2”, long FOCL OS, f’>100 mm

Link between general & technical classification for OS “01” type

- L=”0”, monochromatic OS, |wl1-wl2|<5 nm
- L=”1”, polychromatic OS,   5<|wl1-wl2|<100 nm
- L=”2”, polychromatic OS with expanded spectral rangeQ=”0”, geometrically limited OS, OPD>2wl
- Q=”1”, intermediate quality OS, 0.25wl<OPD<2wl
- Q=”2”, diffraction-limited OS, OPD<0.25wl
- S=”0”, short back focal length (BFL) OS,BFL<0.5FOCL
- S=”1”, intermediate BFL, 0.5FOCL<BFL<FOCL
- S=”2”, increased BFL, BFL>FOCL
- D=”0”, APS is located inside the objective
- D=”1”, APS is removed back (exit pupil)
- D=”2”, APS is removed forward (entrance pupil)

General & technical classificatins

Notation for characteristic	Conventional notation depending on technical data
J	"0"; OS in not fast; D/F'<1:2.8
	"1"; OS is fast; 1:2.8<D/F'<1:1.5
	"2"; OS is super fast; 1:1.5<D/F'
W	"0"; OS with small angular field; $2\omega < 15^\circ$
	"1"; OS with average angular field; $15^\circ < 2\omega < 60^\circ$
	"2"; wide angular OS; $2\omega > 60^\circ$
F	"0"; short focal length OS; F'<50 mm
	"1"; average focal length OS; 50mm<F'<100 mm
	"2"; long focal length OS; F'>100 mm
L	"0"; monochromatic OS; $(\lambda_2 - \lambda_1) < 10\,nm$
	"1"; ordinary polychromatic; 10nm< $(\lambda_2 - \lambda_1) < 210\,nm$
	"2"; super polychromatic correction; $(\lambda_2 - \lambda_1) > 210\,nm$
Q	"0"; "geometrical " image quality; $D_{bz} > 5D_A$
	"1"; "intermediate" image quality; $2D_A < D_{bz} < 5D_A$
	"2"; "diffraction" image quality; $D_{bz} < 2D_A$
S	"0"; OS with short back focal length; S'<F';
	"1"; OS with average back focal length; 0.5F'<S'<F';
	"2"; OS with long back focal length; S'>F';
N	"0"; with entrance pupil located inside OS
	"1"; with entrance pupil located behind OS; (removed back entrance pupil);
	"2"; with entrance pupil in front of OS (removed forward entrance pupil).

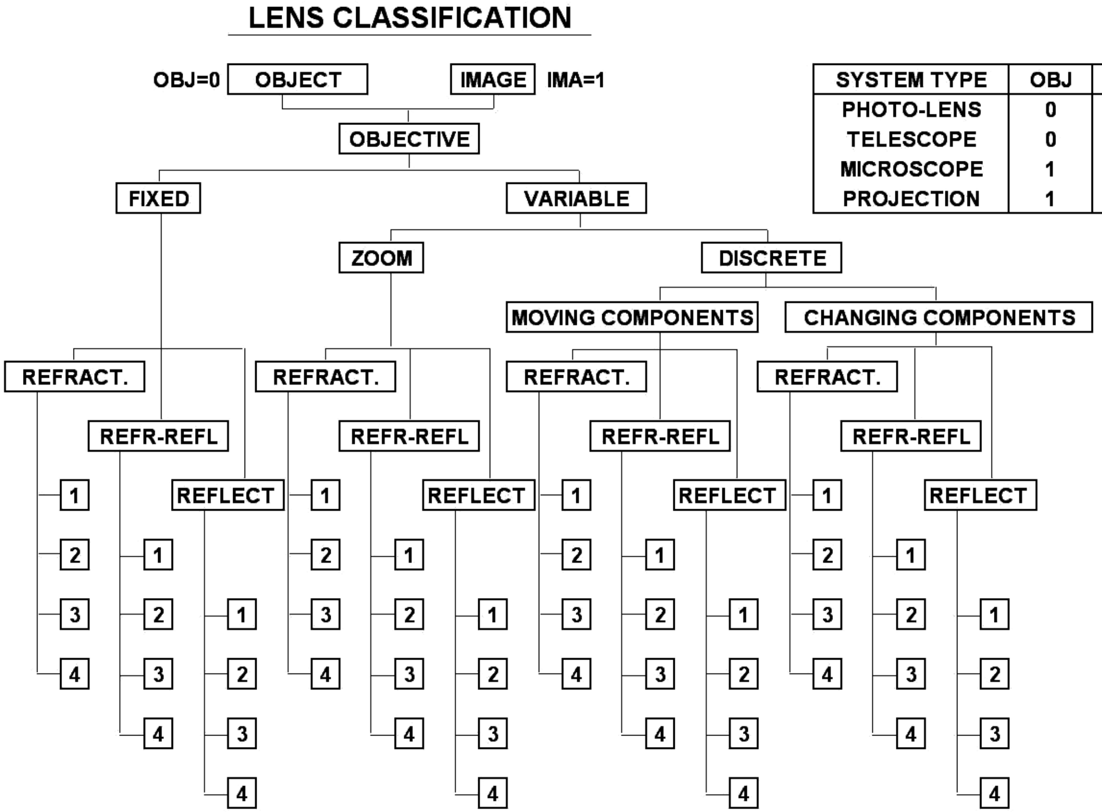
Resume on general classification

- Numbers “0,1,2” are symbols, which belong to general classification and indirectly connected with the selection of starting point for OS.
- “0” is symbol for the technical characteristic of OS, which can be realized in the easiest OS.
- “1” is symbol for technical characteristic which would indefinitely require more elements to build OS than in case “0”, and “2” is for advanced technical characteristic which would require the most complex OS for achievement the required data.
- Using the classification described above we can describe $\mathbf{3^7}$ = 2187 classes of OS, which are located between class “0000000” and “2222222”, for example, “2222222” describes fast wide angle long FOCL OS, polychromatic with expanded spectral range, diffraction limited, with increased BFL, and APS coincident with exit pupil. It is very hard to design OS, which belongs to this class.

Index of complexity

- The sum of all seven general characteristics is called ***index of complexity*** *(IC)* of the objective.Index of complexity (I) varies from 0 to 14.
- Selection of starting point for optical systems depends very much on the systems’ complexity.
- From experience we can say that system with ***IC>7*** is a complex system and, as a rule, requires know-how in optical scheme.
- Numbers “0,1,2” are symbols, which belong to general classification and indirectly connected with the selection of starting point for OS.
- “0” is symbol for the technical characteristic of OS, which can be realized in the easiest OS.
- “1” is symbol for technical characteristic which would

Classification of OS “01” type depending on construction



SYSTEM TYPE	OBJ	IMA
PHOTO-LENS	0	1
TELESCOPE	0	0
MICROSCOPE	1	0
PROJECTION	1	1

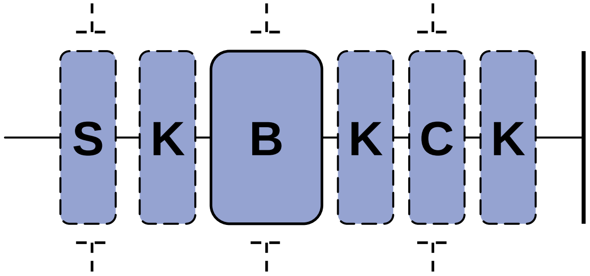
1 - MONOCHROMATIC
2 - ACHROMATIC
3 - APOCHROMATIC
4 - SUPERACHROMATIC

Classification of optical modules (as starting points)

- Simple meniscus lens;
- Doublet;
- Triplet;
- Tessar;
- Retrofocus;
- Petzval;
- Gaus;
- Double Gaus…

Classification of OE depending on their function in OS

- **Basic Elements (B)** – are used to form the optical power in an OS, they are always positive.
- **Correction Elements (K)** – are used to correct residual aberrations of basic elements. Correction elements can be both positive and negative and also afocal, which will depend on the aberration type. They are correcting.
- **“Fast” Elements (C)** – are used for developing the aperture of an optical system, they have only positive optical power, but in distinction to basic elements, they work only from the finite distance.
- **“Wide-angular” Elements (Y)** – are used for developing the field angle in an OS, they are negative or afocal.



Examples of basic elements

Parametrical synthesis

- We put the surface properties information into "SYNOPSYS"® (or other OD SW)
- Glass types are chosen according to the the following general principle:
  - Crown – for positive elements
  - Flint – for negative elements

Manipulating the thicknesses and radii of the correction elements with general surface types we can achieve desired focal length. Last step of optimization – more surfaces are chosen as general type.

Usability index

- *Usability Index* – shows how applicable this element is in a particular OS class

U.I. can be between:

- 0%, such element is totally inapplicable

  and

- 100%, such element is entirely applicable

Properties of all OE were carefully studied by experts who have come out with over hundred usability rules

Classification of optical surfaces

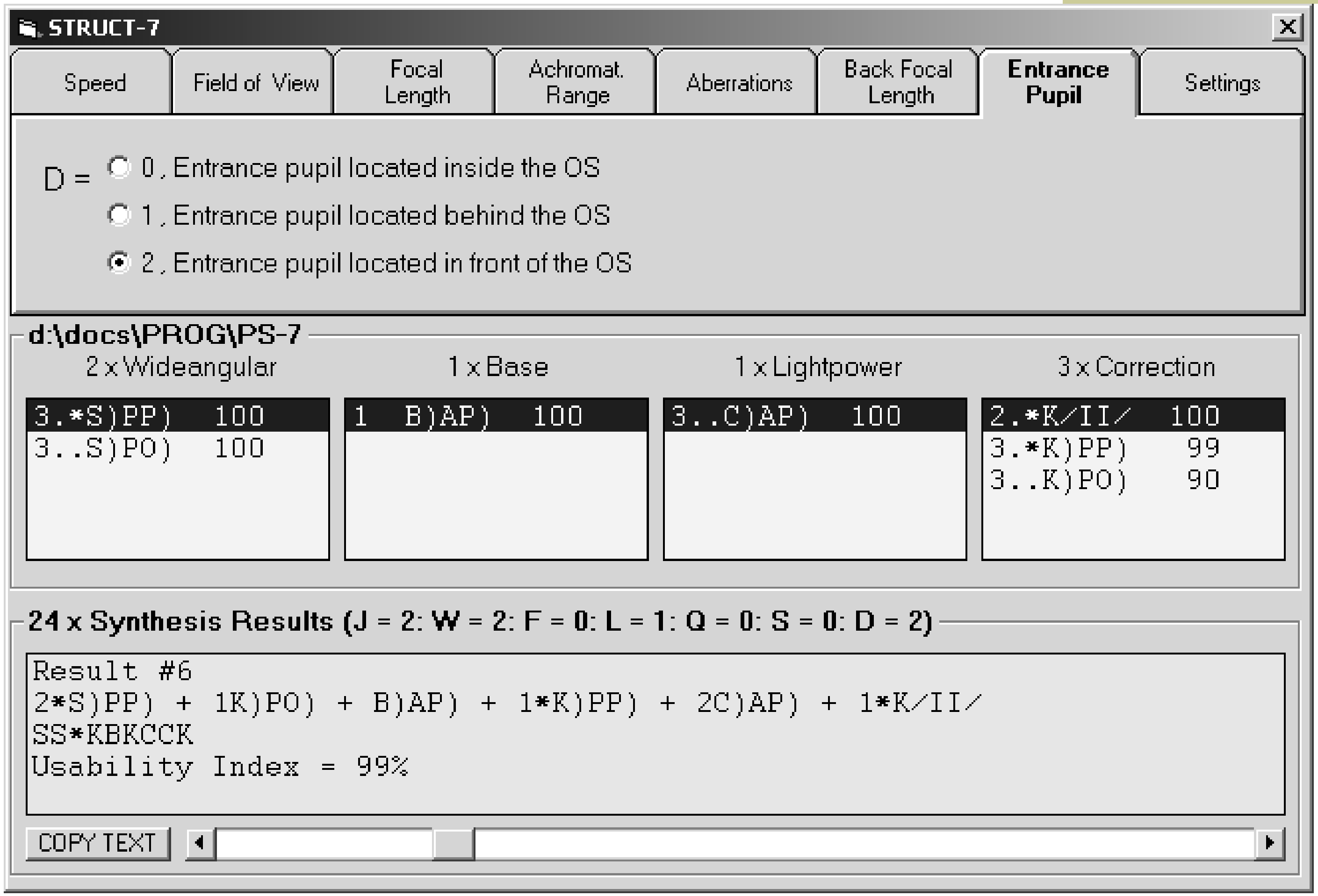
- **A** – Aplanatic; (AMY in SYNOPSYS)
- **I** – Near image;
- **P** – Concentric about the chief ray (to the pupil center); (CCY in SYNOPSYS)
- **V** – Concentric about the aperture ray (to the object/image center); (IMY, incident angle at marginal ray is “0”);
- **O** – Flat;
- **G** – general type surface.

Implementation

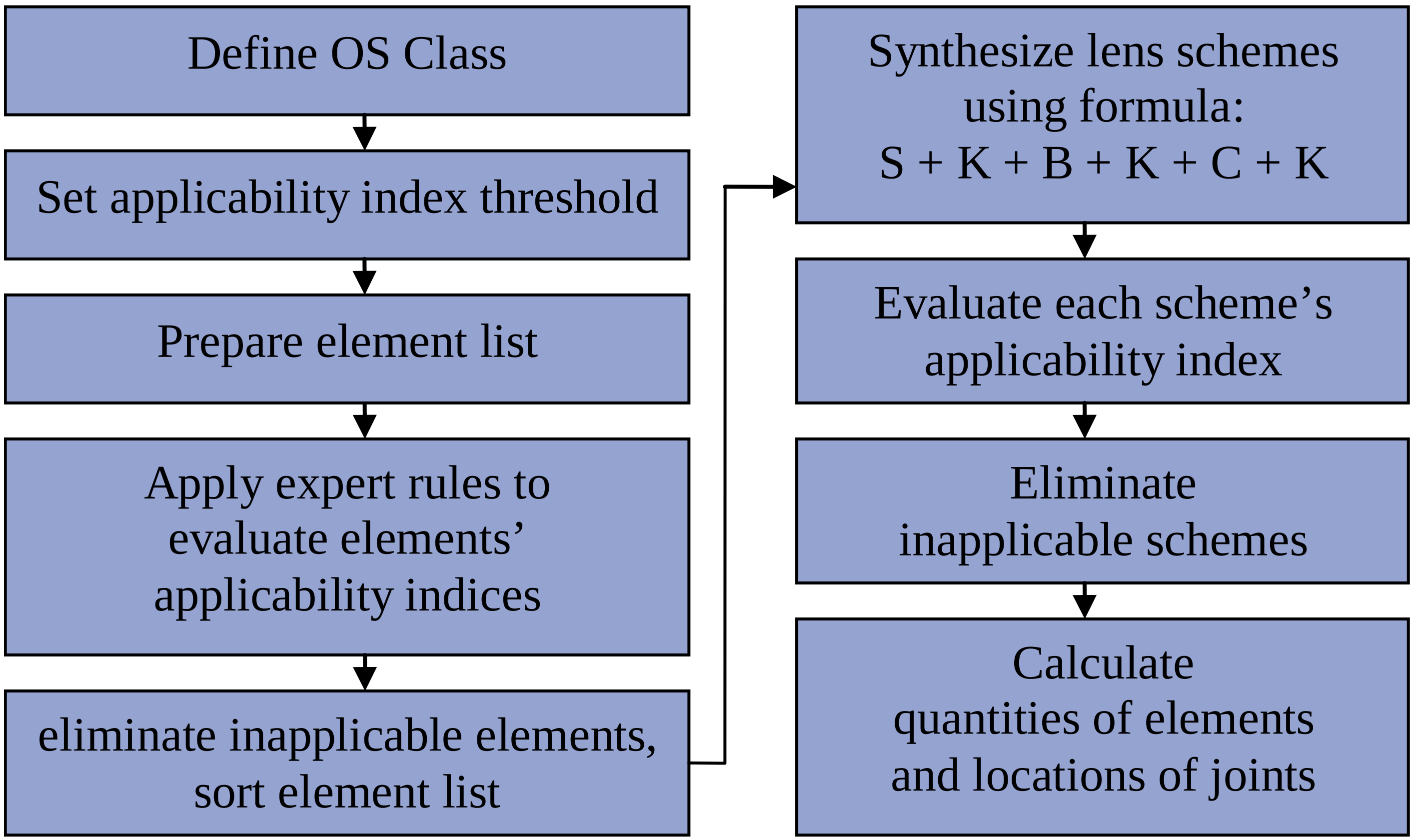
- According to described theory a special algorithm was proposed to automate the process of structural synthesis.

- It was implemented using “Microsoft Visual Basic 6.0” into a program “STRUCT-7” (beta-version) which performs CAD of OS structural scheme.

Application of CAD software



Heuristic algorithm



Selection rules (how & why)

- For modules;
- For elements;
- For surfaces.

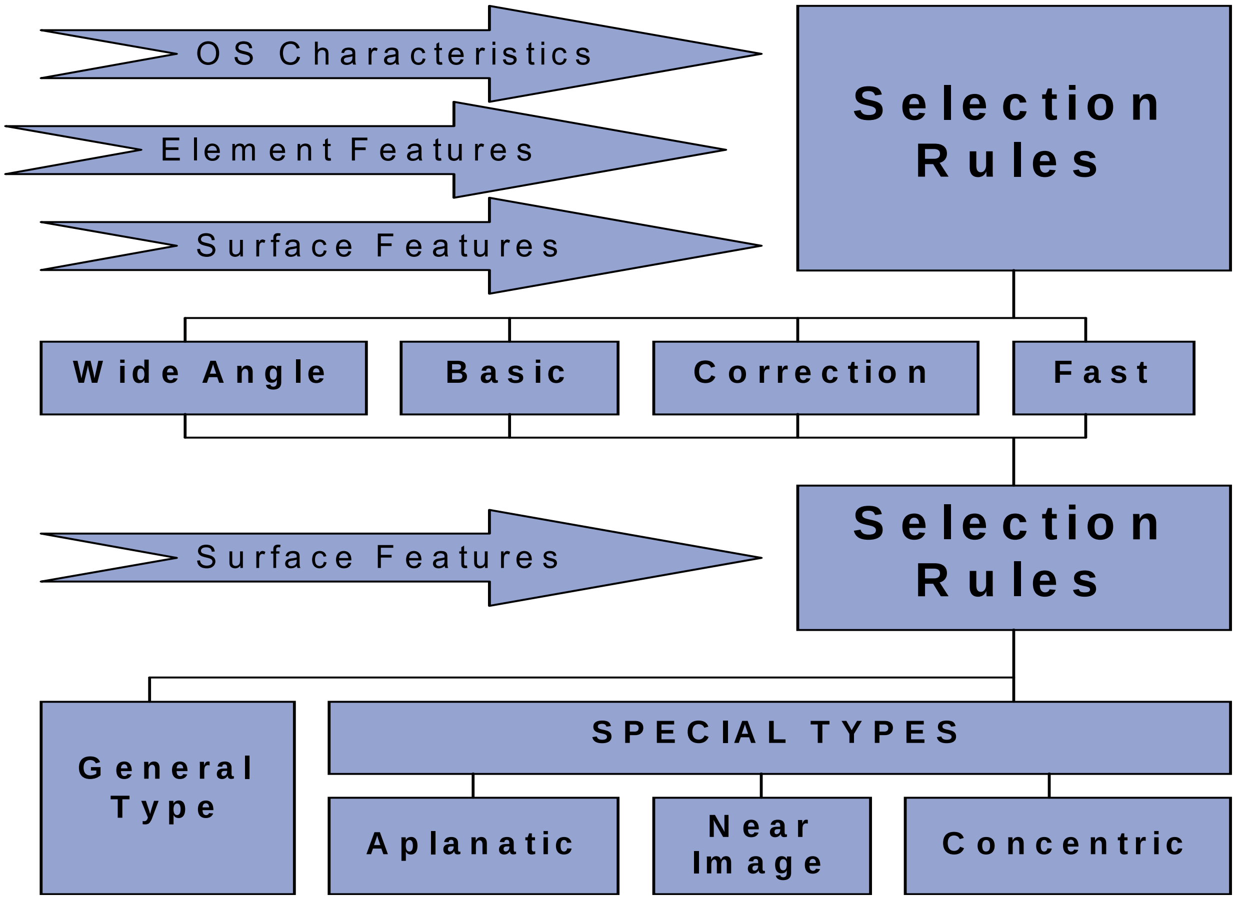
Main steps for starting point selection:

- Structural synthesis – procedure to estimate number,type and location of OEs;
- Parametrical synthesis – procedure to find OEs parameters (radii, OE thickness, distances between OEs, materials, etc.);
- Composing – multi configuration structural synthesis with variable (zoom) OEs.

Important questions for optical expert interview

- After we completed the classifications of optical elements, we asked our experts:
- “What kind of optical element you will use to design such-and-such optical system?”
- “How many elements?”
- “What is index of applicability for each type of the elements?”
- Total number of questions answered by one expert was about 40 questions.

Structural synthesis procedure



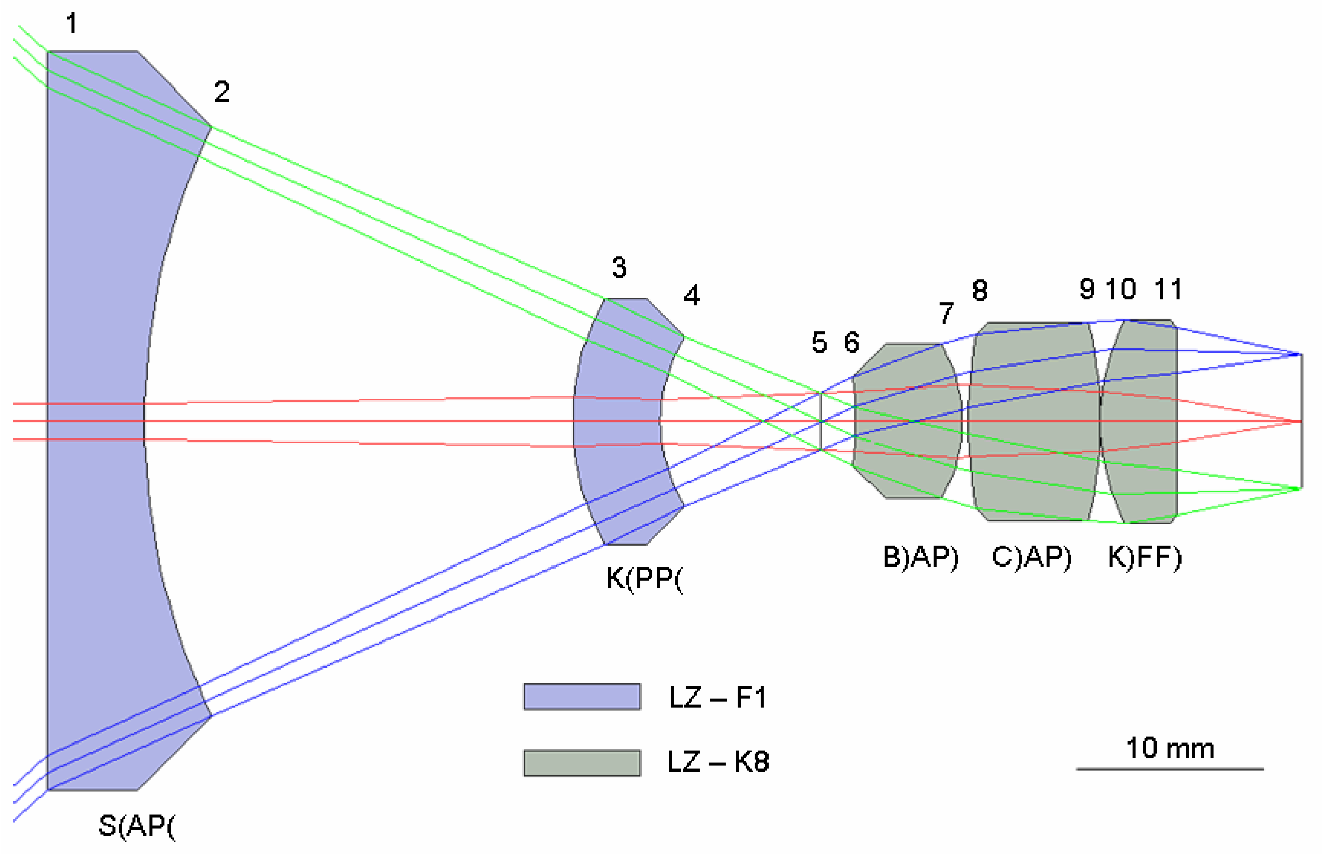
“Taking interview” from patent database

- Expert knowledge together with solving the reverse problem from patent database we plan to use to generate new starting point based on application of genetic algorithm in future.

EXAMPLES

- Presented examples are designs of my Russian and International students as their final exams for the course “Composing and optical systems design”

F1.8; 2w=84°; F’ = 4.5 мм



Lens class: J = 1, W = 2, F = 0, L = 2, Q = 0, S = 2, D = 0, IC=7

Structural formula: S(AP(+ K(PP(+ B)AP) + C)AP) + K)FF)

For contacts

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THANK YOU!

Designed by students

1. Composing and Optical Systems Design
2. Optical Systems Design

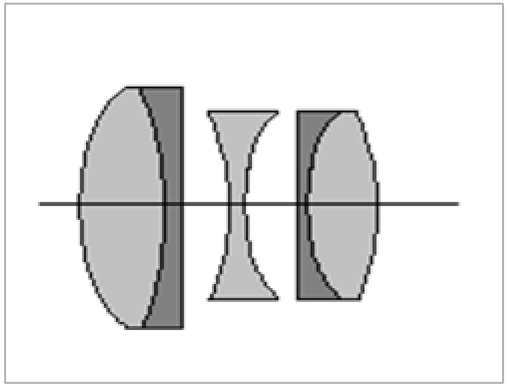
Heliar

(Personal design project)

Jana Jagerska

Target

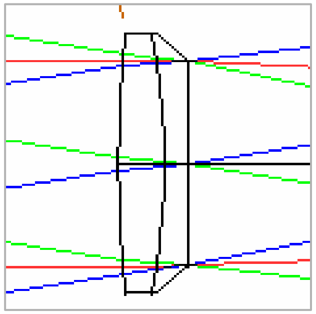
- Heliar optical system specifications given in table below:



	J	W [deg]	F [mm]	L [mm]	Q	S [mm]	D
Value	5	10	100	vis	G	>50	ins
Index	0	1	1-2	1	0	1	0

- The complexity index of the system: 4-5

Starting point



- Achromat doublet taken from SYNOPSYS database:

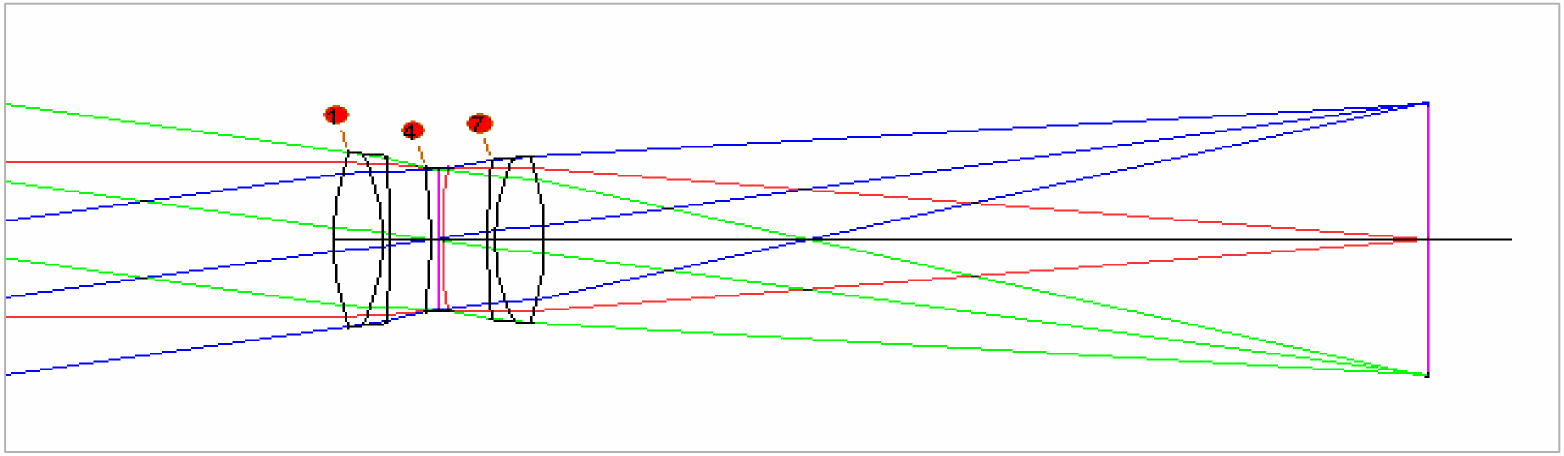
  F = 200, D = 10 JML "DBL 14125"

- Revert & combine the lens to get a symmetric system. The aperture stop position - between the lenses.

- Design weak negative lens close to the aperture stop
- Scale the system to F = 100, F# = 5.

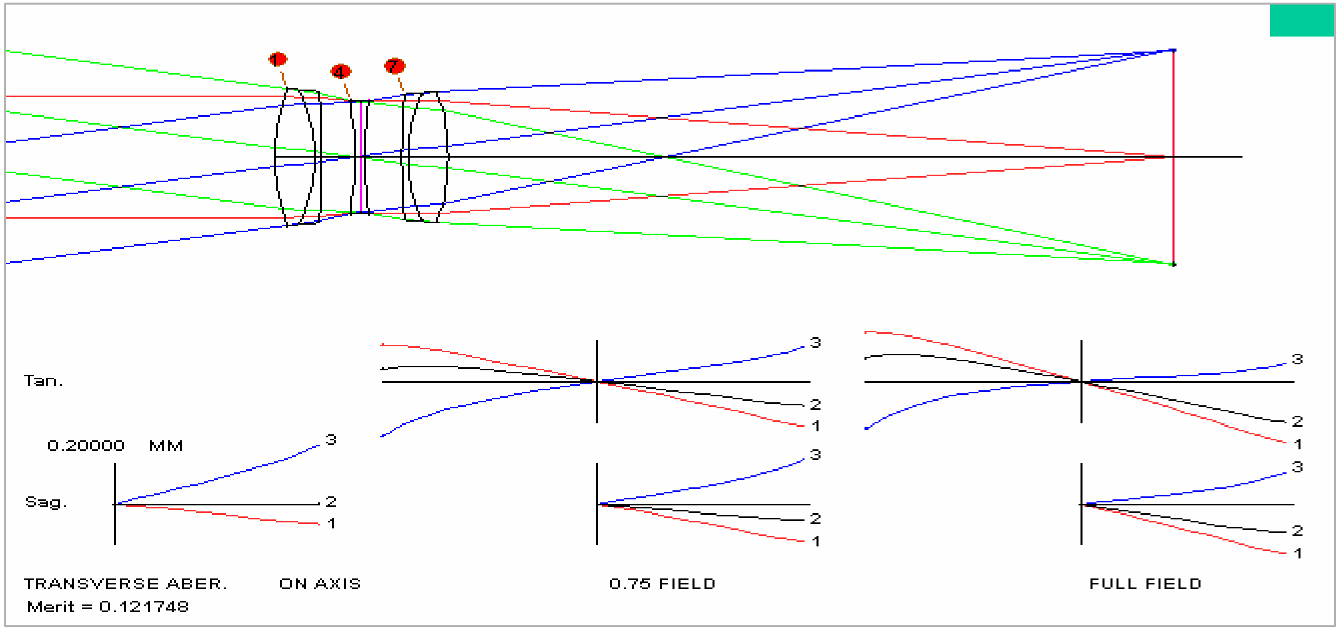
Initial system performance

- Aberrations that dominated in the system: field curvature, chromatic aberration
- Coma, distortion – almost not present due to system symmetry
- Aberration check:
  - Transverse aberration plots in tang. and sag. fans
  - Commands: THIRD, THIRD SURF



Optimization I

- Rough adjustment of curvatures and distances between individual surfaces: done “by hand” directly in the PAD window

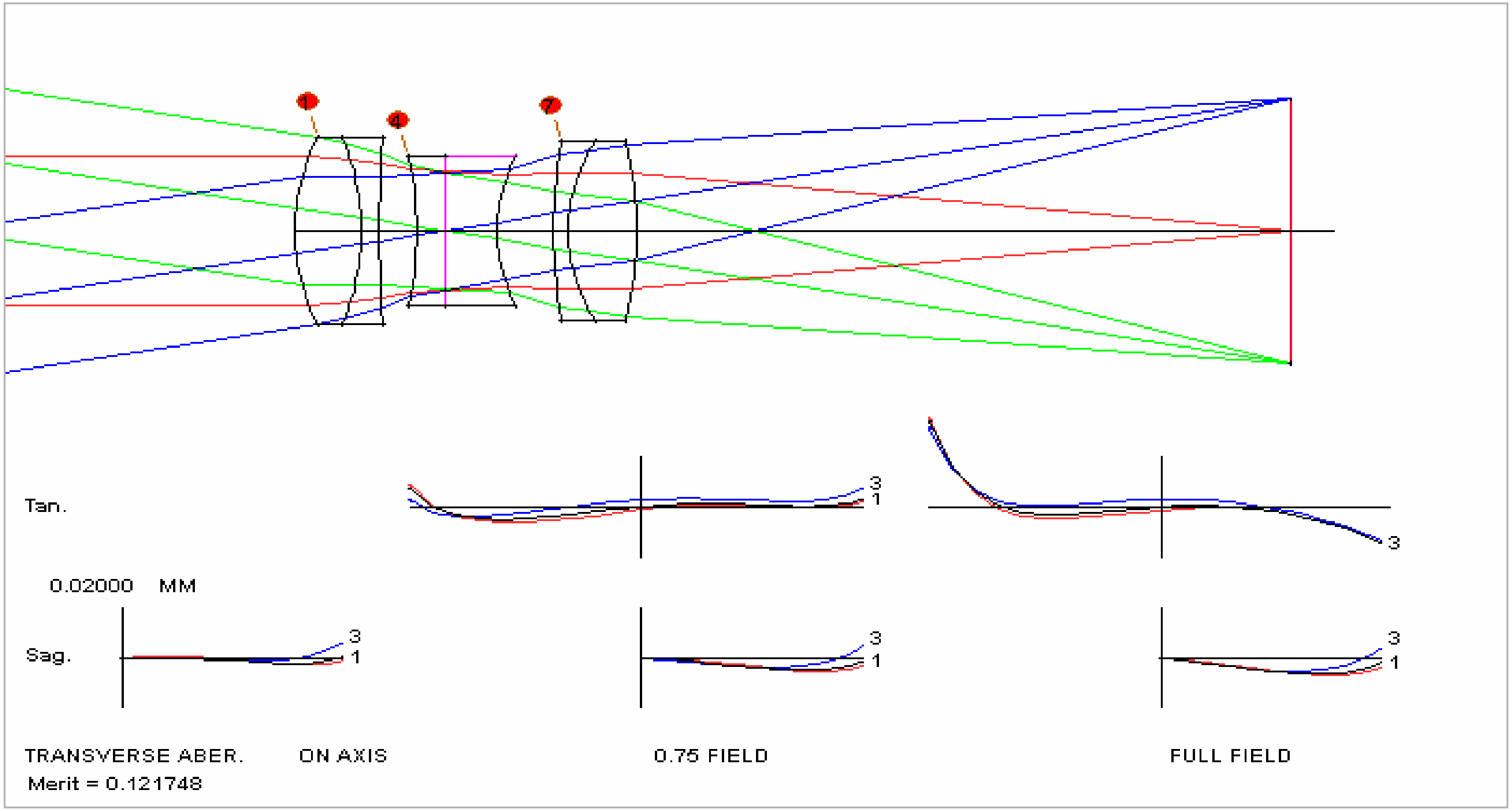


Optimization II

- Fine optimization using SYNOPSYS optimization tool:
  - Parameters: all glasses, all curvatures, thickness of the negative correction lens (limited interval)
  - Merit function:
    - suppress SA3, PAC, PETZ, CO3, maintain FOCL=100
    - !!! prepared merit function #6 (full color grid)
  - Optimization successful, performance of the system close to the diffraction limit

- Glass models exchanged for real glasses
  - Optimization process repeated after each glass exchange

Final system properties I



Final system properties II

- **System specifications:**

OBJECT DISTANCE	(TH0)	INFINITE	FOCAL LENGTH	(FOCL)	100.0000
OBJECT HEIGHT	(YPP0)	INFINITE	PARAXIAL FOCAL POINT		75.5874
MARG RAY HEIGHT	(YMP1)	10.0000	IMAGE DISTANCE	(BACK)	75.5874
MARG RAY ANGLE	(UMP0)	0.0000	CELL LENGTH	(TOTL)	39.5530
CHIEF RAY HEIGHT	(YPP1)	-2.9612	F/NUMBER	(FNUM)	5.0000
CHIEF RAY ANGLE	(UPP0)	10.0000	GAUSSIAN IMAGE HT	(GIHT)	17.6327
ENTR PUPIL SEMI-APERTURE		10.0000	EXIT PUPIL SEMI-APERTURE		9.6900
ENTR PUPIL LOCATION		16.7939	EXIT PUPIL LOCATION		-21.3123

- **Surface data:**

SURF	RADIUS	THICKNESS	MEDIUM	INDEX	V-NUMBER	
0	INFINITE	INFINITE	AIR			
JML:DBL14125						
1	31.04604	7.70817	N-PSK57	1.59240	68.40	SCHOTT
2	-35.82929	2.05926	FK5	1.48749	70.40	SCHOTT
3	182.16838	4.33681	AIR			
4	-49.98868	3.30629	TIF3	1.54765	42.20	SCHOTT
APS	INFINITE	6.00000	PICKUP	1.54765P	42.20	
6	24.43289	6.52712	AIR			
7	84.26873	1.61538	PICKUP	1.48749P	70.40	
8	23.10435	8.00000	PICKUP	1.59240P	68.40	
9	-57.92969	75.58737S	AIR			
10	INFINITE	0.00000	AIR			
IMG	INFINITE					

Final system properties III

- **System aberrations (3rd order):**

- THIRD-ORDER ABERRATION SUMS

	SPH ABERR	COMA	TAN ASTIG	SAG ASTIG	PETZVAL	DISTORTION
	(SA3)	(CO3)	(TI3)	(SI3)	(PETZ)	(DI3(FR))
	-0.01466	-0.01769	0.02391	-0.01365	-0.03243	-0.00153

- PARAXIAL CHROMATIC ABERRATION SUMS

	AX COLOR	LAT COLOR	SECDRY AX	SECDRY LAT
	(PAC)	(PLC)	(SAC)	(SLC)
	0.00321	-0.00576	0.00194	-0.00171

- **System aberrations (5th order):**

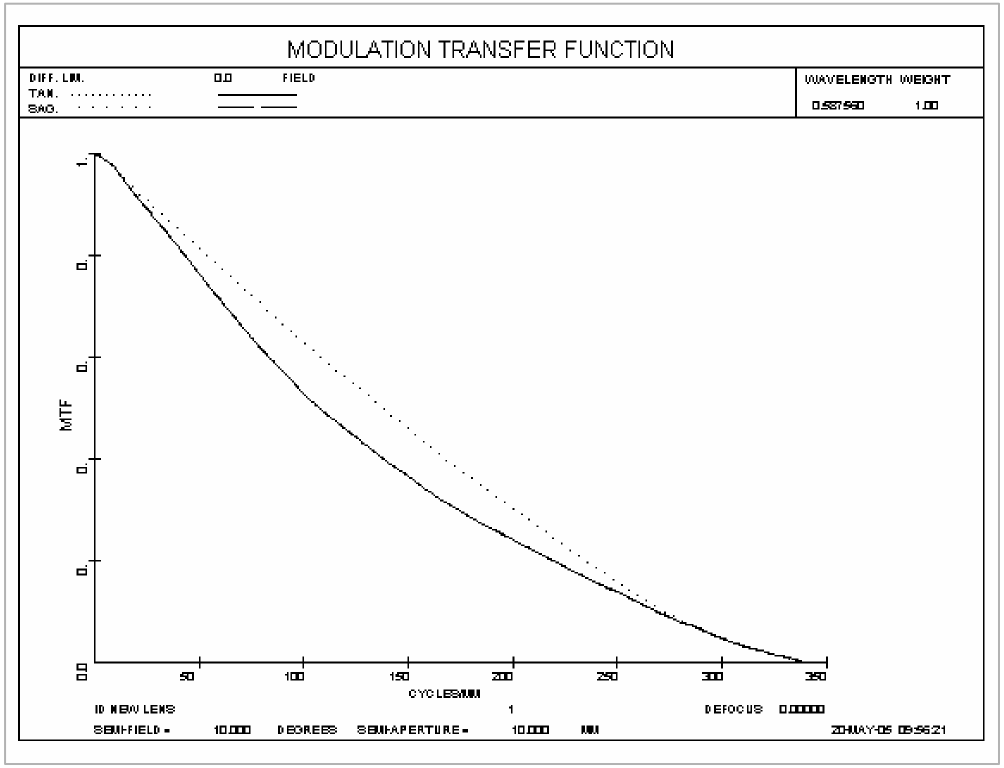
- FIFTH-ORDER ABERRATION SUMS

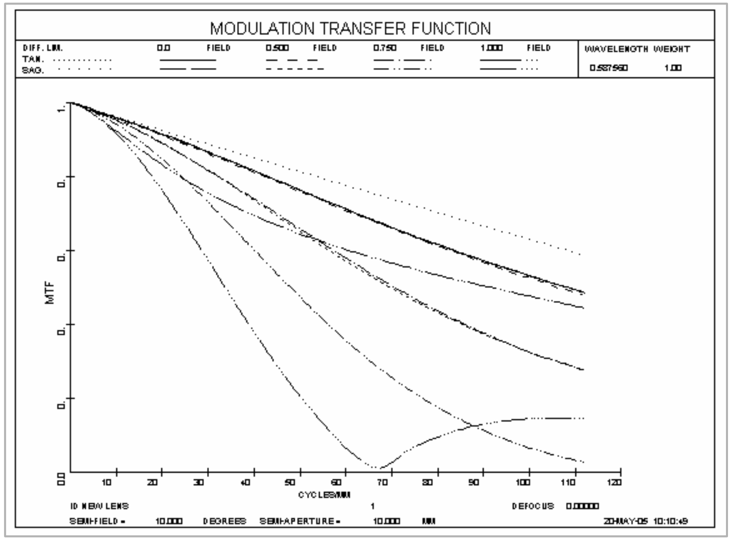
	SPH ABERR	COMA	TAN ASTIG	SAG ASTIG	PETZVAL	DISTORTION
	(SA5)	(CO5)	(TI5)	(SI5)	(PZ5)	(DI5(FR))
	0.01542	0.00828	-0.01399	0.00309	0.00736	-0.00036

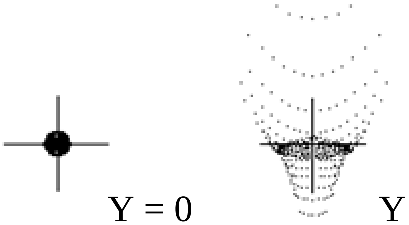
	TAN OBL SA	SAG OBL SA	ELLIP COMA
	(TOBSA)	(SOBSA)	(ECOMA)
	0.01084	0.01022	0.01111

Final system properties IV

SR = 0.7 (index of complexity increased of 1)







Y = 0 Y = 1

20 µm 20 µm

Heliar applications

- Old design (1902) of an optical system used in cameras
- Low field angle, long local length teleobjective

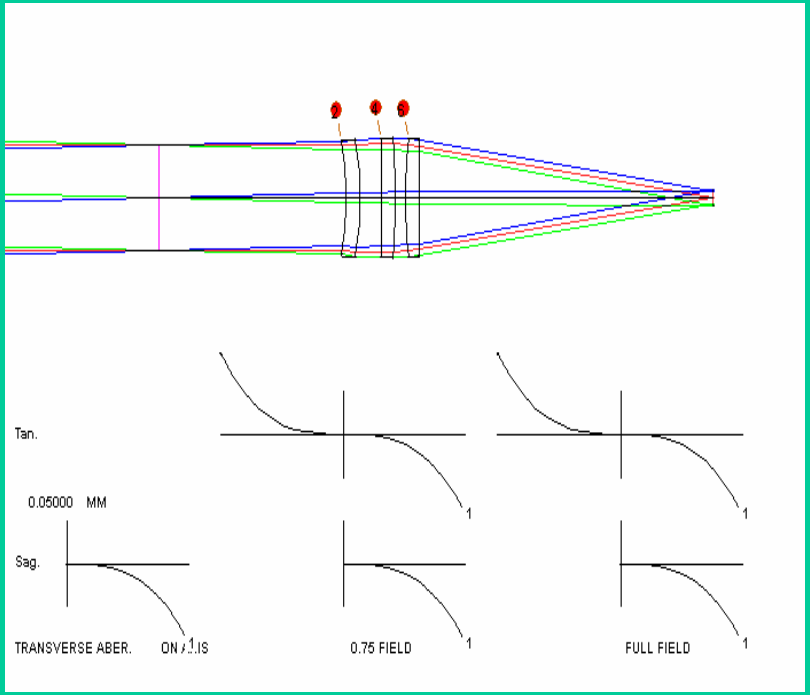
- Low chromatic aberration, small spot size (< 30μm) even for fractional field Y = 1

Laser scanning lens

Specifications

- J = 30 (Aperture speed)
- W = 15 (Angular field)
- F = 508mm (Focal length)
- L = 0 (Spectral range) (488nm)
- Q = (Image quality)
- S > 478 (Back focal length)
- D = Forward (Entrance pupil)
- IC = 6

Start: PP + AP + AP



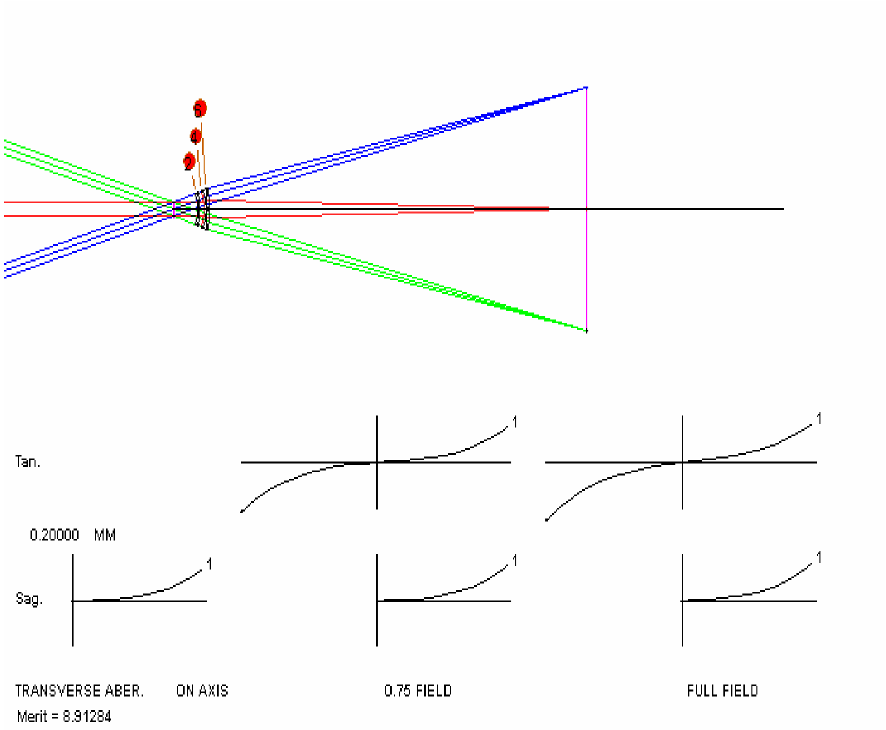
Laser scanning lens

P(opt) + AP + AP

Glass BK7 => SF8

Merit function

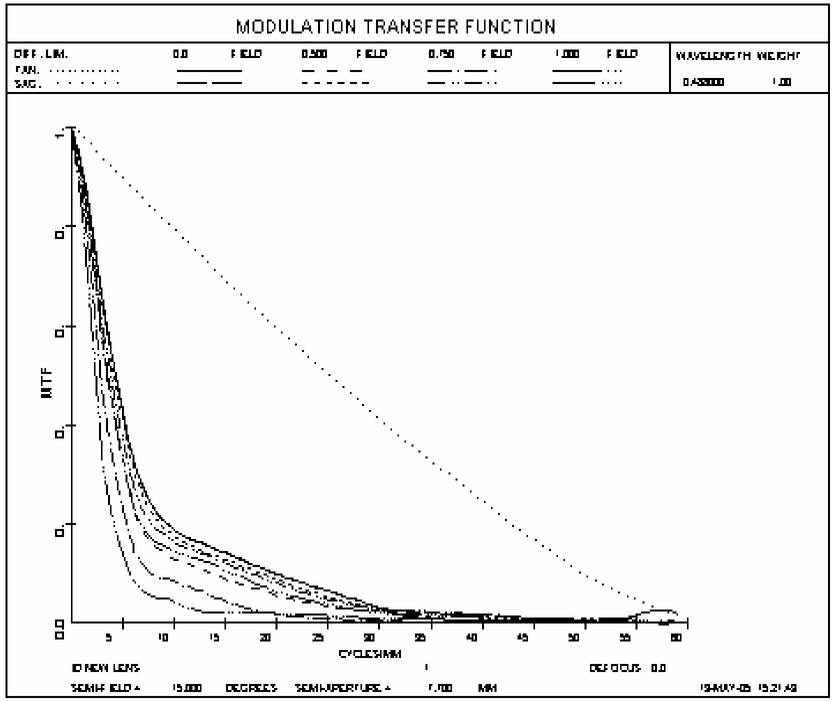
- Focal length
- F#
- Third order aberrations
- Fifth order aberrations



Laser scanning lens

MTF and 3:e aberrations

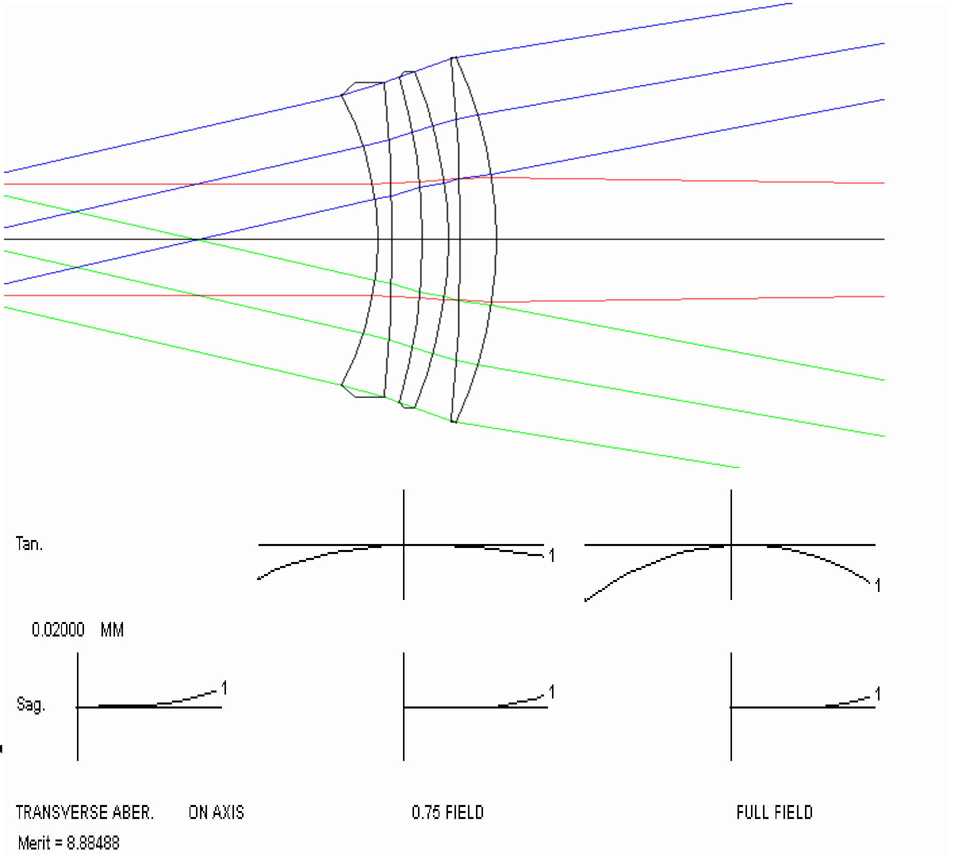
- **(SA3) = 0.14411**
- **(CO3) = -0.03037**
- **(TI3) = 0.07711**
- **(SI3) = 0.01786**
- **(PETZ) = -0.01177**
- **(DI3(FR)) = -0.00911**



Laser scanning lens

Final result

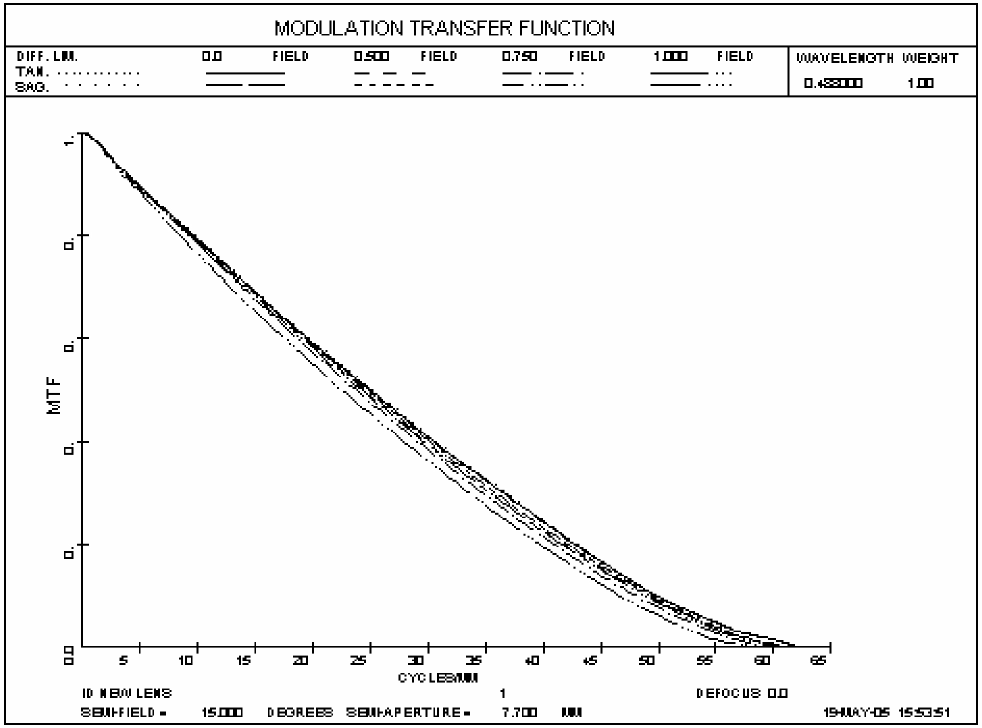
- **F = 507.8069**
- **F# = 30.2266**
- **(SA3) = 0.00582**
- **(CO3) = -0.00166**
- **(TI3) = 0.00227**
- **(SI3) = -0.00578**
- **(PETZ) = -0.00980**
- **(DI3(FR)) = -0.01136**
- Spot size = 4 micrometer



Laser scanning lens

Multi-Field MTF

- Near diffraction limited
- Mission accomplished!



Telecentric system

A telecentric system has its exit pupil at infinity, i.e. the chief ray emerges parallel to the optical axis.

Important facts about telecentric systems:

Telecentric systems are ideal for measurement applications. They are used in a wide range of applications.

Telecentric systems have no parallax distortion. This is a point of great interest for machine vision.

Telecentric systems allow variations in working distance. Within the depth of field, a telecentric system will show no magnification error. This makes setup and calibration easier.

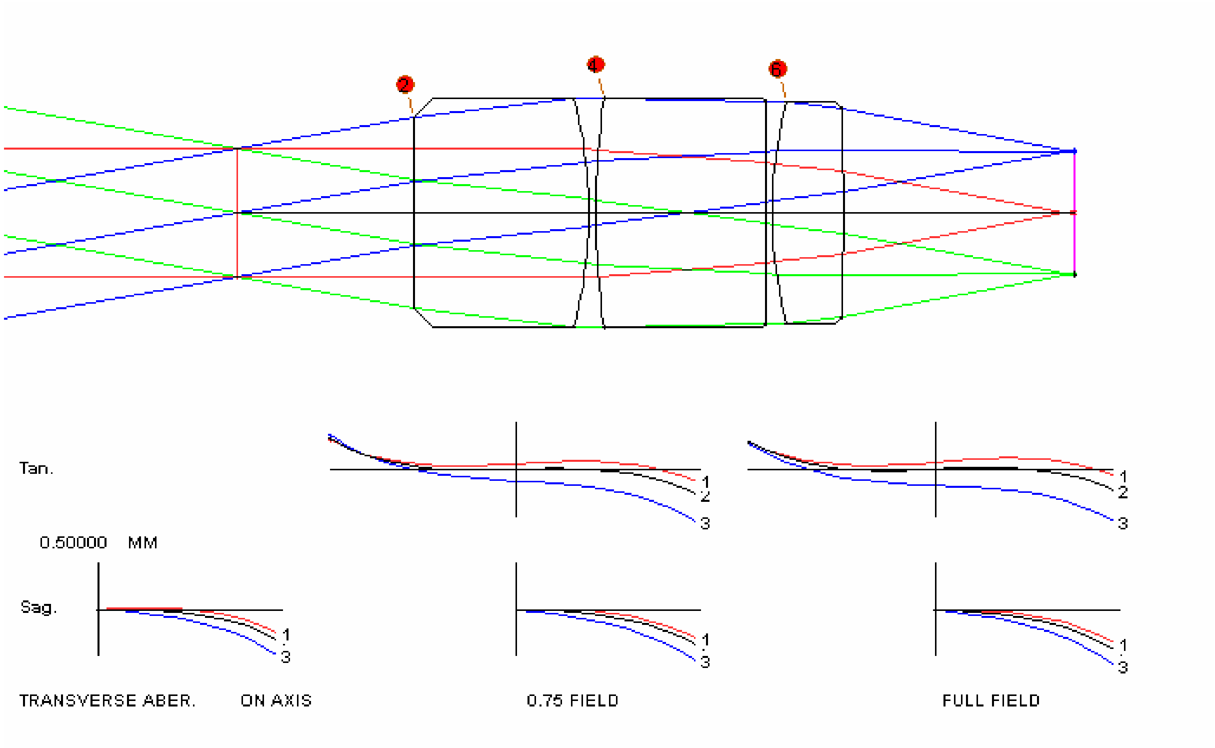
There are different types of telecentric systems. They can be telecentric in object space, in image space or both.

System specifications:

J=2.8	→	J = 0-1
W=10	→	W = 1
F=100mm	→	F = 1-2
L=Visual	→	L = 1
Q=G	→	Q = 0
S>50mm	→	S = 1
D=2nd surf.	→	D = 0

IC= 4-6

Starting system

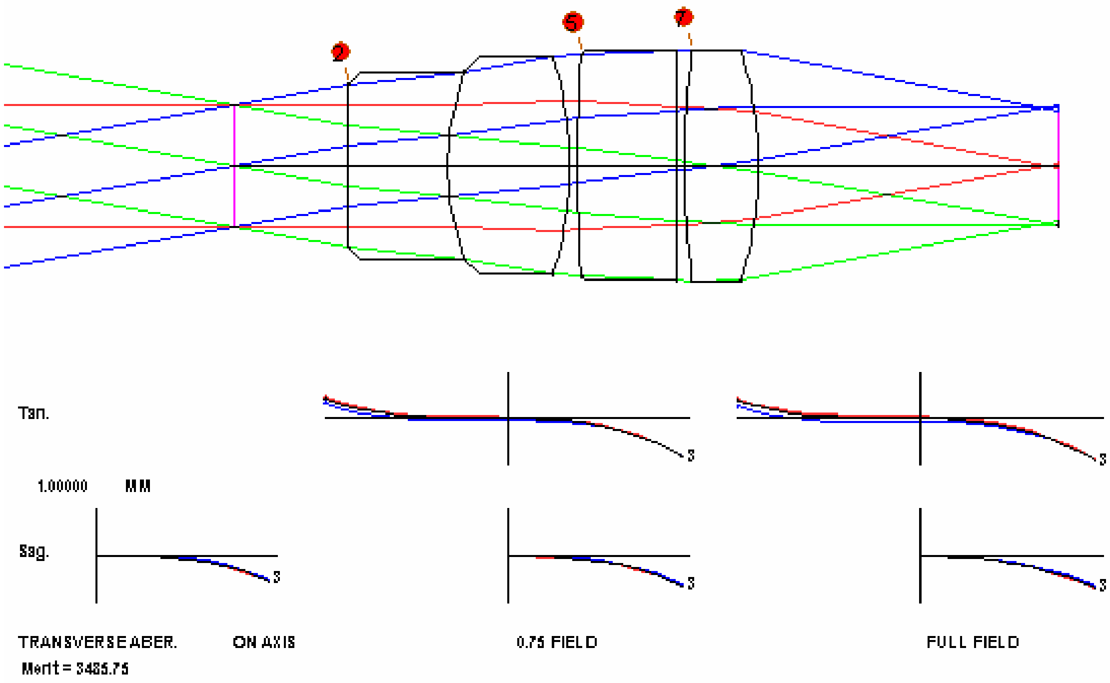


First lens: AP
Second lens: VO
Third lens: V-

V→IMY=0

Big spherical and chromatic aberrations.
Right focal length and F-number.

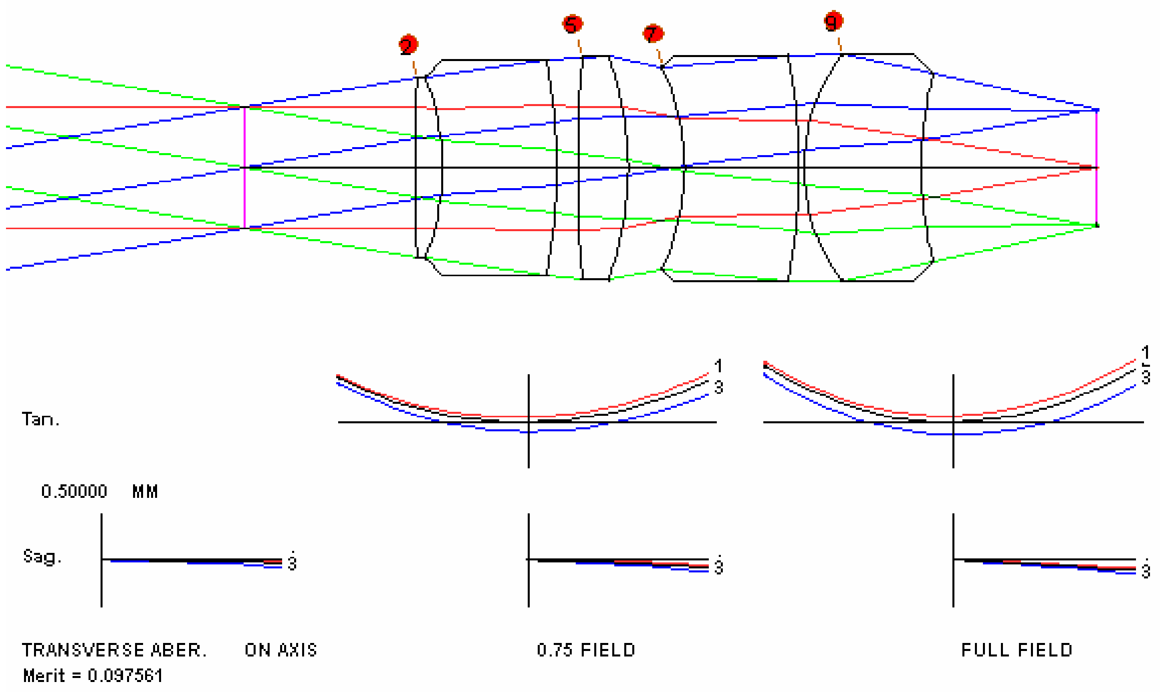
Splitting the first lens to reduce chromatic aberrations.



Doublets glasses: SF10 and BK7

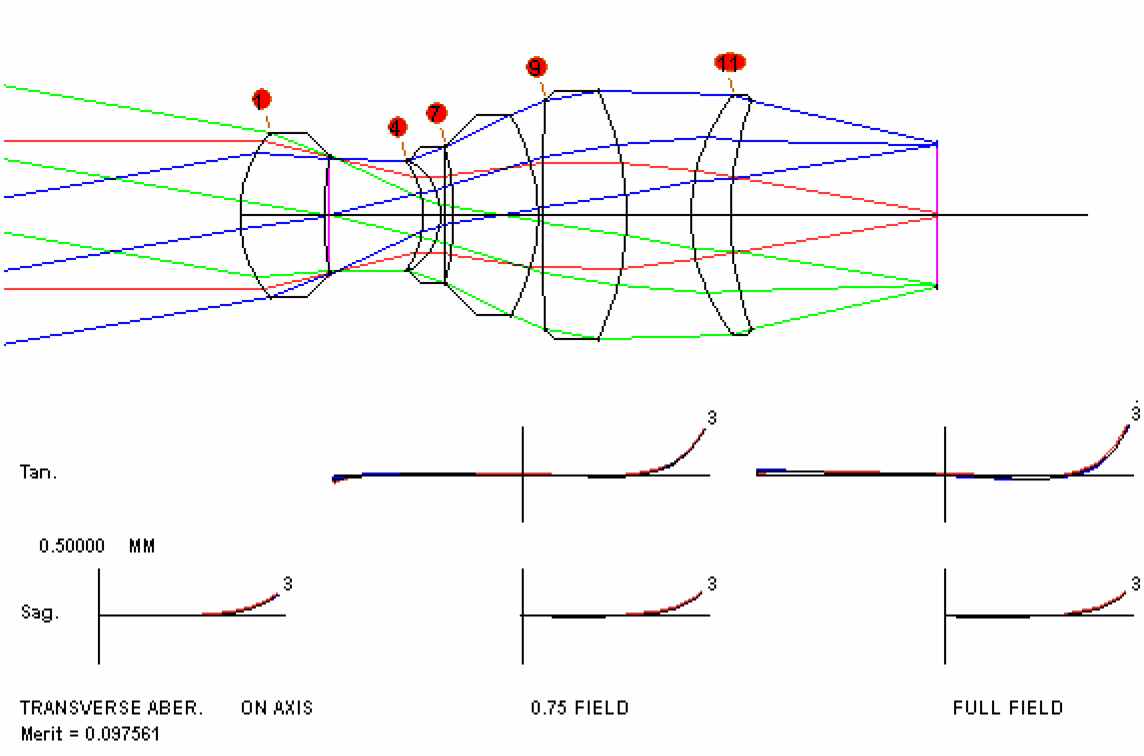
Chromatic aberrations successfully reduced (PAC=-0.04 , PLC=0.08).

Adding a lens after the doublet to reduce spherical aberration.



Spherical aberration successfully corrected (SA3=-0.03).
Introduced quite big coma.

Adding a lens in the first position to eliminate coma.



Aperture on the second surface

Successfully eliminated coma (CO3=-0.09).

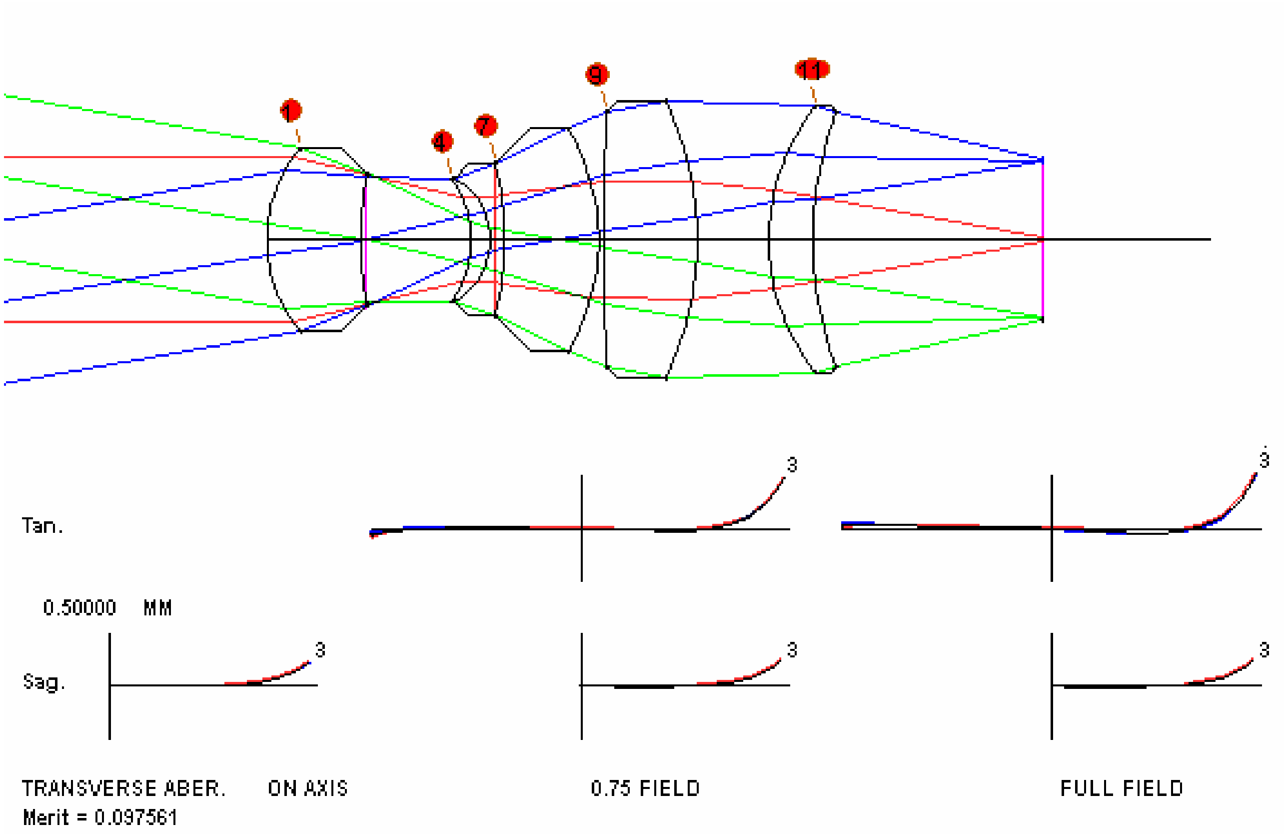
Last steps (of a long walk…)

Inserting the telecentric solve on the last surface:
UPC(principal ray angle) =0

Last optimizations for radii, thicknesses and glass types.

Checking that the specifications are fulfilled.

Final system



SYSTEM SPECIFICATIONS

OBJECT DISTANCE	(TH0)	INFINITE	FOCAL LENGTH	(FOCL)	101.0948
OBJECT HEIGHT	(YPP0)	INFINITE	PARAXIAL FOCAL POINT		50.6848
MARG RAY HEIGHT	(YMP1)	18.0000	IMAGE DISTANCE	(BACK)	50.6848
MARG RAY ANGLE	(UMP0)	0.0000	CELL LENGTH	(TOTL)	120.5300
CHIEF RAY HEIGHT	(YPP1)	-3.4316	F/NUMBER	(FNUM)	2.8082
CHIEF RAY ANGLE	(UPP0)	10.0000	GAUSSIAN IMAGE HT	(GIHT)	17.8257
ENTR PUPIL SEMI-APERTURE		18.0000	EXIT PUPIL SEMI-APERTURE		INFINITE
ENTR PUPIL LOCATION		19.4614	EXIT PUPIL LOCATION		INFINITE

SURFACE DATA

SURF	RADIUS	THICKNESS	MEDIUM	INDEX	V-NUMBER	
0	INFINITE	INFINITE	AIR			
1	31.12519	20.80440	BK7	1.51680	64.17	SCHOTT
2	69.06694	1.00000	AIR			
APS	INFINITE	23.21493	AIR			
4	-24.31992	4.40727	GLM-NdVd	1.50000S	74.60	
5	-15.35830	1.00000	SF10	1.72825	28.41	SCHOTT
6	-7344.73909	2.00000	AIR			
7	-73.51154S	20.85697	LAK28	1.74429	50.77	SCHOTT
8	-48.82119	1.00000	AIR			
9	490.94059	20.77886	GLM-NdVd	1.80000S	48.20	
10	-70.62892	15.89257	AIR			
11	46.75264	9.57496	GLM-NdVd	1.51680S	64.17	
12	77.90966S	50.68482S	AIR			
IMG	INFINITE					

THIRD-ORDER ABERRATION SUMS

SPH ABERR (SA3)	COMA (CO3)	TAN ASTIG (TI3)	SAG ASTIG (SI3)	PETZVAL (PETZ)	DISTORTION (DI3(FR))
-0.02435	-0.09438	-0.04924	-0.01037	0.00906	-0.03234

PARAXIAL CHROMATIC ABERRATION SUMS

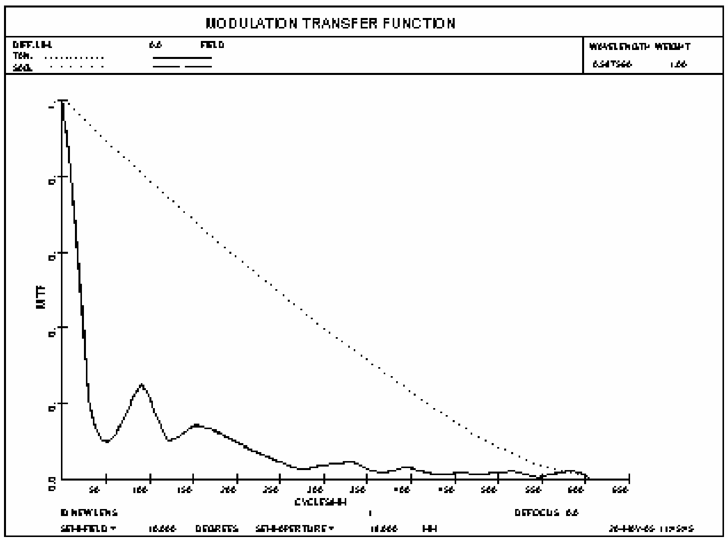
AX COLOR (PAC)	LAT COLOR (PLC)	SECDRY AX (SAC)	SECDRY LAT (SLC)
0.00785	0.00597	0.01769	0.01257

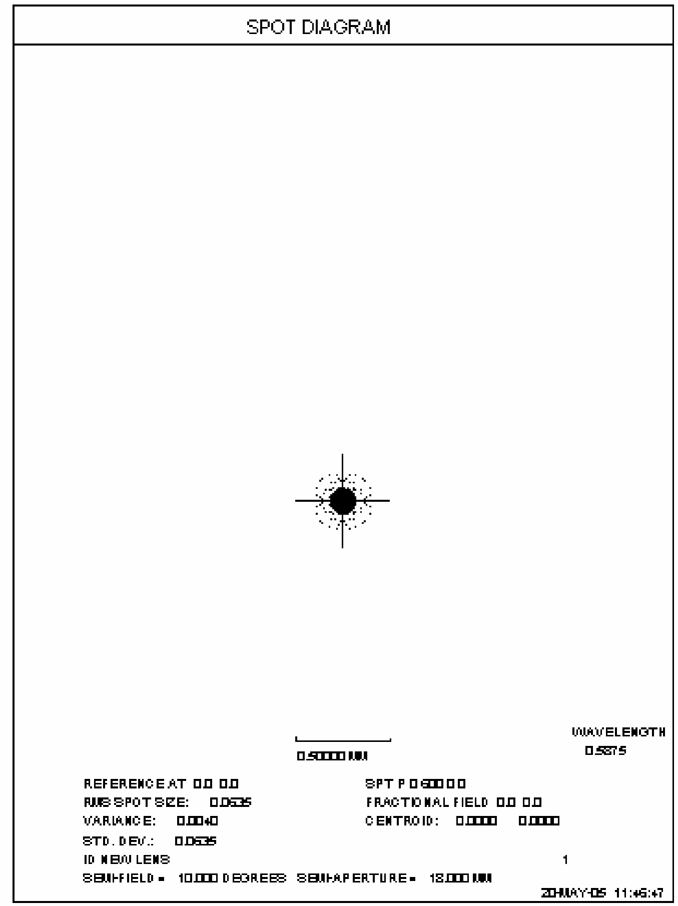
FIFTH-ORDER ABERRATION SUMS

SPH ABERR (SA5)	COMA (CO5)	TAN ASTIG (TI5)	SAG ASTIG (SI5)	PETZVAL (PZ5)	DISTORTION (DI5(FR))
0.19769	0.20626	-0.01917	0.00302	0.00856	-0.00222

TAN OBL SA (TOBSA)	SAG OBL SA (SOBSA)	ELLIP COMA (ECOMA)
0.00103	0.01045	0.00621

Performances



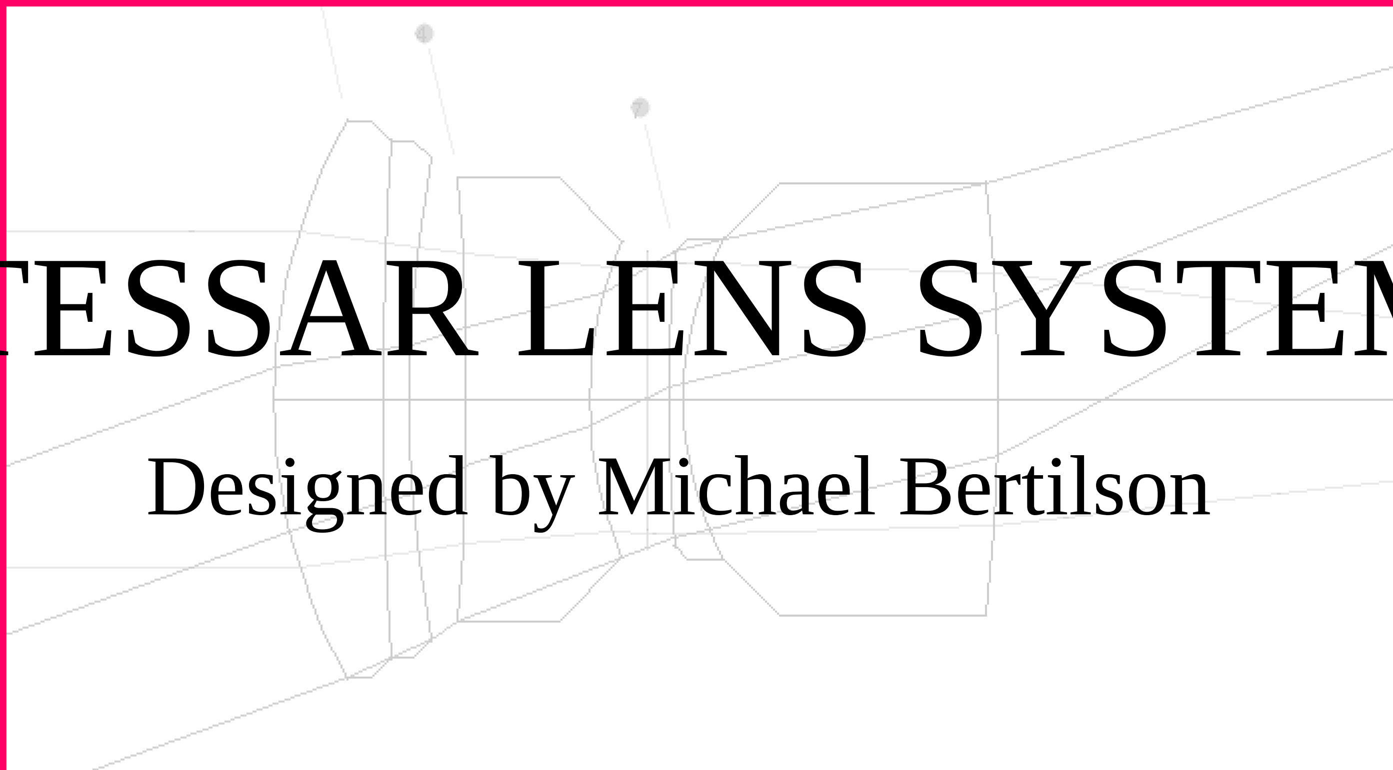


Conclusions

All the specifications are satisfied. Our hypothetical customer would be very happy.

TESSAR LENS SYSTEM

Designed by Michael Bertilson



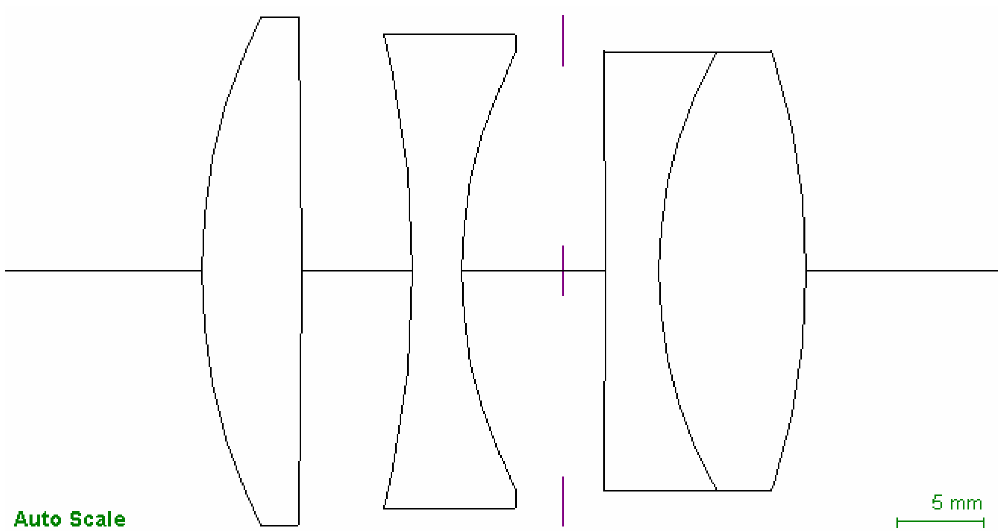
System requirements

- Tessar lens with two acromats
- F-number, 4,5
- Field angle, 40 deg
- Focal length, 100 mm
- Image distance >50 mm
- MTF>0.2 in range 0/mm-50/mm for all image points

- J=0
- W=1
- F=2
- L=1
- Q=0
- S=1
- D=0

<u>IC = 5</u>

LensVIEW starting point



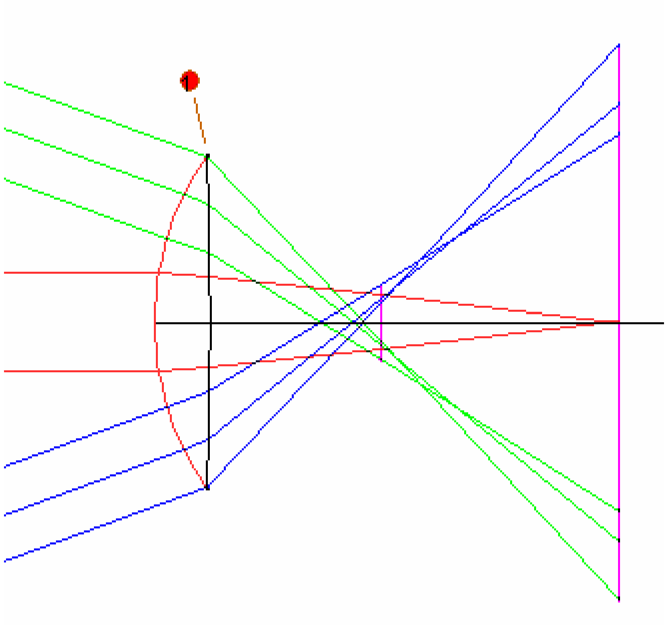
Patent #: 2,084,714
Title: UNSYMMETRICAL PHOTOGRAPHIC OBJECTIVE

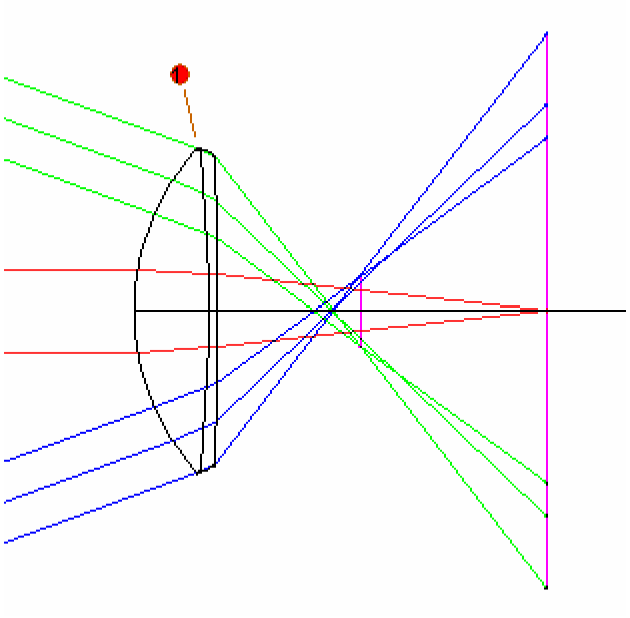
Inventor: Albrecht Wilhelm Tronnier
Address: Bad Kreuznach, Germany

Assignee: Jos. Schneider & Co.
Address: Berlin, Germany

Application Number: 46,809
Date Filed: 10/25/1935
Date Issued: 06/22/1937

Lens element replacement





Starting point

SYSTEM SPECIFICATIONS

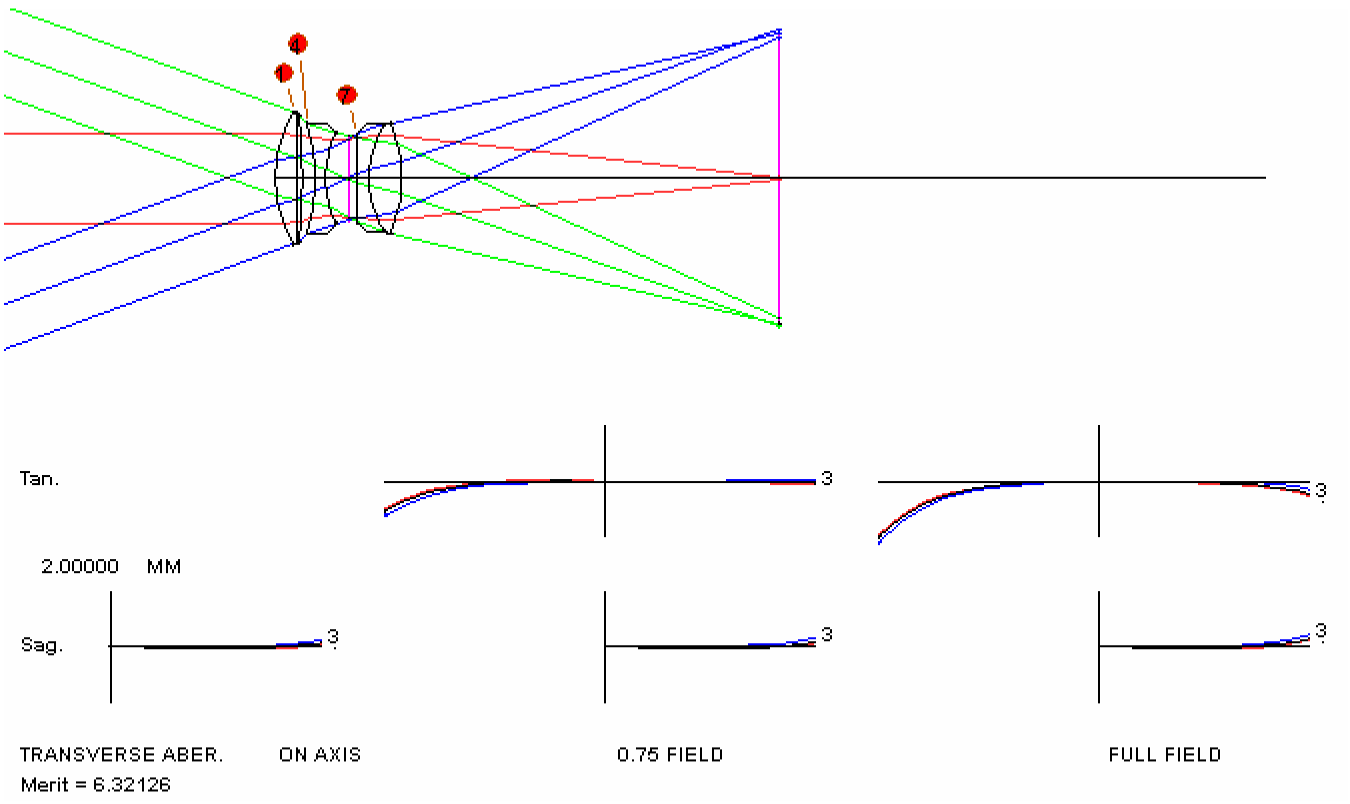
OBJECT DISTANCE	(TH0)	INFINITE	FOCAL LENGTH	(FOCL)	99.9848
OBJECT HEIGHT	(YPP0)	INFINITE	PARAXIAL FOCAL POINT		91.5727
MARG RAY HEIGHT	(YMP1)	11.1100	IMAGE DISTANCE	(BACK)	93.1830
MARG RAY ANGLE	(UMP0)	0.0000	CELL LENGTH	(TOTL)	30.9705
CHIEF RAY HEIGHT	(YPP1)	-6.7387	F/NUMBER	(FNUM)	4.4998
CHIEF RAY ANGLE	(UPP0)	20.0000	GAUSSIAN IMAGE HT	(GIHT)	36.9645
ENTR PUPIL SEMI-APERTURE		11.1100	EXIT PUPIL SEMI-APERTURE		11.3644
ENTR PUPIL LOCATION		18.5145	EXIT PUPIL LOCATION		-10.7020

```
WAVL (uM) .6562700 .5875600 .4861300
WEIGHTS   1.000000 1.000000 1.000000
COLOR ORDER    2   1   3
UNITS                            MM
APERTURE STOP SURFACE (APS)       6    SEMI-APERTURE    10.42614
FOCAL MODE                       ON
MAGNIFICATION           -1.01559E-10
BTH OPTION ON, VALUE =       1.61026
POLARIZATION AND COATINGS ARE IGNORED.
```

SURFACE DATA

SURF	RADIUS	THICKNESS	MEDIUM	INDEX	V-NUMBER	
0	INFINITE	INFINITE	AIR			
1	31.45587	5.06225	N-SK16	1.62041	60.32	SCHOTT
2	1052.07454	1.45653	TIF3	1.54765	42.20	SCHOTT
3	-225.72609	3.19596	AIR			
4	-53.50473	2.62959	LF5	1.58144	40.85	SCHOTT
5	25.20932	5.47830	AIR			
APS	INFINITE	2.32828	AIR			
7	-529.38739	2.87611	TIF3	1.54765	42.20	SCHOTT
8	23.90365	7.94354	N-SK16	1.62041	60.32	SCHOTT
9	-38.76811	93.18297S	AIR			
IMG	INFINITE					

Starting point



Aberrations: Elliptic coma, coma, sph. ab, tan. astigm, petz

Optimization

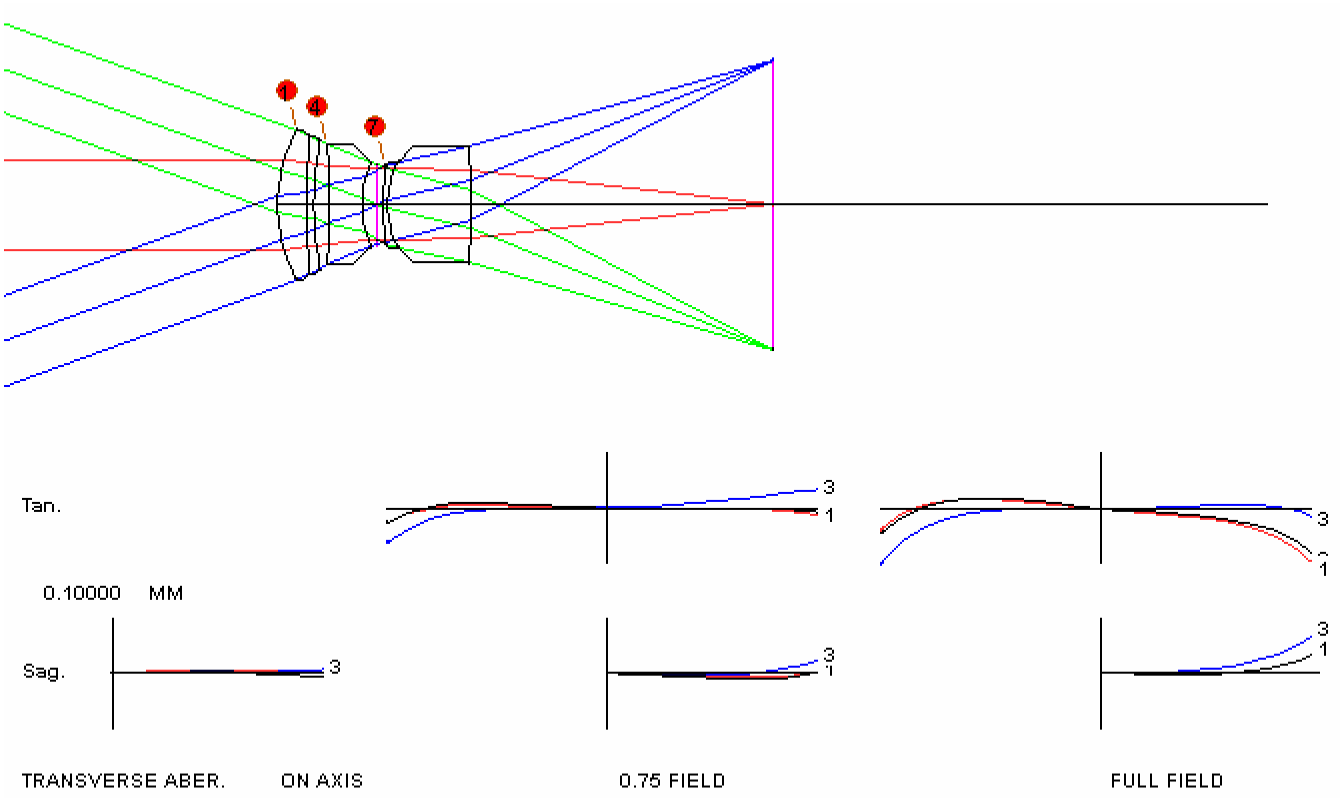
1. Parameters: All curvatures, distances and glasses
2. The merit function was a combination of the built in merit function nr 6 with a full ray grid for the three wavelengths, merit function nr 4 and weight functions for several aberrations of order 3 and 5.
3. Optimization was performed by adjusting weights for the aberrations and by using the sliders to get different starting systems. The kick and annealing tools were also used to improve the system.
4. After optimization the glass model lenses were replaced by known preferred glasses.
5. A final optimization was performed in order to correct parameters for the new glasses.
6. Defocus to best position

```
PANT
VLIST RAD 1 2 3 4 5 7 8 9
VLIST TH 1 2 3 4 5 6 7 8
VLIST GLM 1 2 4 7  8
END
AANT
AEC
ACC
GSR .5 10 5 P 0
GNR .5 2 3 P .7
GNR .5 1 3 P 1
GSR .5 10 5 1 0
GSR .5 10 5 3 0
GNR .5 2 3 1 .7
GNR .5 2 3 3 .7
GNR .5 1 3 1 1
GNR .5 1 3 3 1

GSR .5 10 5 P 0
GNR .5 2 3 P .7
GNR .5 1 3 P 1
M 0 50 A 1 YA 0 0 .7/S 3 YA 0 0 .7
M 0 50 A 1 YA 1 0 0/S 3 YA 1 0 0

M 100 5 A FOCL
M 0 34 A SA3
M 0 18 A CO3
M 0 45 A TI3
M 0 87 A SI3
M 0 100 A PETZ
M 0 8 A PLC
M 0 10 A PAC
M 0 16 A SA5
M 0 30 A CO5
M 0 35 A TI5
M 0 68 A SI5
M 0 76 A PZ5
M 0 47 A ECOMA
M 0 75 A TOBSA
END
SNAP
SYNOPSYS 20
```

Optimized Tessar lens



Lens specifications

SYSTEM SPECIFICATIONS

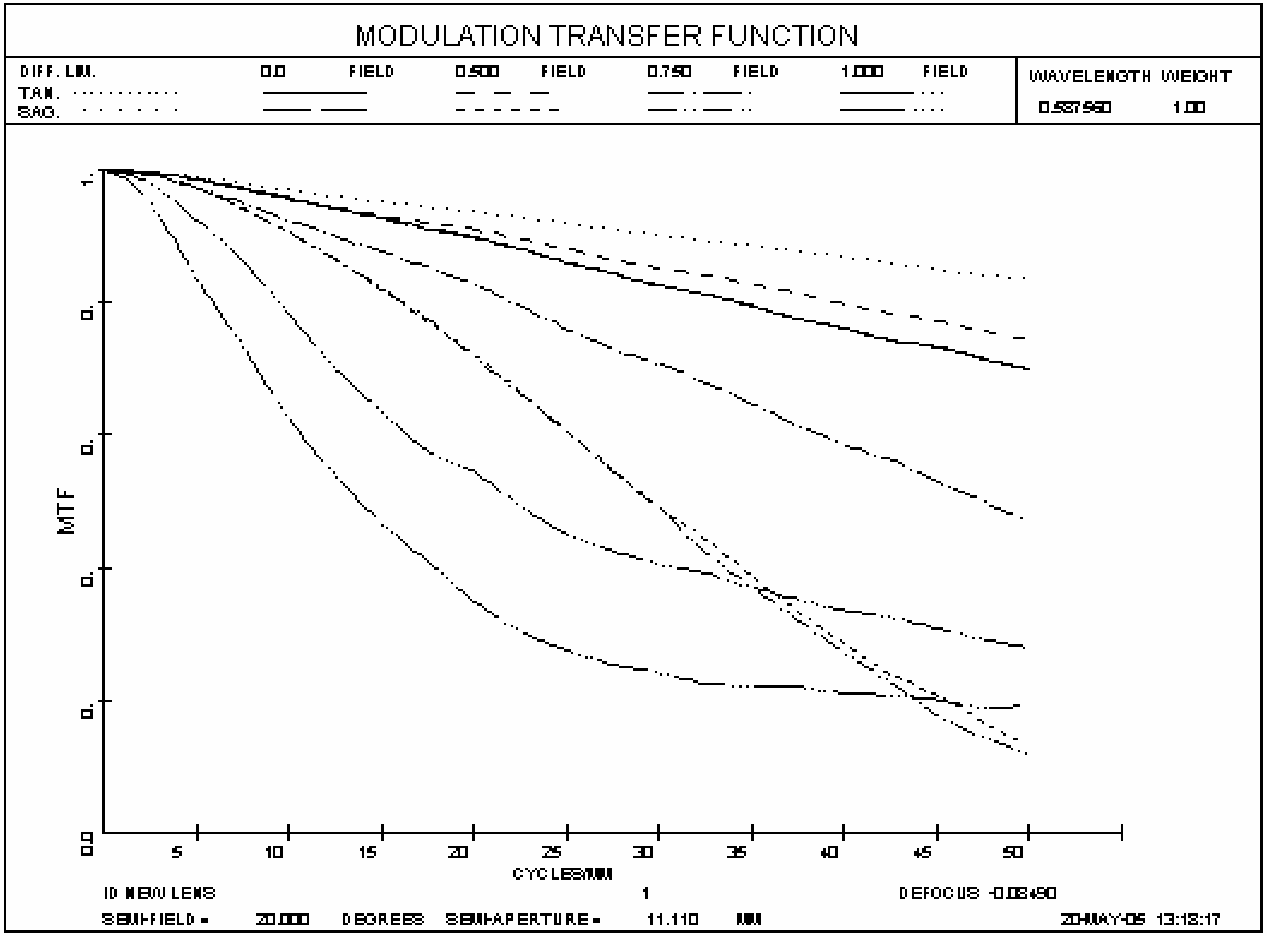
OBJECT DISTANCE	(TH0)	INFINITE	FOCAL LENGTH (FOCL)	100.0003
OBJECT HEIGHT	(YPP0)	INFINITE	PARAXIAL FOCAL POINT	91.5727
MARG RAY HEIGHT	(YMP1)	11.1100	IMAGE DISTANCE (BACK)	74.3230
MARG RAY ANGLE	(UMP0)	0.0000	CELL LENGTH (TOTL)	47.9889
CHIEF RAY HEIGHT	(YPP1)	-9.0740	F/NUMBER (FNUM)	4.5005
CHIEF RAY ANGLE	(UPP0)	20.0000	GAUSSIAN IMAGE HT(GIHT)	36.3626
ENTR PUPIL SEMI-APERTURE		11.1100	EXIT PUPIL SEMI-APERTURE	9.9440
ENTR PUPIL LOCATION		24.9306	EXIT PUPIL LOCATION	-15.0971

WAVL (uM) .6562700 .5875600 .4861300
WEIGHTS 1.000000 1.000000 1.000000
COLOR ORDER 2 1 3
UNITS MM
APERTURE STOP SURFACE (APS) 6 SEMI-APERTURE 9.82028
FOCAL MODE ON
MAGNIFICATION -9.99054E-11
BTH OPTION ON, VALUE = -0.08491
POLARIZATION AND COATINGS ARE IGNORED.

SURFACE DATA

SURF	RADIUS	THICKNESS	MEDIUM	INDEX	V-NUMBER	
0	INFINITE	INFINITE	AIR			
1	37.22990	7.19955	N-LASF44	1.80420	46.50	SCHOTT
2	244.38346	1.78626	N-SF57	1.84666	23.78	SCHOTT
3	88.63171	3.74508	AIR			
4	-201.52314	8.19737	K10	1.50137	56.41	SCHOTT
5	26.40069	3.81897	AIR			
APS	INFINITE	1.39516	AIR			
7	117.71458	1.00000	N-SF5	1.67271	32.25	SCHOTT
8	22.79773	20.84654	N-LAF21	1.78800	47.49	SCHOTT
9	-115.19043	74.32298S	AIR			
IMG	INFINITE					

Performance of the lens



Performance of the lens

THIRD-ORDER ABERRATION SUMS

SPH ABERR	COMA	TAN ASTIG	SAG ASTIG	PETZVAL	DISTORTION
(SA3)	(CO3)	(TI3)	(SI3)	(PETZ)	(DI3(FR))
-0.03453	0.01890	-0.04578	-0.08782	-0.10885	-0.01072

PARAXIAL CHROMATIC ABERRATION SUMS

AX COLOR	LAT COLOR	SECDRY AX	SECDRY LAT
(PAC)	(PLC)	(SAC)	(SLC)
0.01082	-0.00808	0.01093	-0.00385

FIFTH-ORDER ABERRATION ANALYSIS

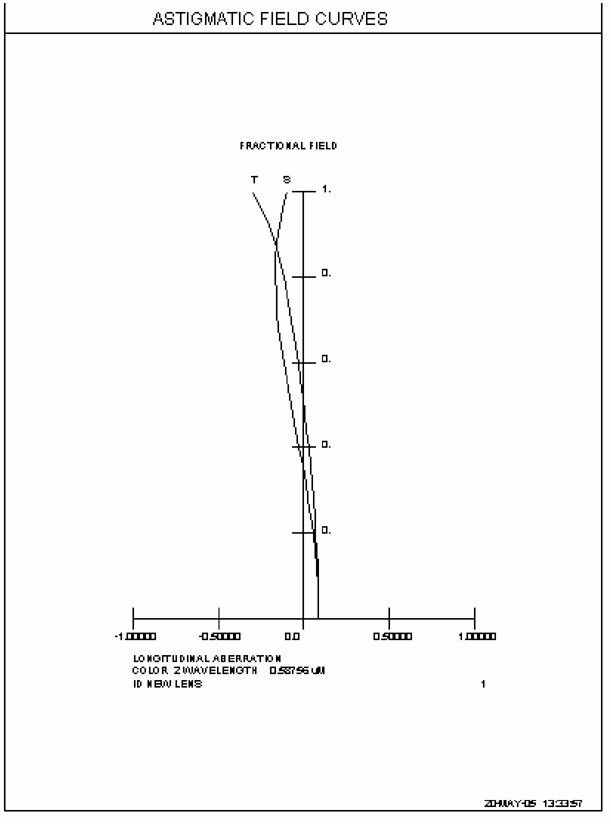
FOCAL LENGTH	ENT PUP SEMI-APER	GAUSS IMAGE HT
100.000	11.110	36.363

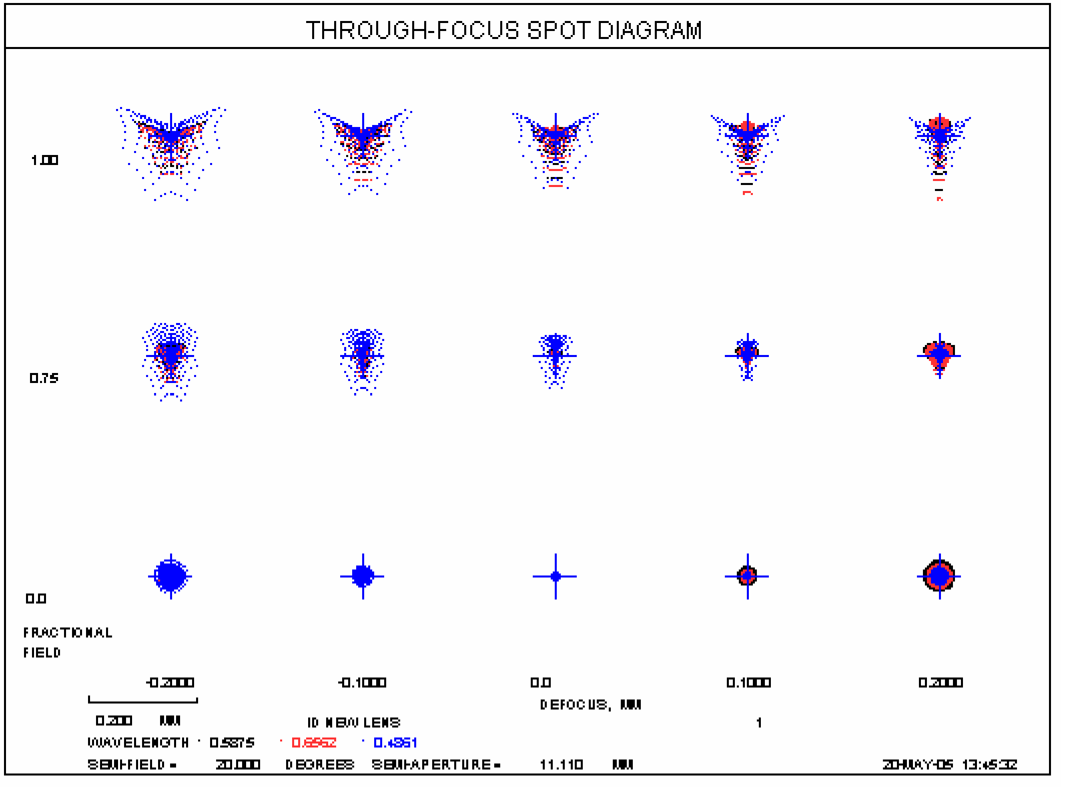
FIFTH-ORDER ABERRATION SUMS

SPH ABERR	COMA	TAN ASTIG	SAG ASTIG	PETZVAL	DISTORTION
(SA5)	(CO5)	(TI5)	(SI5)	(PZ5)	(DI5(FR))
0.01633	-0.03053	0.03510	0.06836	0.07667	-0.00336

TAN OBL SA	SAG OBL SA	ELLIP COMA
(TOBSA)	(SOBSA)	(ECOMA)
0.07551	0.05304	0.04773

Performance of the lens





Tessar
(Personal design project)

Pavel Stejskal

Target

- Design Tessar system with following properties:

	J	W [deg]	F [mm]	L [mm]	Q	S [mm]	D
Value	4.5	20	100	Visual	G	>50	Inside
Index	0	1	1-2	1	0	1	0

- The IC of the system: 4-5

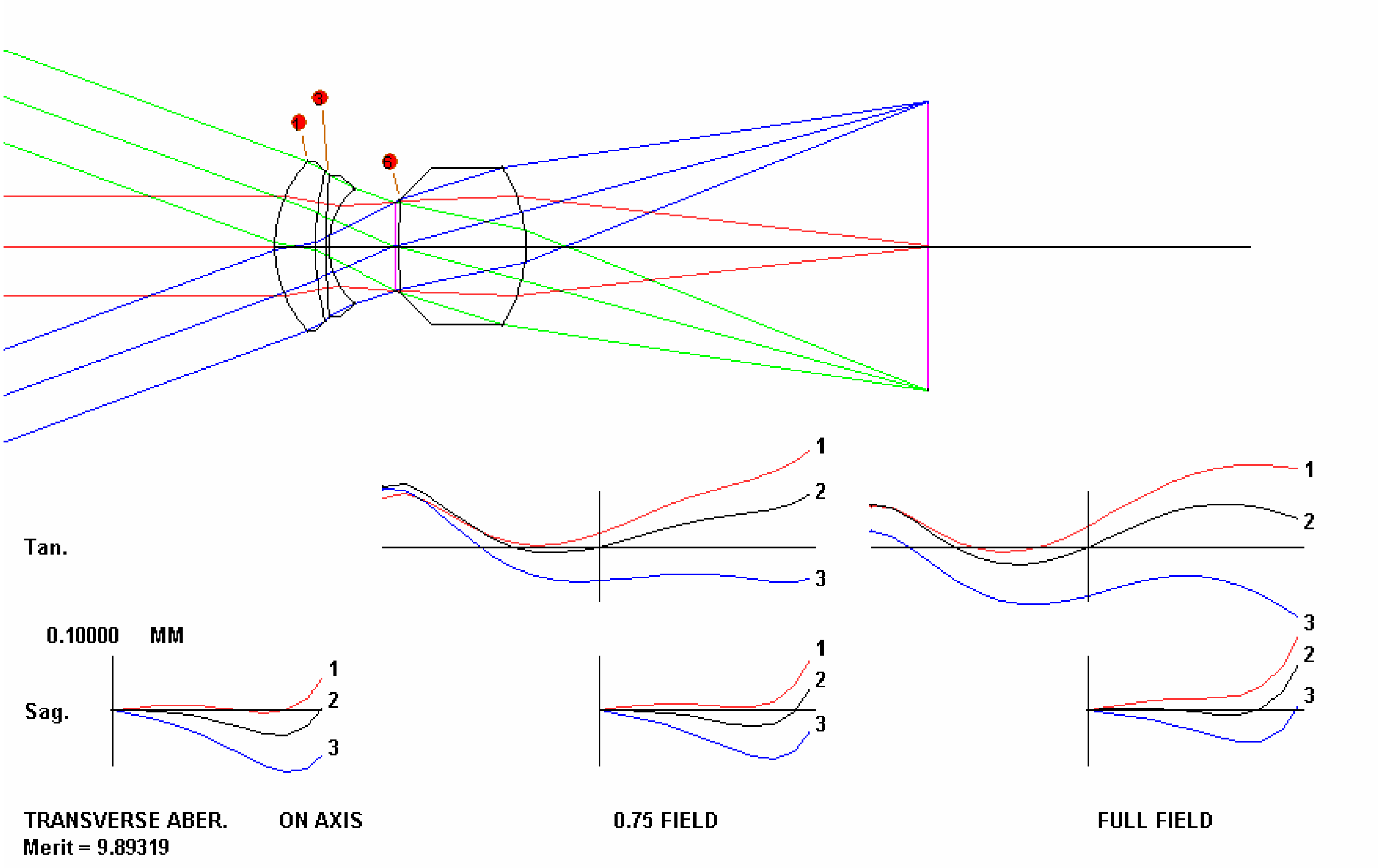
Starting point

- Basic element B(AP) with focal length = 100
- Revert and combine the lens to get a symmetric system. Then insert the negative correction element in front of the aperture.

Performance of the starting point system

- Main aberrations in the system: coma, spherical aberration and chromatic aberration.
- Distortion is very small, other aberrations are in desired limits.
- The optimization was mainly done “by hand”.
- The optimization of the glasses for chromatic aberrations was made alternately with the optimization of curvatures and distances for other aberrations.

Scheme of the starting point system



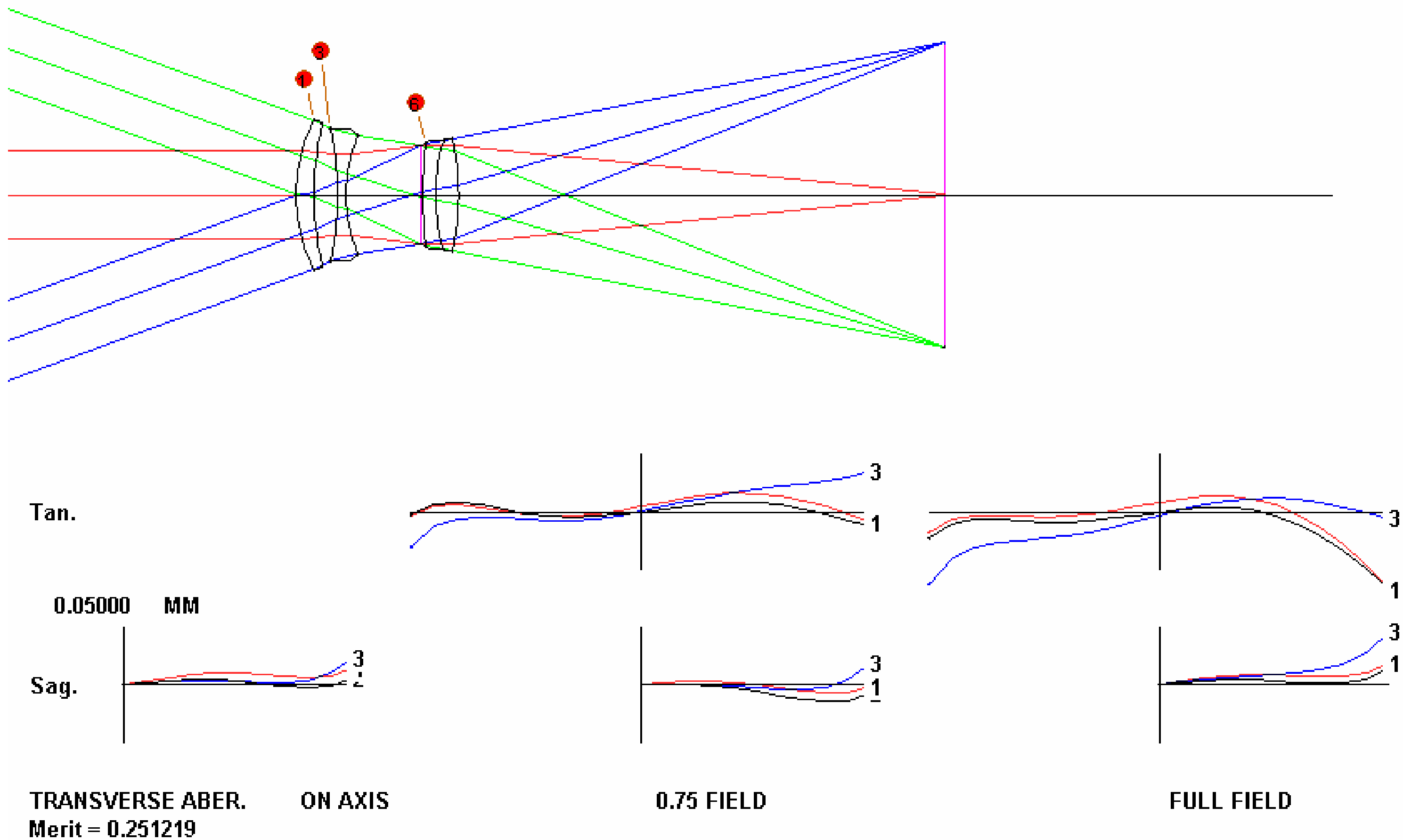
Final System

- To improve the chromatic aberration in the system the last lens was replaced by achromat doublet.
- The optimization process of the final system was the same as in the previous one.

Optimization

- Mainly done by hand
- Using SYNOPSYS optimization tools
  - Parameters: all glasses alternately with all curvatures and all thicknesses (limited interval)
  - Some kicks to the system
  - Merit function:
    - suppress SA3, PAC, PETZ, CO3
    - maintain FOCL = 100 and F# = 4.5
    - predefined merit function #6 (full color grid)
- Optimization successful

Performance of the final system



Performance of the final system II

- **System specifications:**

OBJECT DISTANCE	(TH0)	INFINITE	FOCAL LENGTH	(FOCL)	100.0021
OBJECT HEIGHT	(YPP0)	INFINITE	PARAXIAL FOCAL POINT		109.9570
MARG RAY HEIGHT	(YMP1)	11.0000	IMAGE DISTANCE	(BACK)	109.7599
MARG RAY ANGLE	(UMP0)	0.0000	CELL LENGTH	(TOTL)	36.6294
CHIEF RAY HEIGHT	(YPP1)	-9.9664	F/NUMBER	(FNUM)	4.5456
CHIEF RAY ANGLE	(UPP0)	20.0000	GAUSSIAN IMAGE HT	(GIHT)	36.3635
ENTR PUPIL SEMI-APERTURE		11.0000	EXIT PUPIL SEMI-APERTURE		12.7029
ENTR PUPIL LOCATION		27.3824	EXIT PUPIL LOCATION		-5.5260

- **Surface data:**

SURF	RADIUS	THICKNESS	MEDIUM	INDEX	V-NUMBER
0	INFINITE	INFINITE	AIR		
1	37.20036	4.00037	GLM-NdVd	1.68996S	57.88
2	70.02183	5.33011	AIR		
3	-68.91762	1.95381	GLM-NdVd	1.50000S	74.60
4	35.09767	16.72561	AIR		
APS	-4.40509E+08	0.53744	AIR		
6	108.48664	2.87170	GLM-NdVd	1.80000S	23.78
7	42.87006	5.21040	GLM-NdVd	1.72101S	55.15
8	-55.22327	109.75992S	AIR		
IMG	INFINITE				

Performance of the final system III

- **System aberrations (3rd order):**

- THIRD-ORDER ABERRATION SUMS

	SPH ABERR	COMA	TAN ASTIG	SAG ASTIG	PETZVAL	DISTORTION
	(SA3)	(CO3)	(TI3)	(SI3)	(PETZ)	(DI3(FR))
	-0.08955	0.09965	0.01007	-0.08887	-0.13834	-0.05649

- PARAXIAL CHROMATIC ABERRATION SUMS

	AX COLOR	LAT COLOR	SECDRY AX	SECDRY LAT
	(PAC)	(PLC)	(SAC)	(SLC)
	0.02304	-0.00284	0.01784	0.00314

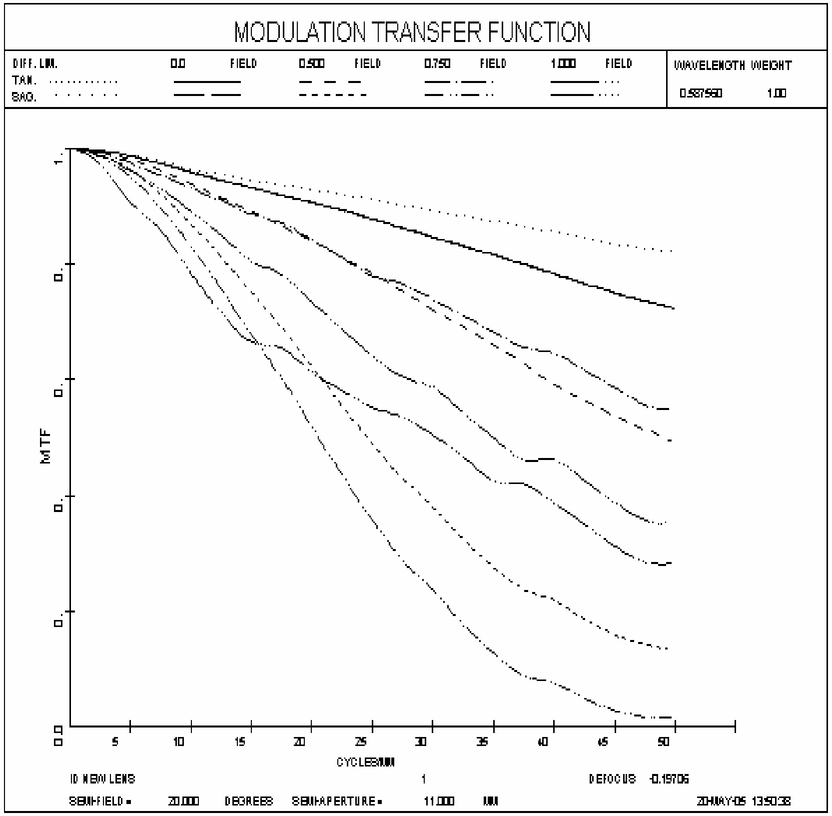
- **System aberrations (5th order):**

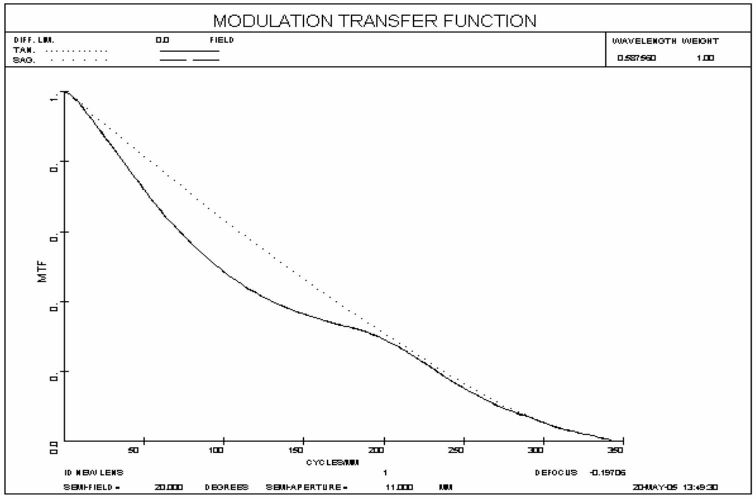
- FIFTH-ORDER ABERRATION SUMS

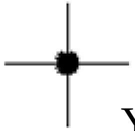
	SPH ABERR	COMA	TAN ASTIG	SAG ASTIG	PETZVAL	DISTORTION
	(SA5)	(CO5)	(TI5)	(SI5)	(PZ5)	(DI5(FR))
	0.06656	-0.04193	0.00066	0.09428	0.11768	0.00090

	TAN OBL SA	SAG OBL SA	ELLIP COMA
	(TOBSA)	(SOBSA)	(ECOMA)
	-0.04192	0.00334	-0.07195

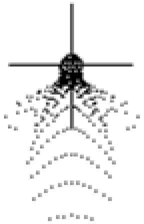
Performance of the final system IV







Y = 0

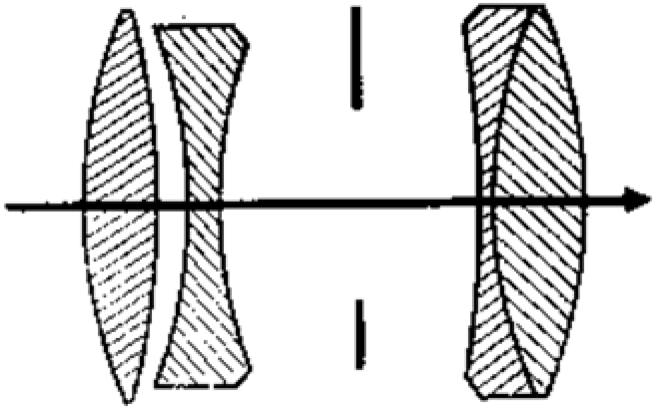


Y = 1

Scale: 50 µm

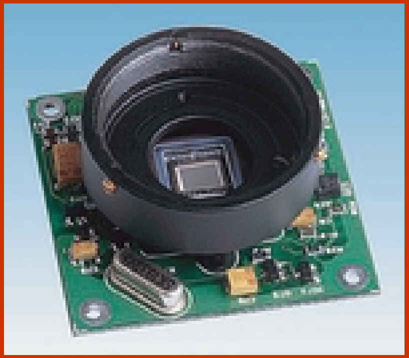
Tessar applications

- Originally designed by Paul Rudolph in 1902 for the Carl Zeiss company.
- Mainly used as objectives in cameras.



Background

- CCD available from ELFA (550 SEK)
- CCD size: 4.4 x 3.3 mm (512 x 582 pixels)
- Pixel size: 8.6 x 5.7 um
- Sensitivity: 0.4 lux
- Weigth: 30 g



Target System:

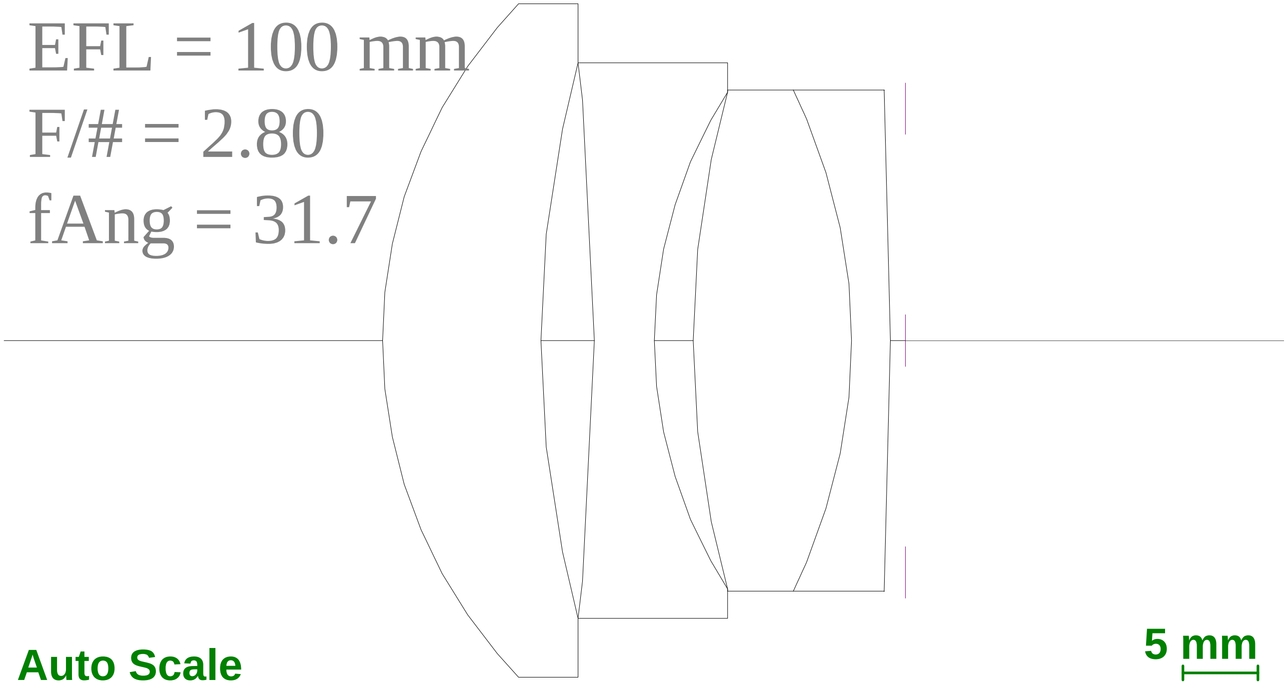
- Compact
- Low weight
- Pixel limited resolution
- As low F/# as possible

Specification

- F/# = 4.9
  gives ~390 lux on CCD
  diffraction limit ~ 3 um
- Field angle = 24.6 degrees (fills the diagonal)
- Focal length = 6 mm
- Wavelength range: Visible
- Maximum spatial frequency: 88 mm^-1
- Back focal length: Any
- Aperture position: Any

Starting Point

- Tessar System from LensView with patent number 4,676,607



Index Of Complexity

J	W	F	L	Q	S	D
4.9	24.6˚	6 mm	Visual	G	Any	Any
0	1	0	1	0	0	1

IC = 3

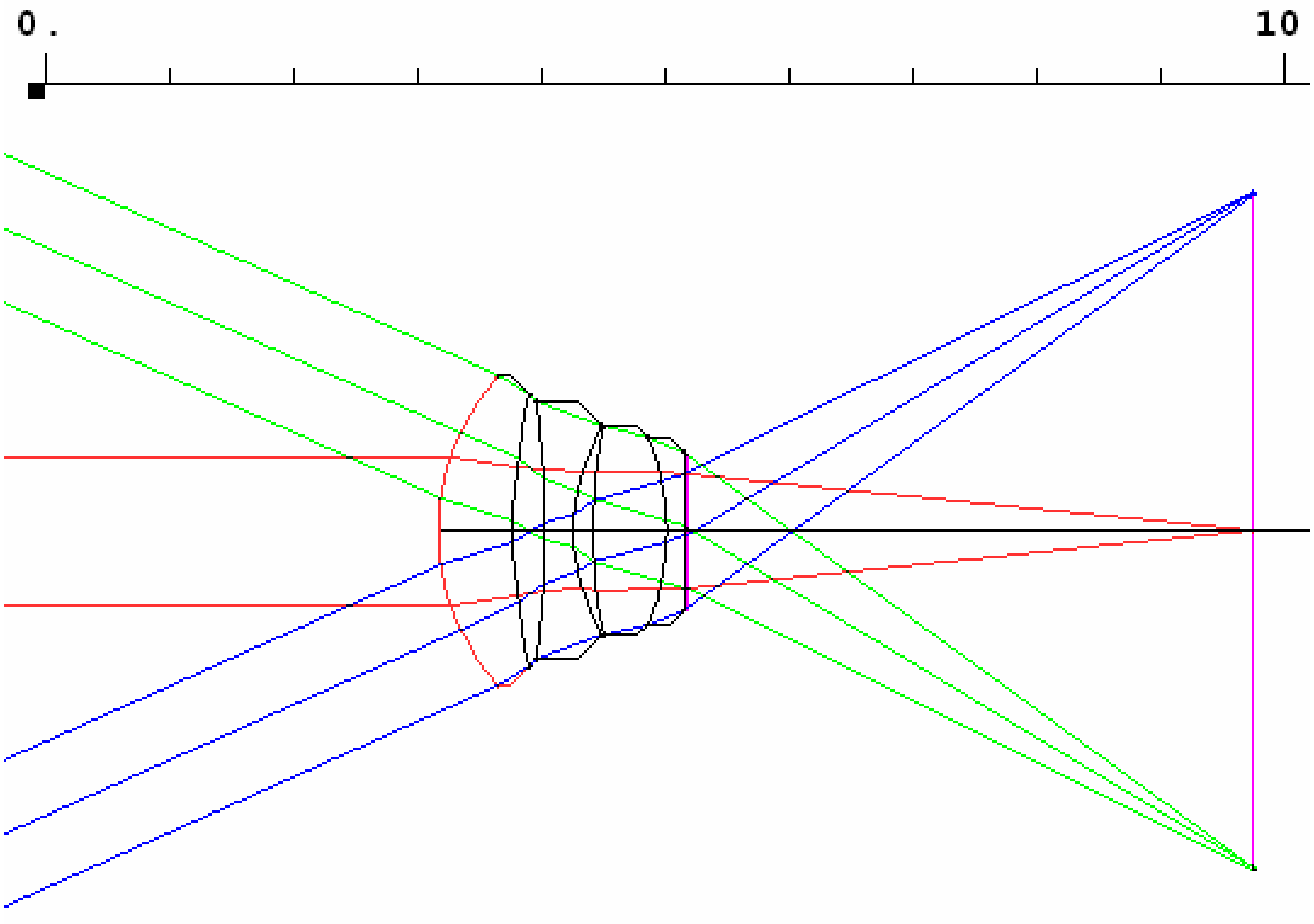
Adaptation Of Focal Length And F/#

- Starting point diffraction limited for F/# = 10 and field angle of 24.6 degrees.
- Focal length scaled to 6 mm
- Gradual reduction of F/# to avoid lenses from intersecting
- Replacing glass materials to vendor materials
- Tolerancing curvatures and thicknesses

Optimization Scheme

- MOM script was used to change the curvatures (prepared # 6+FOCL+3RD+5TH)
- Distance between lenses was made by hand to avoid lenses from intersecting
- Final system not stable when MOM script is applied?!

Optical System F/# = 4.9



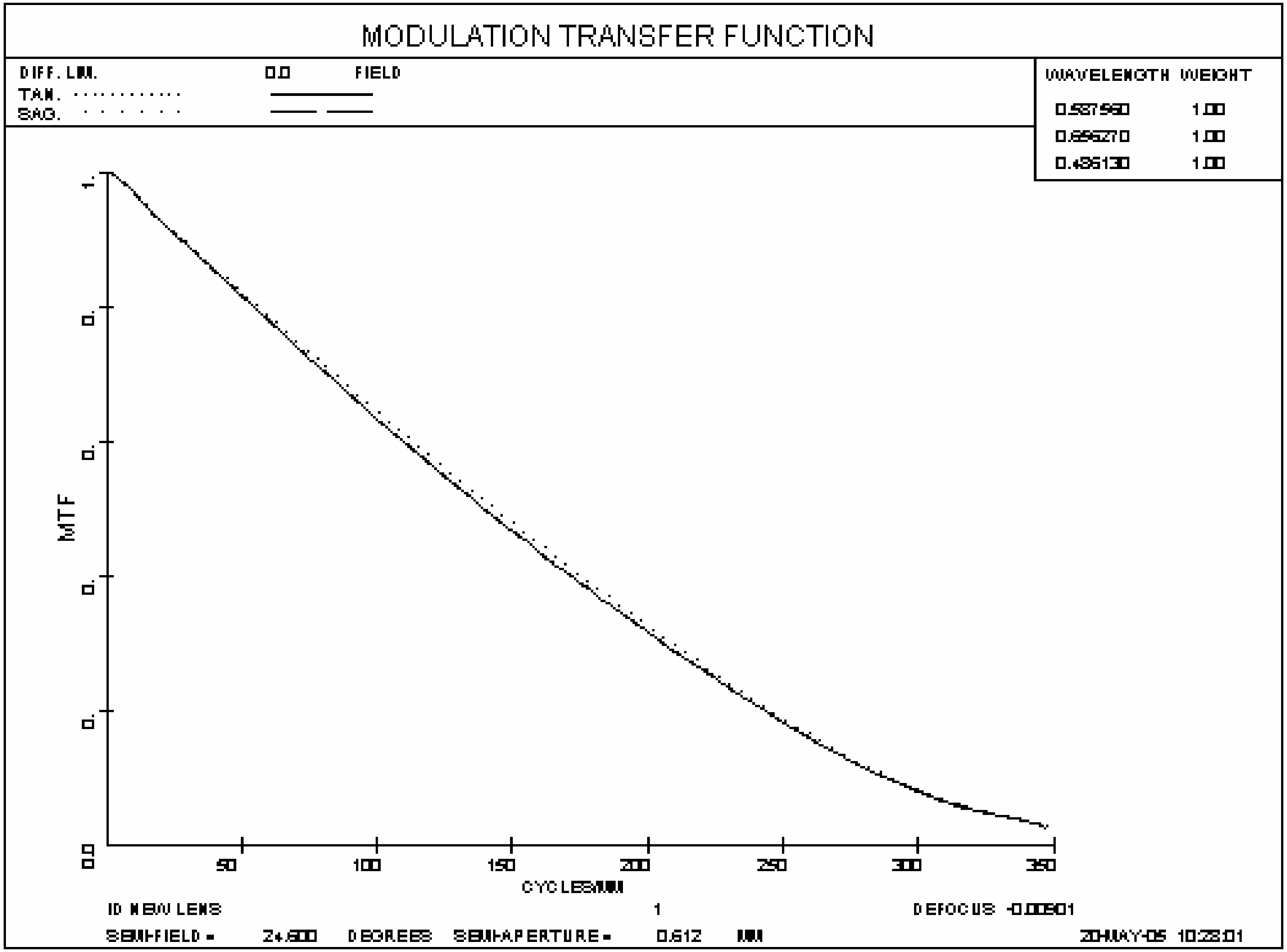
System Specifications

OBJECT DISTANCE	(TH0)	INFINITE	FOCAL LENGTH	(FOCL)	5.9958
OBJECT HEIGHT	(YPP0)	INFINITE	PARAXIAL FOCAL POINT		4.5890
MARG RAY HEIGHT	(YMP1)	0.6122	IMAGE DISTANCE	(BACK)	4.5800
MARG RAY ANGLE	(UMP0)	0.0000	CELL LENGTH	(TOTL)	2.0000
CHIEF RAY HEIGHT	(YPP1)	-0.8900	F/NUMBER	(FNUM)	4.8966
CHIEF RAY ANGLE	(UPP0)	24.6000	GAUSSIAN IMAGE HT	(GIHT)	2.7397
ENTR PUPIL SEMI-APERTURE		0.6122	EXIT PUPIL SEMI-APERTURE		0.4686
ENTR PUPIL LOCATION		1.9439	EXIT PUPIL LOCATION		0.0000

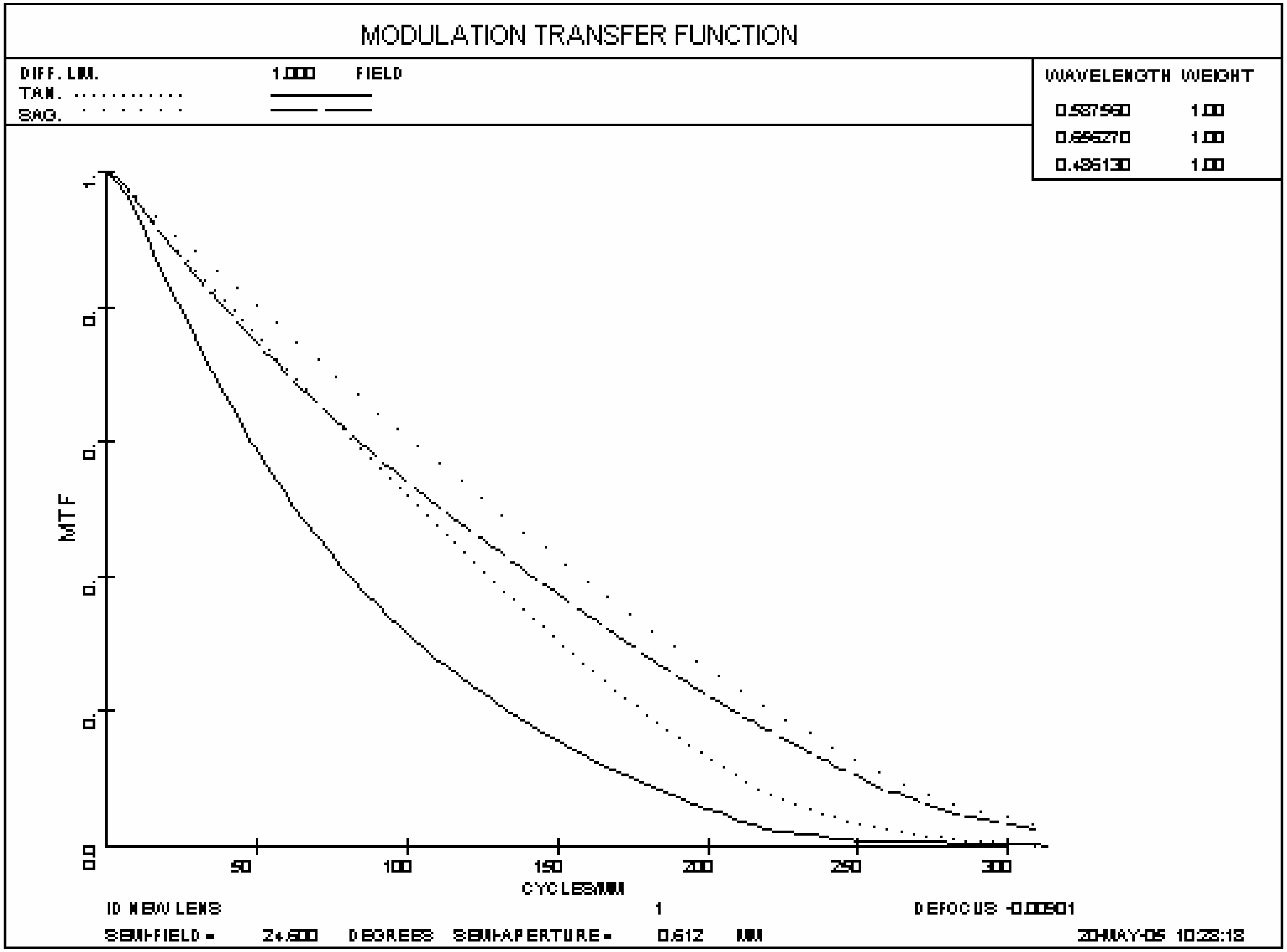
SURFACE DATA

SURF	RADIUS	THICKNESS	MEDIUM	INDEX	V-NUMBER
0	INFINITE	INFINITE	AIR		
1	1.94000	0.60000	N-LAF34	1.77250	49.62 SCHOTT
2	4.57000	0.26000	AIR		
3	-8.37000	0.23000	SF1	1.71736	29.51 SCHOTT
4	1.76000	0.15000	AIR		
5	3.70000	0.60000	N-LASF30	1.80318	46.38 SCHOTT
6	-2.07000	0.15000	BK7	1.51680	64.17 SCHOTT
7	-21.32000	0.01000	AIR		
APS	INFINITE	4.58001S	AIR		
IMG	INFINITE				

On Axis MTF


MODULATION TRANSFER FUNCTION
DIFF. LIM.
TAN.
SAG.
0.0 FIELD
WAVELENGTH WEIGHT
0.587560 1.00
0.656270 1.00
0.486130 1.00
MTF
CYCLES/MM
ID NEW LENS
DEFOCUS
SEMI-FIELD =
DEGREES
SEMI-APERTURE =
0.612
MM

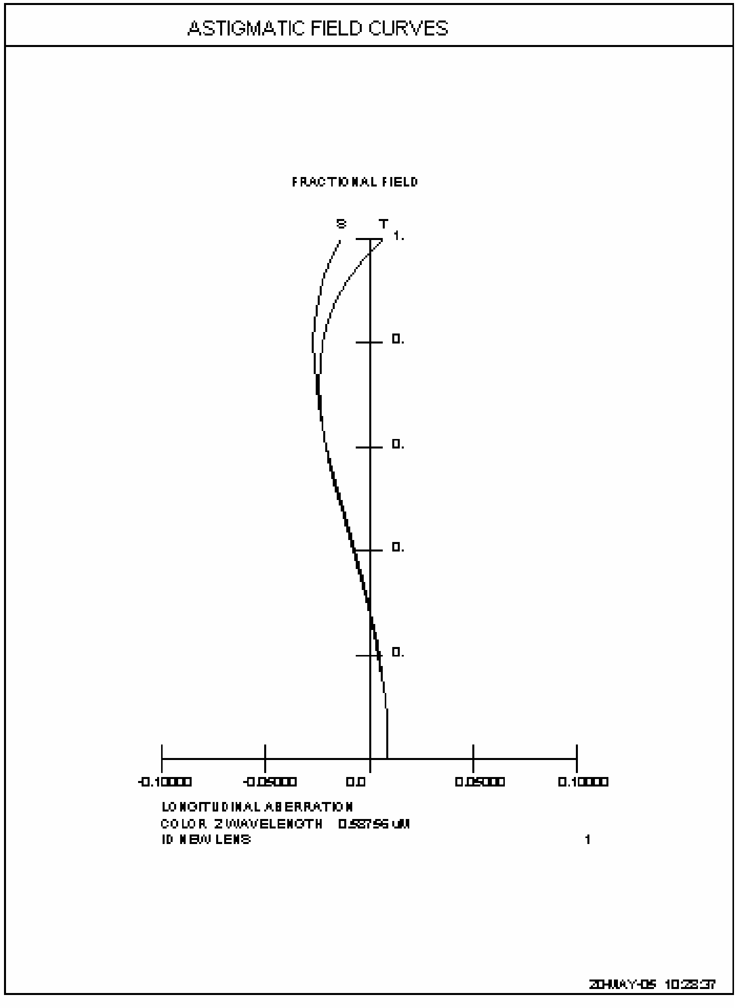
Off Axis MTF



MODULATION TRANSFER FUNCTION
DIFF. LIM.
TAN.
SAG.
FIELD
WAVELENGTH WEIGHT
MTF
50
100
150
200
250
300
1
DEFOCUS
DEGREES

Field Curvature

Depth of focus for the system is 24 um, which is comparable with the amount of field curvature for the system (27 um).



Application Recommendation

Filthy Rich RC Freaks!