Tutorial

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Practical tutorial: A simple strategy to start a pinhole lens design

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Abstract: Modern lens design software improves the performance of a given design. However, a novice may not have a suitable starting design available. This paper presents several methodologies that can be applied to a variety of optical design problems, in order to generate a configuration with a high likelihood of meeting a set of goals.

Keywords: merit function; optical design; optimization; pinhole lens; starting point.

1 Introduction

When a beginner first confronts an optical design software, he will likely experience some confusion as to where and how he should start. This publication is intended to help a novice designer overcome the first hurdle – that of starting point selection. We use a pinhole lens example and work the problem on the SYNOPSYS™ lens design program (SYNOPSYS™ is a trademark of Optical Systems Design, Inc., East Boothbay, Maine, USA).

Of course, one can invest in special training, which can give a young optical designer some of the skills and confidence needed in this important and interesting field. The course called SMETHODS [1] is an example of this kind of instruction. However, not everyone is in a position to take a training course. In this paper, we would like here to share some simple recommendations resulting from our experience in teaching practical optical design to many students in various countries.

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What does one need to start a project in practical optical design?

- Knowledge in optics, first of all;
- Special optical design software and some understanding of how to use it; and
- Strong desire to succeed.

For first-time users of optical design software, we recommend that you select a program that offers a free demo or trial version. This will help reduce your cost yet still give you an idea what lens design is all about and what tools you will have available.

1.1 The first step

Most design tasks start with an analysis of the customer's request. This is where the optical designer will get the data to put into the software. When the basic requirements of the customer are clear, many designers may first try to find an existing solution with similar technical requirements from books, patents, their own archives, and so on, because access to an appropriate database can speed up the selection process. Some theoretical approaches can also help to create a starting point 'from scratch' [2, 3].

At this step, you have to decide which surfaces you are going to use – refractive only, reflective, or a combination. Usually, it is not difficult to determine this, but keep in mind that the use of mirrors is not recommended for fast or wide angular systems. Reflective or catadioptric optical systems work best for wide-spectrum designs, long focal-length lenses, and systems with a small field of view. Some typical customer specifications for a pinhole lens are given in Table 1. For this task we decide that our pinhole lens will only have refractive surfaces.

1.2 Example of a pinhole lens design

To clarify this process, we used these requirements to design a pinhole lens. This kind of lens [4] is a popular design form with various applications, the most important

Table 1: Example of customer's requirements.

Customer's request	Technical specification	General specification[a]
J – F/number	F/4.5	0
W – angular field	90°	2
F – focal length	4.5 mm	0
L – spectral range	0.486–0.652 µm	1
Q – quality requirements	Geometrically limited	0
S – back focal length	2 mm	1
D – position of aperture stop	Removed forward	2
	R designates index of complexity	6

[a]I. Livshits, V. Vasilyev, Q & A tutorial on optical design, Adv.Opt. Techn. 2013; 2(1): 31–39.

Table 2: Options for starting point selection.

Customer's request	Technical specification	General specification[a]
J – F/number	F/4.5	0
W – angular field	90°	2
F – focal length	4.5 mm	0
L – spectral range	0.486–0.652 µm	1
Q – quality requirements	Geometrically limited	0
S – back focal length	2 mm	1
D – position of aperture stop	Removed forward	2
	R designates index of complexity	6

[a]I. Livshits, V. Vasilyev, Q & A tutorial on optical design, Adv.Opt. Techn. 2013; 2(1): 31–39.

of which are for covert video surveillance, mobile phone camera lenses, f-theta lenses, underwater lenses, and so on. An example of one of these is shown in Figure 1.

In Table 1, we show a typical customer's specification for a pinhole lens. In this table, the quantity R refers to an index of complexity. The meaning of these general classifications and index of complexity are explained in references [2, 3, 5]. Table 2 shows some of the options for selecting a starting point, and from these, the designer must choose at least one. After one decides which option best suits the needs, he then inserts the data for a selected starting design into an optical design program, both to judge the quality of that lens and use it as a guide in making a decision about the next steps.

Aberration analysis will probably be useful in the design process, especially in selecting variables for optimization. Sometimes it is useful to calculate 3rd and 5th order aberrations to determine the influence of each surface in your optical scheme, as well as the lenses thicknesses and separations between elements on those aberrations. Several software programs are available on the market for doing these calculations.

In Table 3, we explain several specification parameters that can be useful for beginners. We recommend inserting the specifications first, because doing so is simple and you may already have all the data from the customer's request.

2 System data (specification) input

The object position is the first item we insert, because it makes a difference if the system works from a finite distance or from infinity. Even the units of the specifications will be different (see Table 4). In this step one first needs to select a suitable optical design program; we used SYNOPSYS™ [6]. When the program is opened, the system data are entered as shown in Figure 2. The next step is to insert some starting lens parameters and begin the calculations.

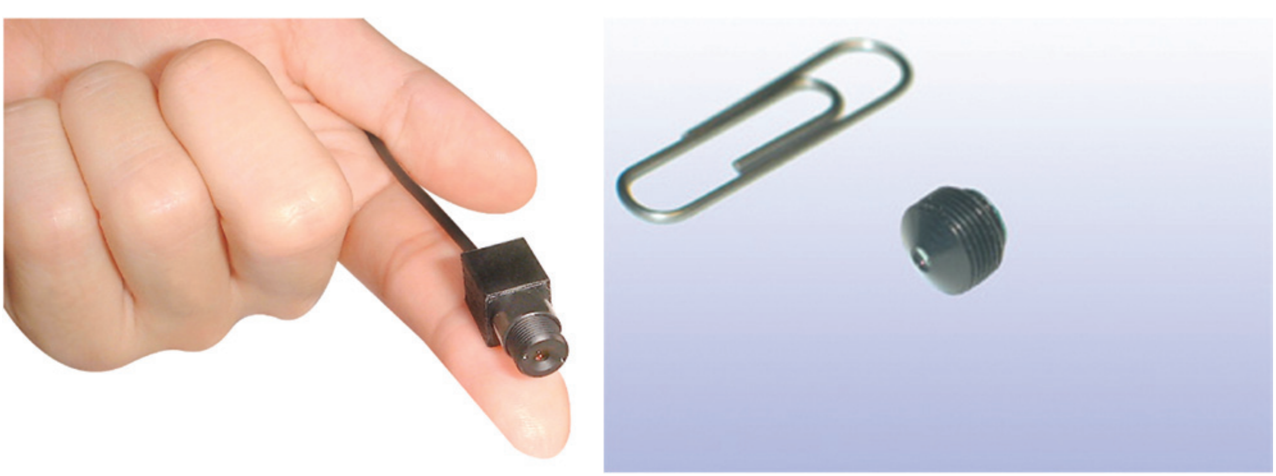

Figure 1: A pinhole lens.

Table 3: Explanations of the specifications and parameters.

Specifications (target) come from customer's request	Parameters come from starting point selection, and are the responsibility of the designer
System data	Surface data: radii, aspheric coefficients, other shape data
Object, image, positions	Thickness, distance between surfaces
Aperture	Material (depends on spectral range)
Field of view	Position of aperture stop
Magnification (if the lens is focal)	
Spectral range	
System quality (depends on the nature of the receiver)	
Position of aperture stop (sometimes given as a design parameter).	

Table 4: Influence of object position on the specification input.

Specification from customer's request	Infinite object – units	Finite object – units
Aperture	Linear units – mm, inches	Angular units
Objects size	Angular units	Linear units – mm, inches
Object position	Infinity	Linear units – mm, inches

2.1 Starting from a patent

If you take the starting parameters from patent data, you simply enter the data and jump immediately to the next step, system evaluation. In Figure 3, the data were taken from a Russian patent [5]. Then you can evaluate the image quality and, if necessary, optimize the lens to meet the customer's request.

In this example, the field of view of the lens from the patent was 70°, but the customer requested 90°. Thus, we increased the field of view and reoptimize the lens. Figure 4 shows this lens with the field enlarged. It is obvious that some improvement is needed – the rays do not go through, as shown in the red arrow in Figure 4. This vignetting comes from the insufficient thickness of the third lens.

These are the steps we can take to improve the situation:
– Add thickness;
– Decrease field; and
– Decrease aperture.

In any case, whether you succeed in finding a suitable patent, after performing a search you will likely get a clearer understanding how many elements your future design will have, which is a step in the right direction.

2.2 Starting from a vendor's catalogue

One can start from a vendor's catalogue if the parameters of the optical system are given, such as those outlined in Table 3. If all the lens parameters are provided, they can be encoded into the optical design software and then you learn whether the catalogue lens fits the customer's request. In our pinhole lens example, we found no stock lens that fit the customer's request. This means that we have to try a different option for finding a starting point.

2.3 Letting the software find the starting point

What options for finding a starting point can we expect from the lens design software itself? A longstanding notion is to start with plane-parallel plates and then optimize from there. Students sometimes try to start a design that way, but the results depend strongly on which lens design program is being used. Different programs have different optimization algorithms, and most of those do poorly with such starting points. One reason we selected SYNOPSYS™ for this exercise is that its PSD [7, 8] algorithm is more robust and can quickly find reasonable lenses, given a set surfaces that are flat or nearly so. This idea is discussed in more detail below.

One objection to this approach, however, is that the designer gains little insight into *how* and *why* a lens works when the computer does all the work for him. In fact, some designers prefer to rely on their own insight instead of on the computer. There is one modification of this 'lazy' method that usually works, even on other programs.

2.3.1 Using optimization

If you start with surfaces that are not all flat, for example, if you put in one positive lens with a focal length equal to the focal length requested by the customer, you get a starting point, such as that shown in Figure 5. The system specifications of this starting lens are given in Table 4. Note that for all following optical systems we specified some basic requirements as listed below.

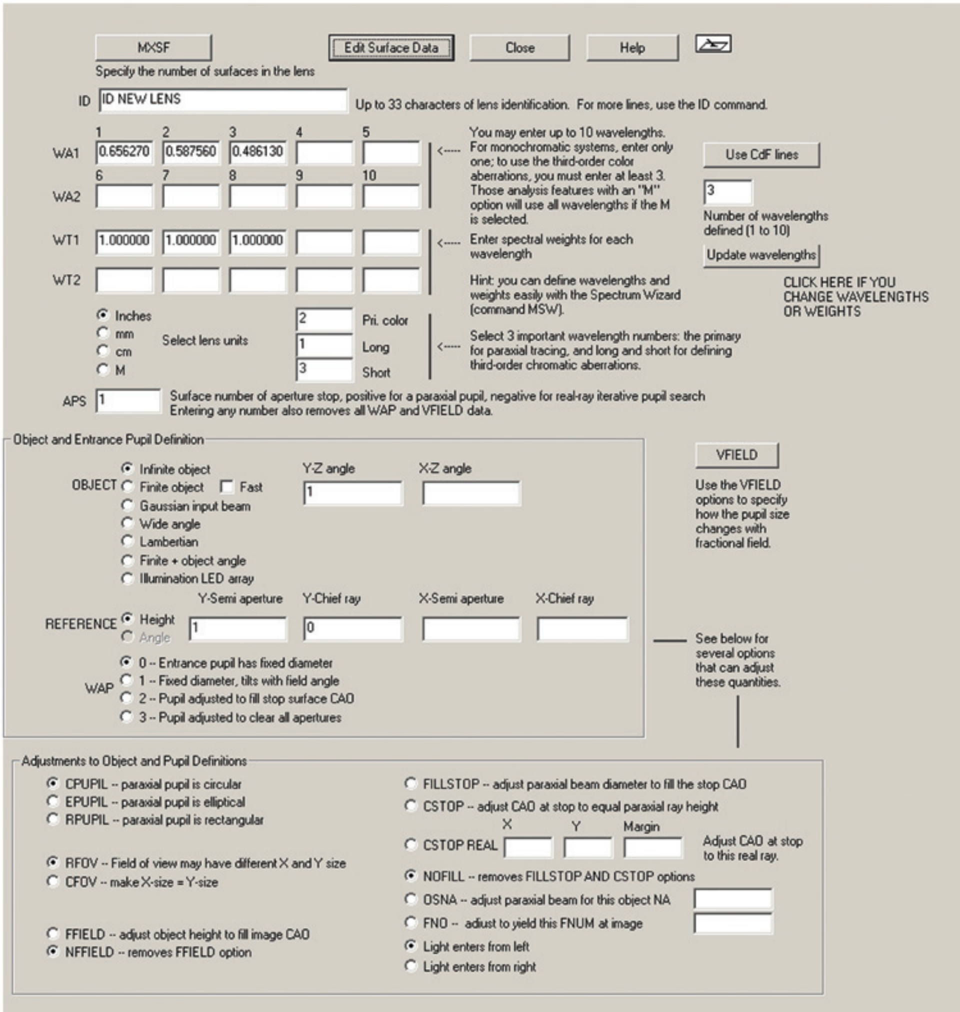

Figure 2: The system editor page of SYNOPSYS.

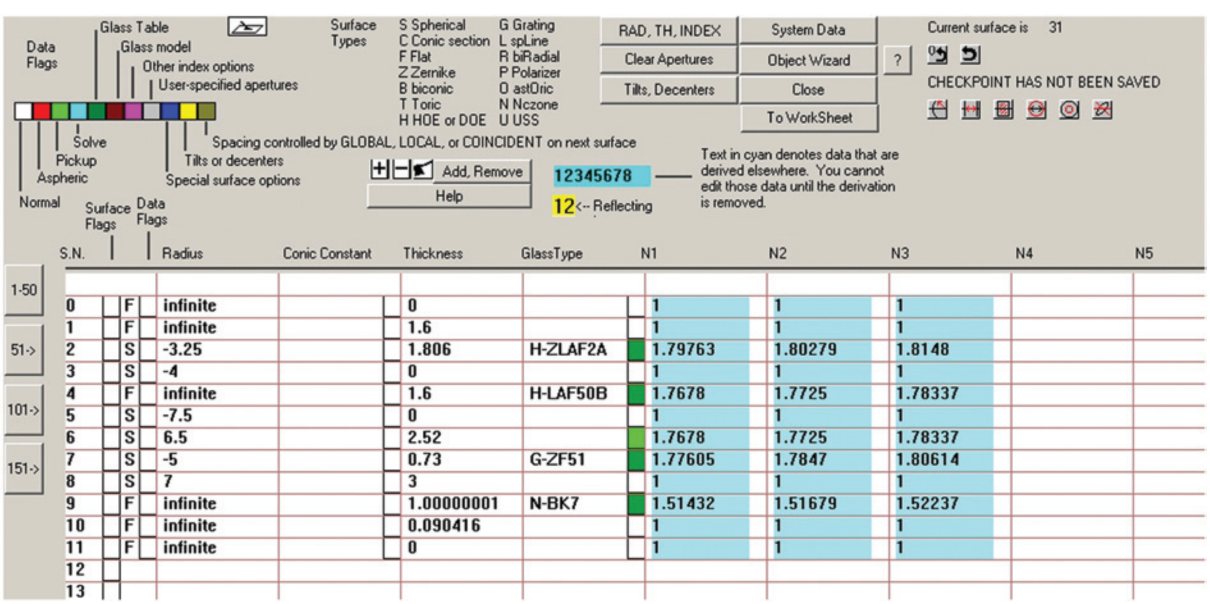

Figure 3: Sample SYNOPSYS spreadsheet with patent data entered.

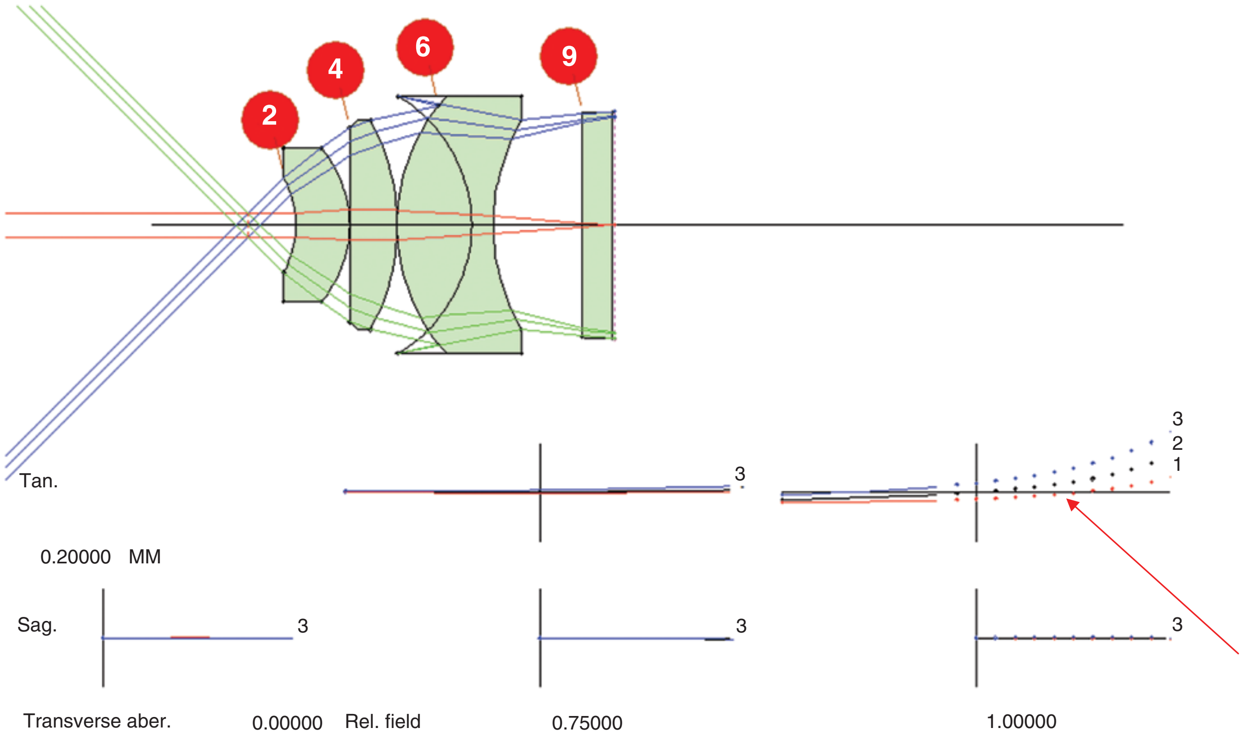

Figure 4: Lens from the patent with an enlarged field as per customer's request.

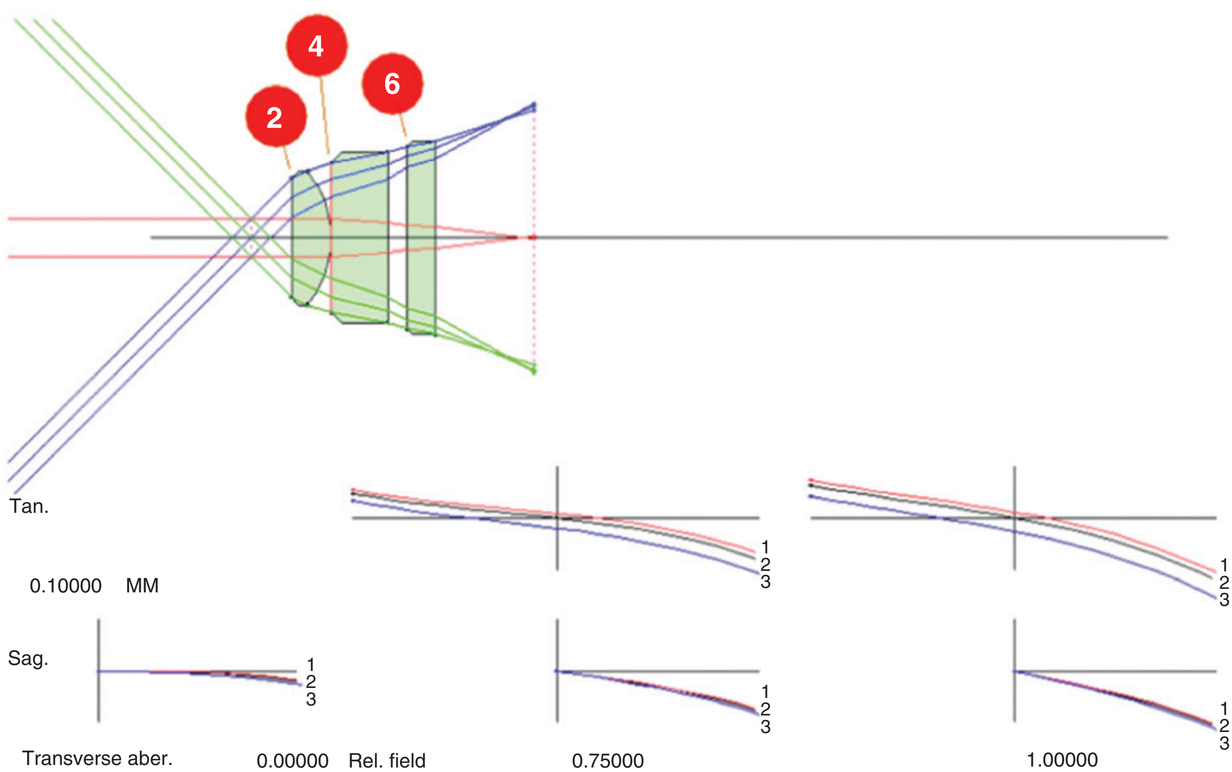

Figure 5: Starting point from one positive lens and two plane parallel plates.

Table 5: System specifications for lens shown in Figure 5.

Specification	Value	Specification	Value
OBJECT DISTANCE (THO)	INFINITE	FOCAL LENGTH (FOCL)	4.5000
OBJECT HEIGHT (YPP0)	INFINITE	PARAXIAL FOCAL POINT	2.6104
MARG RAY HEIGHT (YMP1)	0.5000	IMAGE DISTANCE (BACK)	2.6104
MARG RAY ANGLE (UMP0)	0.0000	CELL LENGTH (TOTL)	4.8304
CHIEF RAY HEIGHT (YPP1)	0.0000	F/NUMBER (FNUM)	4.5000
CHIEF RAY ANGLE (UPP0)	45.0000	GAUSSIAN IMAGE HT (GIHT)	4.5000
ENTR PUPIL SEMI-APERTURE	0.5000	EXIT PUPIL SEMI-APERTURE	0.8056
ENTR PUPIL LOCATION	0.0000	EXIT PUPIL LOCATION	-4.6399

Table 6: Specifications for the lens in Figure 6.

Specification	Value	Specification	Value
OBJECT DISTANCE (THO)	INFINITE	FOCAL LENGTH (FOCL)	4.5353
OBJECT HEIGHT (YPP0)	INFINITE	PARAXIAL FOCAL POINT	1.2018
MARG RAY HEIGHT (YMP1)	0.5000	IMAGE DISTANCE (BACK)	1.2018
MARG RAY ANGLE (UMP0)	0.0000	CELL LENGTH (TOTL)	7.2371
CHIEF RAY HEIGHT (YPP1)	0.0000	F/NUMBER (FNUM)	4.5353
CHIEF RAY ANGLE (UPP0)	45.0000	GAUSSIAN IMAGE HT (GIHT)	4.5000
ENTR PUPIL SEMI-APERTURE	0.5000	EXIT PUPIL SEMI-APERTURE	0.5479
ENTR PUPIL LOCATION	0.0000	EXIT PUPIL LOCATION	-3.7683

Spectrum range WAVL (uM) 0.6563000 0.5876000 0.4861000
WEIGHTS 1.000000 1.000000 1.000000
COLOR ORDER 2 1 3
UNITS MM
APERTURE STOP LOCATION IS IMPLIED BY THE VALUE OF YP1
WIDE-ANGLE PUPIL OPTION (WAP) 1
FOCAL MODE ON
MAGNIFICATION-4.50000E-12
POLARIZATION AND COATINGS ARE IGNORED.

Table 5 gives the specifications for the same system after simple optimization in SYNOPSYS. Optimization is a very important part of the optical design process, but here, we do not go into detail because it is a subject for a different publication. Surface data for optimized system are given in Table 6. We used one of the default merit functions from SYNOPSYS to start the process. Later, we may optimize with a specially created merit function to obtain performance that better fits the customer's request.

2.3.2 Comments on Figures 5 and 6.

From Tables 4 and 5 we can see that our lens, after optimization, fits the customer's request. In Figure 5 shows the starting point for our pinhole lens (one positive lens and two plane parallel plates), and Figure 6 shows the starting lens after optimization. When we compare these two figures, we see that we now have two positive lenses and one negative lens. The scale of the aberration plot has decreased from 0.1 to 0.02 mm, so we obtained a pinhole lens that is five times better than the starting point.

We used all radii, all thicknesses, and all glasses as variables for optimization. The default standard SYNOPSYS merit function was used to define the aberrations for correction. The result achieved in Figure 6 could be used to continue optimization until the requested image quality is achieved, which is determined by the customer upon identifying in which receiver the pinhole lens is going to be used.

2.3.3 Using DSEARCH™

A global-optimization feature of SYNOPSYS provides a very handy way to create a starting point. This feature is called DSEARCH [9], and it operates automatically in a manner similar to that described above. The program generates a set of prototype elements, usually with very low power, and then optimizes a collection of candidate lenses formed by assigning positive or negative power to those elements. It has several modes of operation, but a

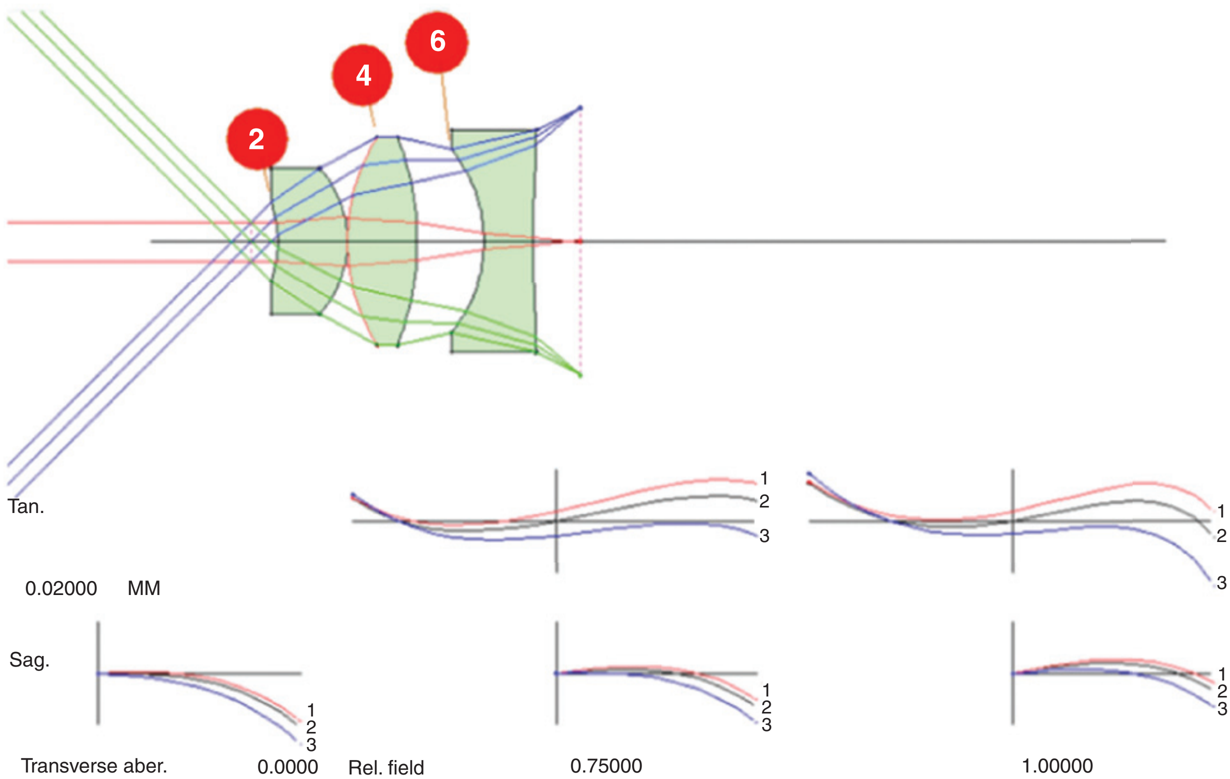

Figure 6: The lens from Figure 5 after optimization.

very efficient one examines every possible combination of positive and negative powers, in binary order. A variety of potential starting lenses is usually obtained in a just a few minutes. In order to illustrate the power of this method, we create the following input to DSEARCH:

```
DSEARCH 1 QUIET
SYSTEM
ID DSEARCH SAMPLE
OBB 0 45 0.5
WAVL 0.6563 0.5876 0.4861
WAP 1
UNITS MM
END
GOALS
ELEMENTS 3
FNUM 4.5
BACK 2 1
TOTL 0 0
STOP FIRST
STOP FREE
RT 0
FOV 0.0 0.75 1.0 0.0 0.0
FWT 5.0 3.0 1.0 1.0 1.0
NPASS 10
ANNEAL 200 20 Q
COLORS 3
SNAPSHOT 10
QUICK 10 20
END
SPECIAL AANT
AAE.1 1.1
AGE.5 1.1
LLL 1.7 1.1 A BACK
S P ZA 1 0 0 0 LB1
M 0.3 10 A P YA 1 0 0 0 1
END
GO
```

(Details of this input can be found in the SYNOPSYS™ User's Manual). After running this job, we get an attractive lens, and after some additional optimization, we obtain the results shown in Figure 7. The program selects the 10 best candidates and shows them on a drawing; an excerpt is given in Figure 8. The specification for the starting point created by DSEARCH is presented in Table 7 and surface data for this variant are given in Table 8.

From this method we developed a different starting point for this lens; now it has a slightly negative first lens and two positive lenses, as shown in Figure 7. The scale for the aberration plots is 0.02 mm, which is very good for the starting point.

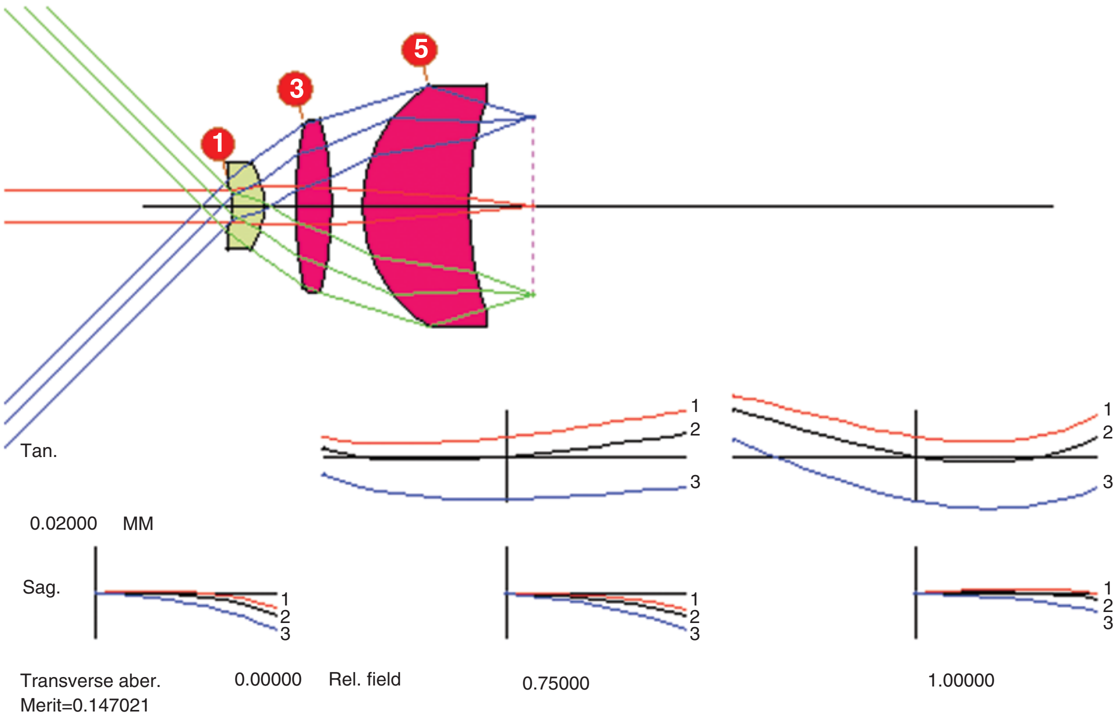

Figure 7: Starting point produced by DSEARCH, a feature of SYNOPSYS™.

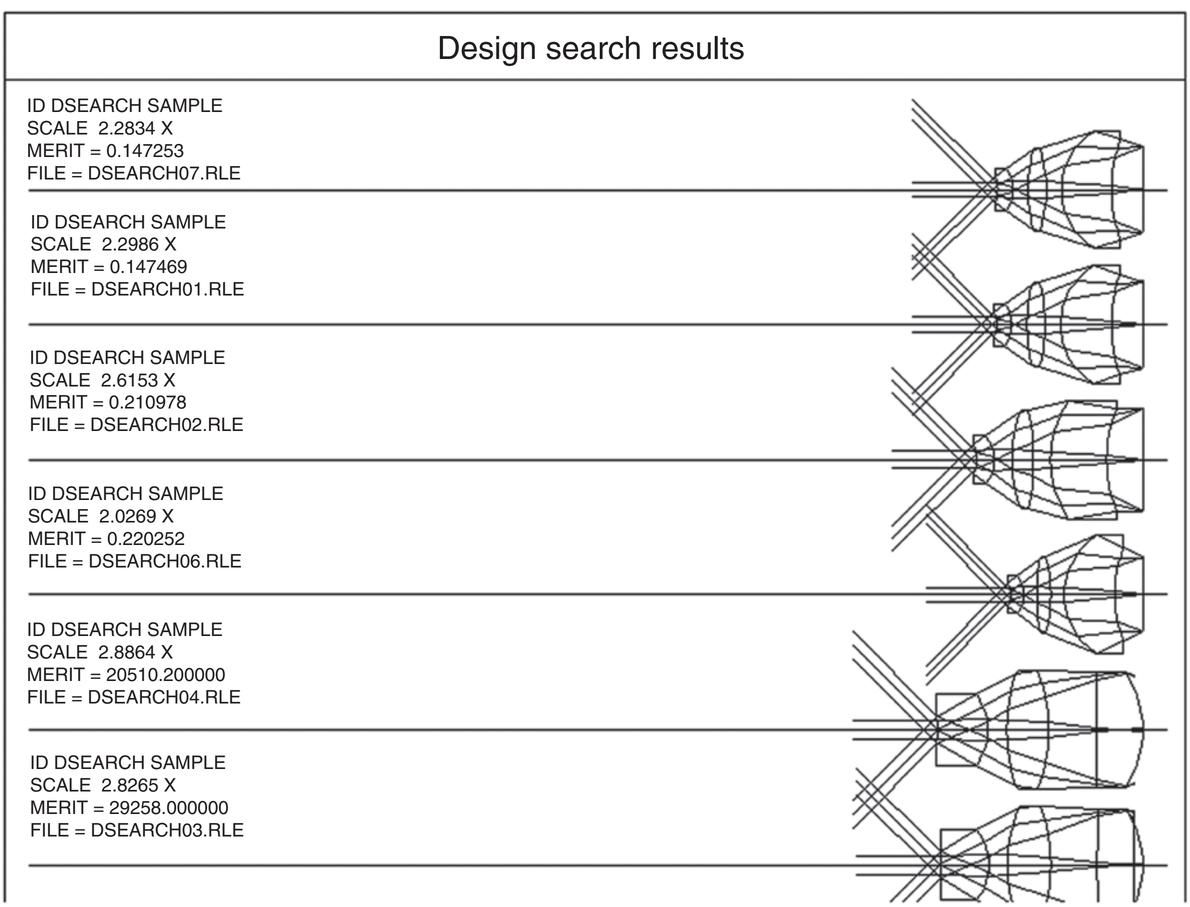

Figure 8: A portion of the DSEARCH results.

Table 7: Surface data for the lens in Figure 7.

Surface no	Radius	Thickness	Medium	Index	V-number
0	INFINITE	INFINITE	AIR		
1	INFINITE	0.68829	AIR		
2	-3.18590	1.77742	GLM	1.66250S	59.02
3	-2.76272	0.00000	AIR		
4	5.04380	1.80715	GLM	1.618850S	62.98
5	-7.41382	1.70708	AIR		
6	-3.73230	1.25712	GLM	1.80000S	25.05
7	50.43883	1.20179S	AIR		
IMG	INFINITE		AIR		

2.3.4 Modifying a design with the Saddle-Point-Build method

As it appears there is no better configuration with only three elements, we can try four. Here, we used the saddle-point-build feature of SYNOPSYS™. This method, unlike DSEARCH, can investigate cemented elements as well as air-spaced. DSEARCH has created an optimization MACro automatically, and we simply added a line at the top:

AEI 2 1 6 CEMENT

This activates the Automatic Element Insertion feature, which is a special case of the saddle point method. (Details of this format can also be found in the SYNOPSYS User's Manual). In a few seconds, we are presented with the design shown in Figure 9.

2.4 Selection starting point from experience based on the method of composition of optical elements

Professor Roosinov first proposed this method in 1970 [10, 11] and used elements with known properties in optical design. This method was later used by his successors [1, 2, 4, 5, 12].

The main idea is that every element in an optical system plays its own functional role. Given that we aim to design an objective with an object located at infinity and an image located at finite distance, we make several deductions as listed below.

- A Basic (B) element is responsible for optical power of the system, and it is always positive.
- A Correction (C) element corrects residual aberrations of a basic element.
- A Fast (V) element is responsible for increasing the aperture of the system; it is always positive, but works from a finite distance as contrasted with a basic element.
- A Wide-angle (Y) element is installed into the system if one needs a wide field angle.
- All elements (except 'basic') should be installed only if they are wanted, which can be decided after analysis of the customer's request.

The general scheme of this composition is presented in Figure 10. The details of this method for starting point selection are discussed in [1, 2, 4, 5, 12]. This theory offers important insights into the use of elements with surfaces with well-known properties, such as aplanatic, concentric, near image, and so on. The idea was developed not only in Russia, but also by David Shafer in the USA [3], who successfully used it in his designs.

- Now we will use this method to construct a starting point for our pinhole lens. First, we selected the following optical elements:
- Basic: The first surface is aplanatic about marginal ray (flat from infinity); the second surface is concentric about chief ray.
- Fast: The first surface of element 2 has a pick-up from surface 3 with the opposite sign of the radius.
- Correction: Here we use a bi-concentric meniscus.

Using a special curvature solve option in SYNOPSYS, we can immediately get all radii from the software without

Table 8: Specifications for the starting point created by DSEARCH.

Specification	Value	Specification	Value
OBJECT DISTANCE (THO)	INFINITE	FOCAL LENGTH (FOCL)	4.5000
OBJECT HEIGHT (YPP0)	INFINITE	PARAXIAL FOCAL POINT	2.0510
MARG RAY HEIGHT (YMP1)	0.5000	IMAGE DISTANCE (BACK)	2.0510
MARG RAY ANGLE (UMP0)	0.0000	CELL LENGTH (TOTL)	7.5366
CHIEF RAY HEIGHT (YPP1)	0.3216	F/NUMBER (FNUM)	4.5000
CHIEF RAY ANGLE (UPP0)	45.0000	GAUSSIAN IMAGE HT(GIHT)	4.5000
ENTR PUPIL SEMI-APERTURE	0.5000	EXIT PUPIL SEMI-APERTURE	1.0800
ENTR PUPIL LOCATION	-0.3216	EXIT PUPIL LOCATION	-7.6691

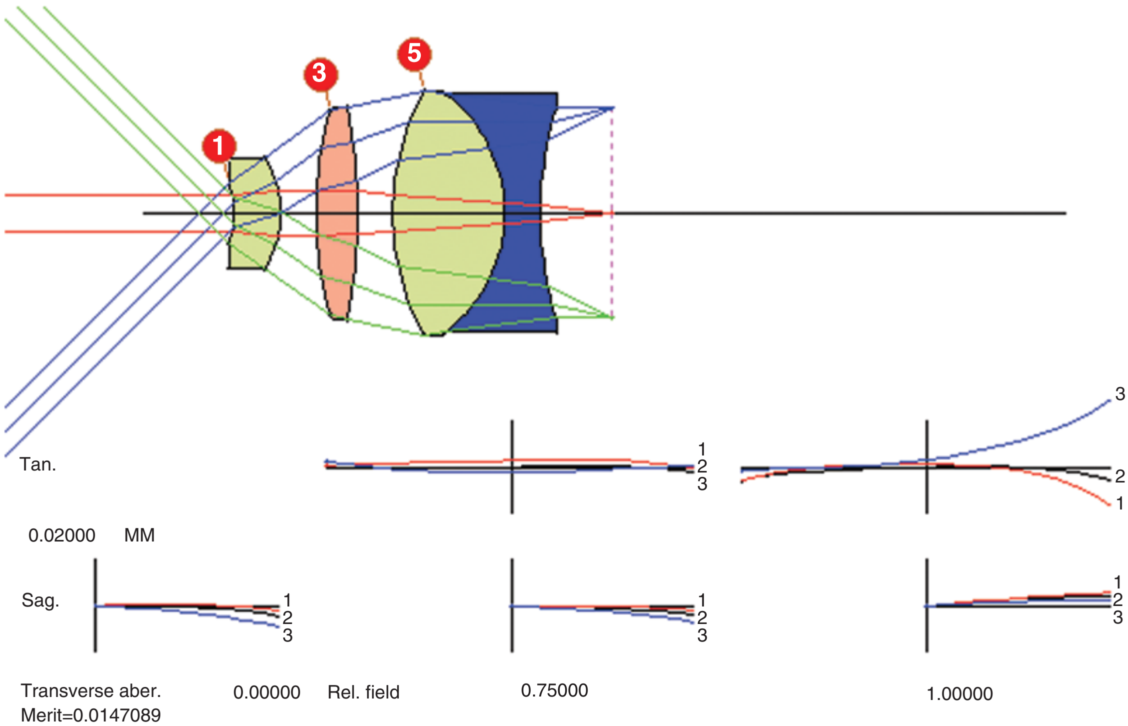

Figure 9: The lens from DSEARCH as modified by AEI.

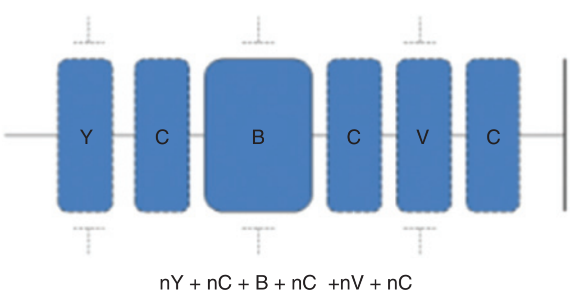

Figure 10: General scheme of optical system composing, where n is a quantity of one type of elements in the same position.

Table 9: Surface data for the lens in Figure 6.

Surface no	Radius	Thickness	Medium	Index	V-number
0	INFINITE	INFINITE	AIR		
1	-2.01656	1.00000	GLM	1.80000S	46.63
2	-2.32604	1.00000	AIR		
3	12.84746	1.14873	GLM	1.53310S	70.67
4	-9.88676	1.00000	AIR		
5	4.56709	3.38800	GLM	1.50000S	73.65
6	10.11694S	2.05096S	AIR		
IMG	INFINITE				

any preliminary calculations by hand. This result is shown in Tables 9 and 10 and in Figure 11. For the starting point we always take only one element in a given position, and then we can put two or three elements in that position if necessary. The next step is to cancel all solutions and optimize the lens. The result of optimization is presented in Table 11 and Figure 12.

2.5 Summary

A comparison of the above starting point selections is presented in Figure 13.

2.5.1 Comments on the result

For a simple three-element design, we obtained a variety of results. If you are not interested in the reason why certain elements appear in the optical scheme and just want to get a starting point, you can take methods 1 or 2. In this case, the software does most of the work. If you want to understand how system works, you choose method 3: put in elements with well-known properties and then perform the optimization.

2.6 Color correction

For the three-element starting points presented above, monochromatic aberrations are corrected well enough.

Table 10: Specifications for the lens in Figure 11.

Specification	Value	Specification	Value
OBJECT DISTANCE (THO)	INFINITE	FOCAL LENGTH (FOCL)	4.5013
OBJECT HEIGHT (YPP0)	INFINITE	PARAXIAL FOCAL POINT	0.6797
MARG RAY HEIGHT (YMP1)	0.5000	IMAGE DISTANCE (BACK)	0.6797
MARG RAY ANGLE (UMP0)	0.0000	CELL LENGTH (TOTL)	9.6053
CHIEF RAY HEIGHT (YPP1)	0.0000	F/NUMBER (FNUM)	4.5013
CHIEF RAY ANGLE (UPP0)	45.0000	GAUSSIAN IMAGE HT(GIHT)	4.5013
ENTR PUPIL SEMI-APERTURE	0.5000	EXIT PUPIL SEMI-APERTURE	2.0699
ENTR PUPIL LOCATION	0.0000	EXIT PUPIL LOCATION	-17.9546

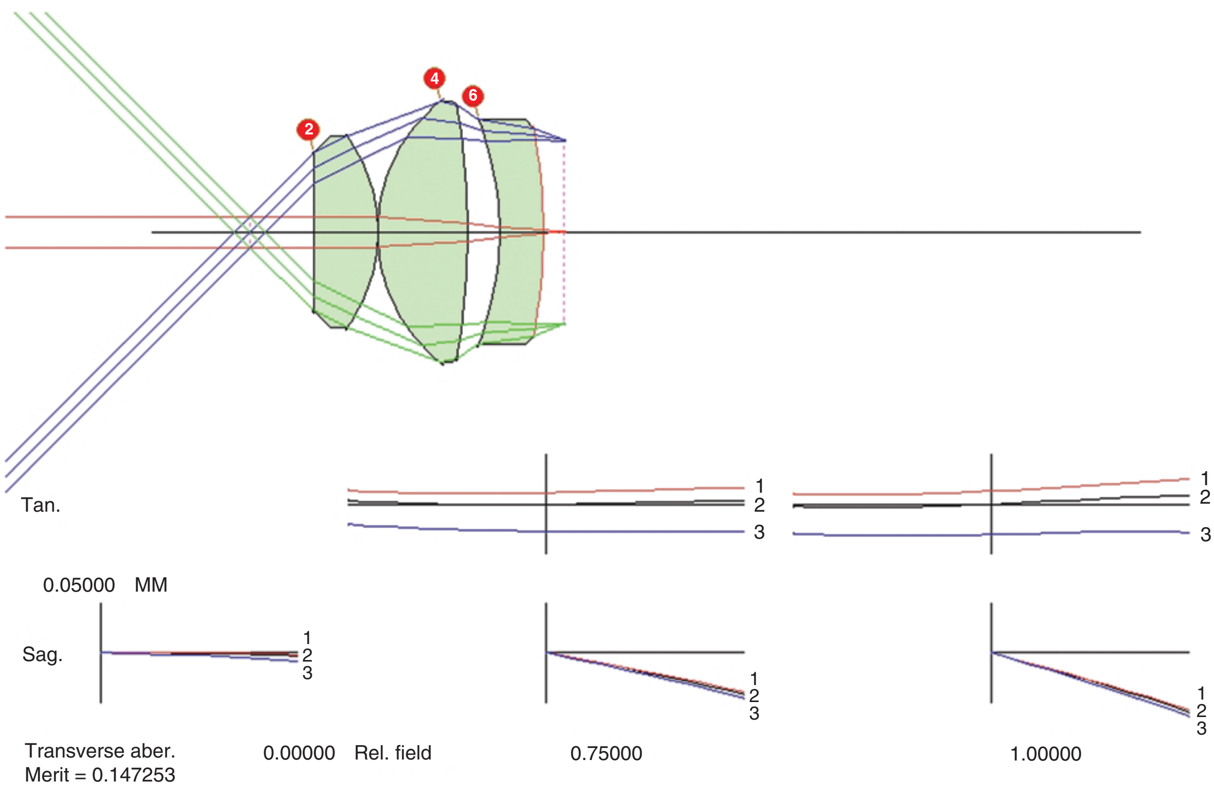

Figure 11: Starting point for pinhole lens using surfaces with well-known properties.

Table 11: Surface data for the lens in Figure 11.

Surface no	Radius	Thickness	Medium	Index	V-number
0	INFINITE	INFINITE	AIR		
1	INFINITE	2.09445	AIR		
2	INFINITE	2.09445	GLASS	1.61117S	55.92
3	-5.46895S	0.00000	AIR		
4	5.46895	2.93222	GLASS	1.611170S	55.92
5	-25.60964S	1.04722	AIR		
6	-10.19835S	1.43694	GLASS	1.61384S	34.53
7	-17.95459S	0.67970S	AIR		
IMG	INFINITE		AIR		

Table 12: Surface data for the lens in Figure 12.

Surface no	Radius	Thickness	Medium	Index	V-number
0	INFINITE	INFINITE	AIR		
1	INFINITE	0.20000	AIR		
2	-2.206659	1.20000	GLM	1.60409S	64.28
3	-2.49140	0.00000	AIR		
4	3.90555	2.40000	GLM	1.65686S	59.52
5	-5.70513	1.62401	AIR		
6	-2.28143	1.43694	GLM	1.80000S	25.05
7	-7.39471	0.93143S	AIR		
IMG	INFINITE		AIR		

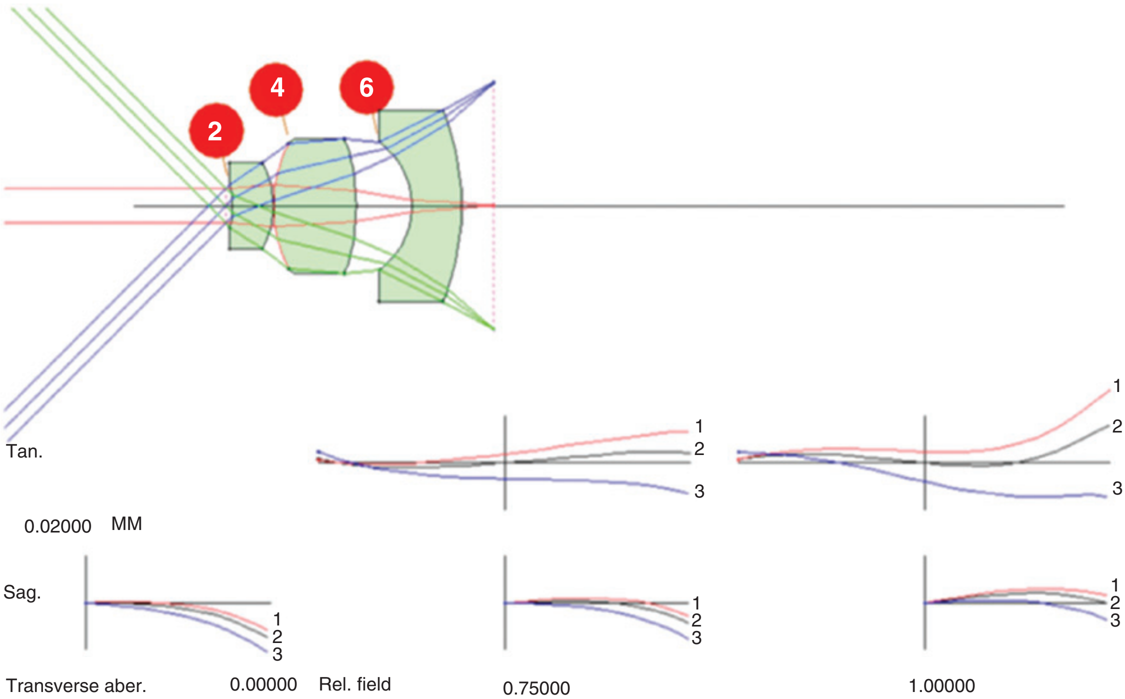

Figure 12: Lens from Figure 11 after optimization with cancellation of surface properties, see Table 12.

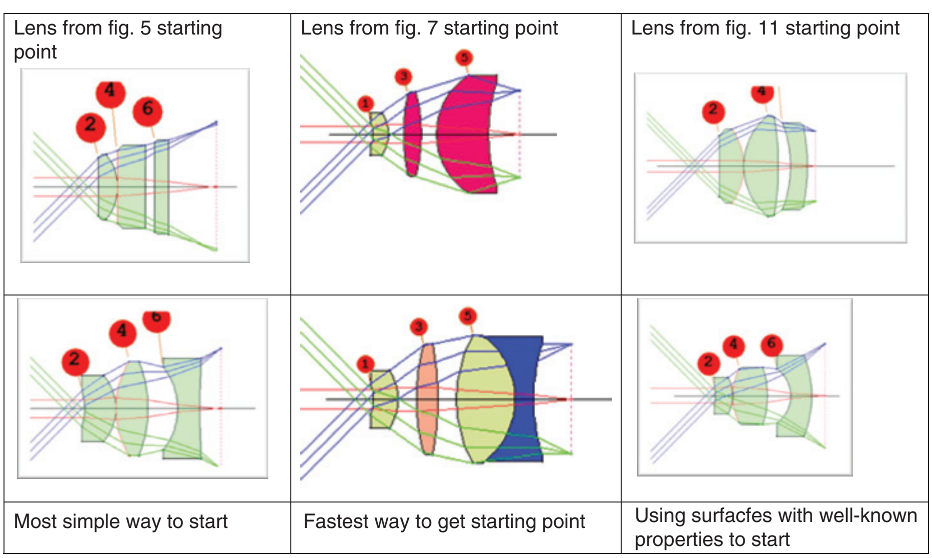

Figure 13: Comparison of three methods of starting point selection.

Now the next step is to correct chromatic aberration. For this purpose, we use different glass types and cemented lenses elements. We are going to install an additional surface to correct chromatic aberration. The question is, given that we have three lenses in our starting point, where is it better to correct color: in the first, second or the third lens? The results from AEI already found that a cemented element on the last lens worked quite well. Figures 14 through 16 show the image quality of some of these designs.

3 Conclusion

Here, we showed how the location of the cemented lens in the pinhole objective affects the results. In this case,

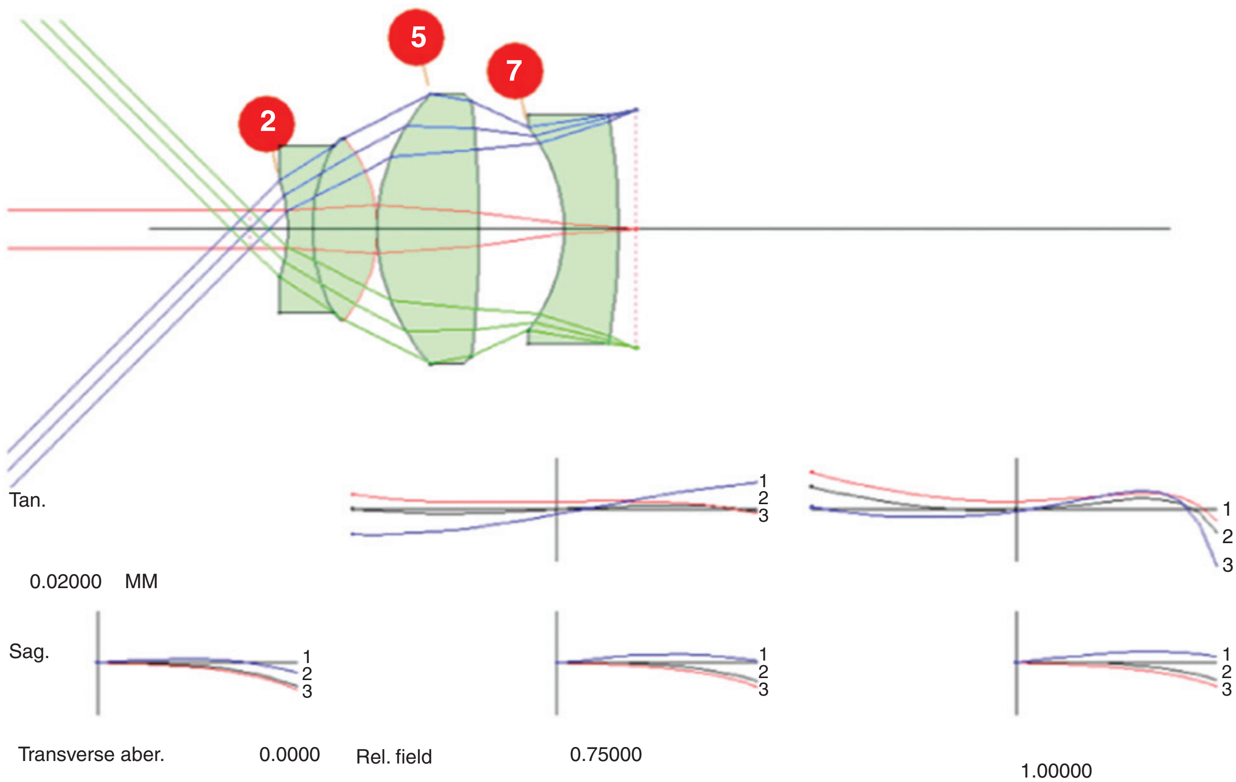

Figure 14: The lens with a doublet on the first element.

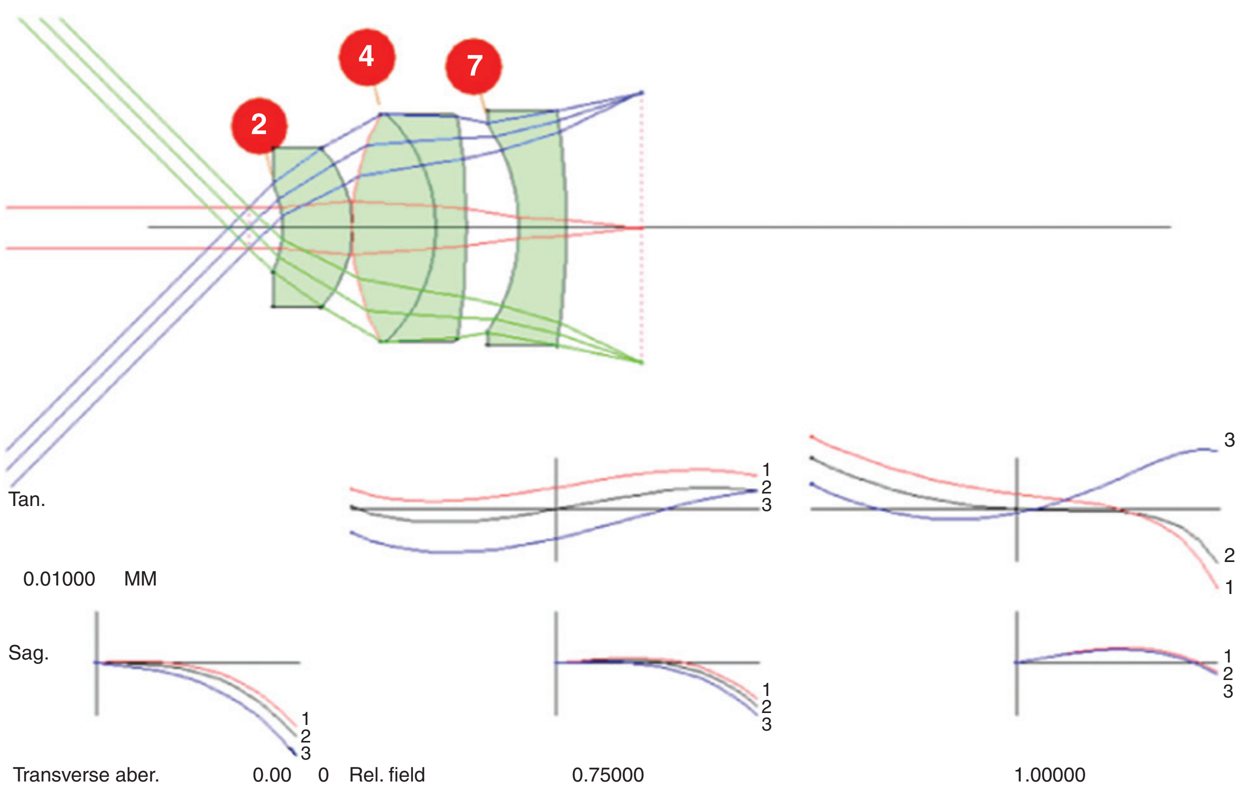

Figure 15: The lens with a doublet on the second element.

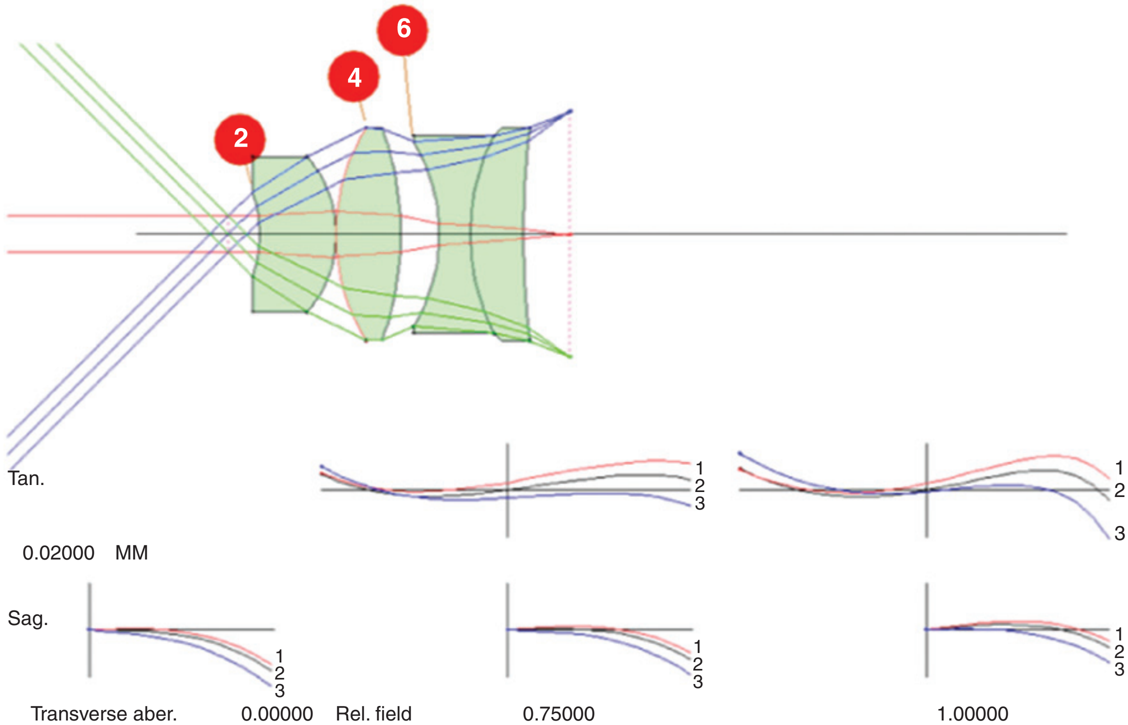

Figure 16: The lens with a doublet on the third element.

the customer preferred the variant shown in Figure 15. He made his choice because of the excellent image quality obtained in this scheme (see the scale on the aberration plots: 0.01 mm in this example), and because of the shape of the elements, which look better than those in Figures 14 and 16 from the point of view of mechanical construction. However, we can generally say that the question of making decision about which variant is better is not always obvious and could be a topic for separate discussions.

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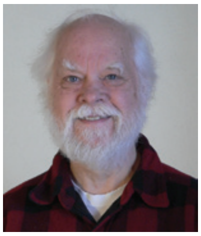

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