

SYNOPTSYS™ (*SYNthesis of OPTical SYStems*)

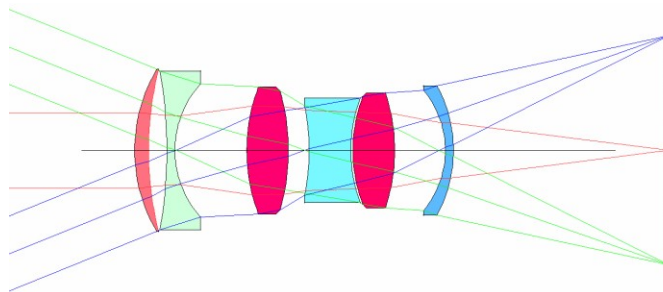
Lens Design Software

Automatic Design Tools

DSEARCH™ (Design Search)

ZSEARCH™ (Zoom Search)

AEI/AED (Automatic Element Insertion/Deletion)



Design search: 7 element system (F2.8) built in seconds

SYNOPTSYS™ is a trade name used by
Optical Systems Design Inc. commercially
since 1981.

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Introduction

This document presents a brief introduction to some of the important Automatic Design tools in SYNOPSIS™:

- DSEARCH™ (Design SEARCH)
- ZSEARCH™ (Zoom SEARCH) for zoom lenses
- AEI (Automatic Element Insertion)

DSEARCH™ and ZSEARCH™ are Automatic Design tools that help search for useful starting points based on simple inputs. They are also useful in exploring the design space in order to discover new design forms that may not have been thought of by traditional designers trained with conventional design methods.

After identifying the design candidates with DSEARCH™ or ZSEARCH™, you can use other Automatic Design tools, such as AEI (Automatic Element Insert) to improve the system, and AED (Automatic Element Deletion), which can find the best place to remove an element without significantly impacting the system performance.

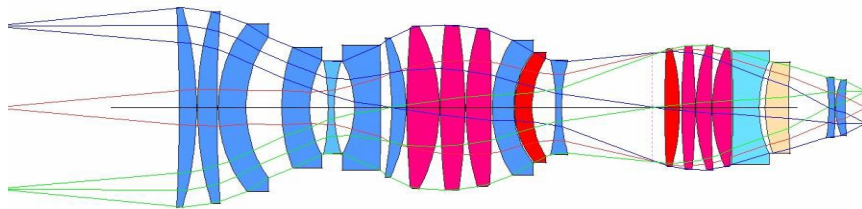
Traditional (design) methods have long relied on having a good starting point, a design not too far from the desired goals, and then working to improve it. If the starting point was indeed a good one and your skills were sharp enough, you could in that way arrive at a great design. However, one rarely has such a starting point, and only a few of us have the required skills. Thus the job is hard for most, and difficult even for the experts, most of the time. The core problem here is the fact that, except in a few simple cases, there is no closed-form solution to the lens design problem. That means there is no formula you can simply plug numbers into and obtain a great design. You have to think, try things, learn from experience, and iterate. My goal in writing the SYNOPSIS™ program has been to put as much of the burden on the computer as possible, freeing you from the most tedious of traditional tasks.

**Donald Dilworth, Creator of the SYNOPSIS™ Lens Design Software
Lens Design, Automatic and quasi-autonomous computational methods and
techniques**

**SYNOPSIS™ Lens Design Software
Essential Tool for Optical Design**

DSEARCH™

SEARCH and OPTIMIZE in a breeze



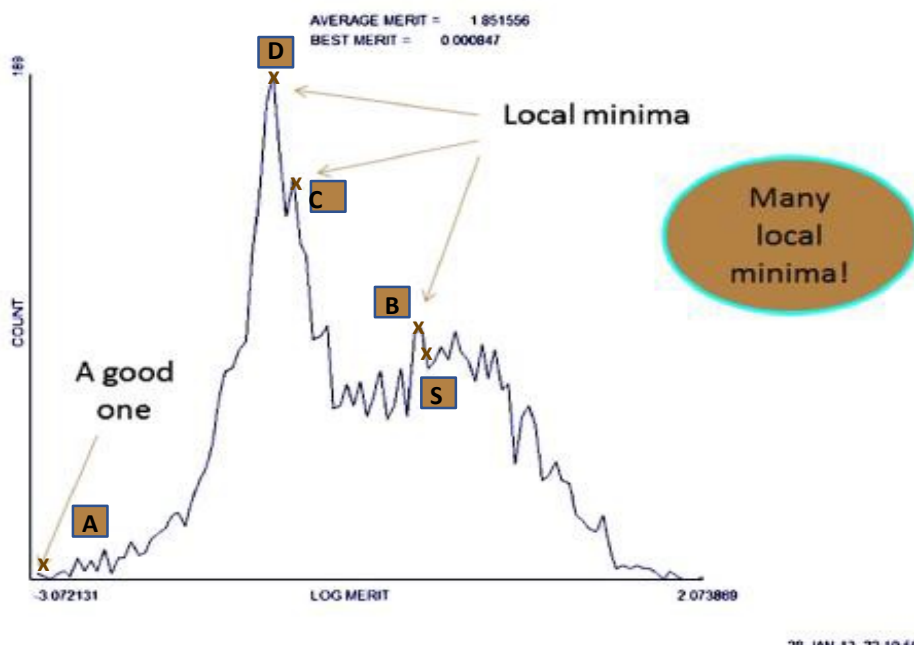
**21-element microlithography objective designed by SYNOPSIS™
automatic design search (DSEARCH™) in 44 minutes.**

Merit Function, Optimization, and Design Space

In optical design, the designer seeks configurations that deliver optimized performances. In the traditional approach, the designer starts with a reasonably good starting point (usually based on some published paper, patents, or previous designs) that is close enough to the desired system. He then defines a merit function that models the system specifications or design goals. The optimization algorithm of the design software then varies the selected lens data (the optimization parameters) and drives the system from its current state (the starting point) into an optimized configuration that minimizes the merit function. A complex lens has many optimization parameters and thus the optimization process takes place in a high dimensional hyperspace. This design hyperspace is analogous to a mountain range, with many minima. As when one skis down from the mountain top, the initial descending direction will play a crucial role in determining which minimum the system will reach.



Ideally, one would hope to land at the lowest valley in the design space (point A in the illustration below). However, it is difficult to reach; especially in the traditional approach where the designer usually starts with a certain configuration that is close to the desired system. It means that the traditional starting point usually is already near a certain local minimum (for example, point S). The optimization process then drives the system into some nearby local minimum (for example, point B) and stops there, and thus misses the other design forms that can deliver yet better performances (for example, points C and D).



DSEARCH™ (Design Search) and the Design Space

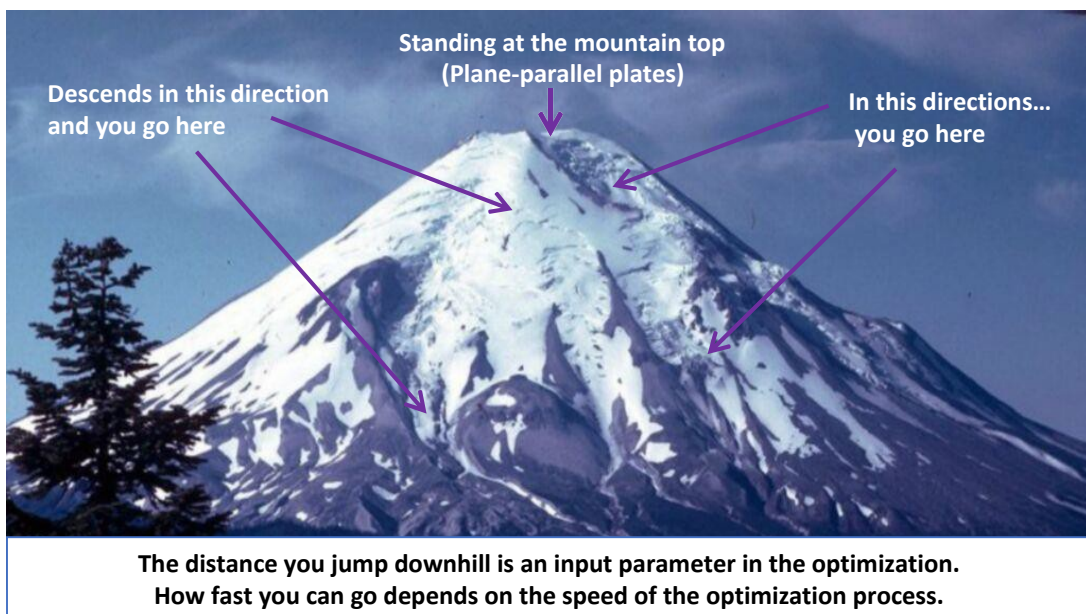
The DSEARCH™ feature of SYNOPSIS™ is an Automatic Design tool created to provide an effective, fast, and practical solutions for optical design. It is created

1. To ease the burden on the designer in finding good starting points for their design projects.
2. To explore the design space efficiently to discover alternative design forms that may deliver better performances

The principle behind it can be visualized easily using the analogy of skiing down the mountain top to find the valleys:

- From the top of a mountain, you can see all the valleys.
- To search for the lowest valley, send out multiple probes that descends from the mountain top in different directions.

Because the search is not limited to the vicinity of a pre-selected starting point (as in the traditional approach), this method is also referred to as a Global Search method.



To implement the DSEARCH™ method, we

- a. Start with a system consisting of flat plates (standing at the mountain top).
By starting with the flat plate systems and then modifying the optical power of the plates, we can probe the massive design space in an efficient way and can reach corners that are less visited by conventional design methods. Such exploration of the optical design space can lead to design forms not seen before--and can only be done efficiently with modern computers.
- b. Generate enough trial designs (descent directions) to sample the design space effectively and scout out other valleys.
Before descending from the merit function mountain top, one asks, 'which directions will bring the system to a deep minimum?'. Trying each direction is too time consuming and not practical. In SYNOPSIS™, an effective selection of trial directions is implemented via the 'binary search' algorithm, where a binary number is generated to represent the system in the search space.
- c. Equip the search process with fast optimization algorithm
The PSD III optimization algorithm in SYNOPSIS™ is fast and effective.
- d. Aim for good or better designs, not the holy grail of the 'absolute best'

Binary Search in DSEARCH™

We start DSEARCH™ with the declaration of the number of optical elements in the system being designed. This determines the length of the binary number employed in the binary search algorithm: a binary number of N bits is used to represent a system with N optical elements.

The binary search process will then assign either a positive (binary bit 1) or negative (bit 0) optical power to each element in the flat plate system. Each unique combination of these binary bits defines an initial prescription to the system and thus constitutes an initial trial system. For a system with N element, there are 2^N distinct values for the binary number, and thus 2^N trial systems (i.e., 2^N descent directions).

For example, a system with 8 elements will be assigned a binary number of 8 bits:



There are in total $2^8 = 256$ unique values for this binary number, and thus 256 distinct initial prescription for the trial systems (i.e., 256 different probes going down the mountain top at its designated initial descent direction).

- The binary number

1	0	0	1	0	1	1	0
---	---	---	---	---	---	---	---

 describes a system where the 1st, 4th, 6th, and 7th elements are positive; the rest are negative.
- Similarly,

0	1	0	1	0	0	1	0
---	---	---	---	---	---	---	---

 indicates that the 2nd, 4th, and 7th elements of the system are positive; the rest negative.

These initial trial systems represent some very poor designs with a high merit function at the mountain top of the optimization space. To send the probes down the merit function mountain, the program starts the PSD (Pseudo Second Derivatives) III optimization process to improve the design trials.

The PSD method was first developed by Don Dilworth, the creator of the SYNOPSIS™ software, in the 1980s with the goal of improving the then-standard damped-least-squared (DLS) method, which converges very slowly for many problems. By considering the effects of the higher-order derivatives in the calculation of the Jacobian matrix, the PSD method and its descendants (currently, PSD III) converges to deeper minima, faster than does the DLS method.

Consider a 12-element lens system. There are 4096 possible trials. If each optimization takes 1 minute to converge to a minimum (reaching a valley), it will take more than 60 hours to thoroughly examine all the trials in order to reach the favorable design forms.

For a successful implementation of the Global Search method, a fast optimization algorithm is essential. The PSD III optimization algorithm in SYNOPSIS™ is fast and powerful enough to do the job. It can often do each optimization in less than one second, and with this kind of speed the search methods become practical.

For more information on the PSD optimization method, please refer to Appendix B, 'Lens Design, Automatic and quasi-autonomous computational methods and techniques', by Donald Dilworth, IOP Publishing

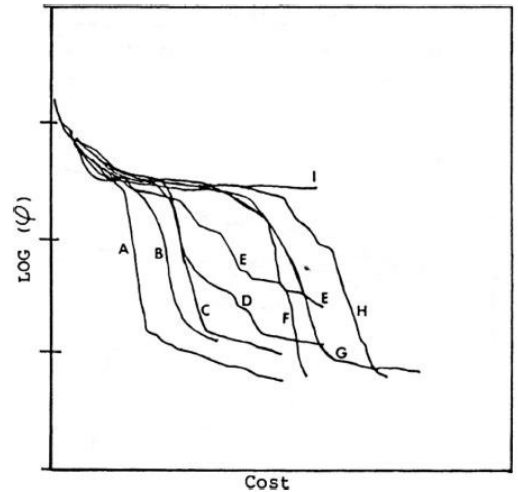
PSD III Optimization in SYNOPSIS™

The graph to the right shows a comparison of convergence rate for several algorithms when optimizing a triplet. The vertical axis is the logarithm of the value of the merit function (ϕ), and the horizontal axis shows the number of iterations (the Cost). Curve I is classic DLS, curve C is PSD I, and curve A is for PSD III. It is clear that PSD III can reach a deeper minimum (smaller merit function) faster (fewer iterations) than all of the others.

The following link shows a video demonstrate the speed of PSD III in optimizing a very poor system in about a second:

- The system starts with seven elements, all flat.
- Equal glass thicknesses and airspaces.
- Model glass in center of glass map.

Goal: close to 6 microns average RMS spot size over field.



http://osdoptics.com/wp-content/uploads/2020/12/optimization_of_7_lenses.mp4

Accelerators in DSEARCH™: Quick mode and Multicore

For most practical modern optical systems, there are a large number of trials to evaluate. Therefore we want to speed things up, and to do this there are two mechanisms in SYNOPSIS™ that help accelerate the search process.

1. Quick mode: there are two optimization modes in the DSEARCH™ process
 - a. Quick mode: Optimize each case with only 3rd and 5th-order aberrations (plus a few real rays.) This expedites the process of ranking and screening the initial design trials. Anneal each trial if requested (see note below).
 - b. Then the 10 best lenses are optimized thoroughly with real rays to further improve them. Anneal if requested.

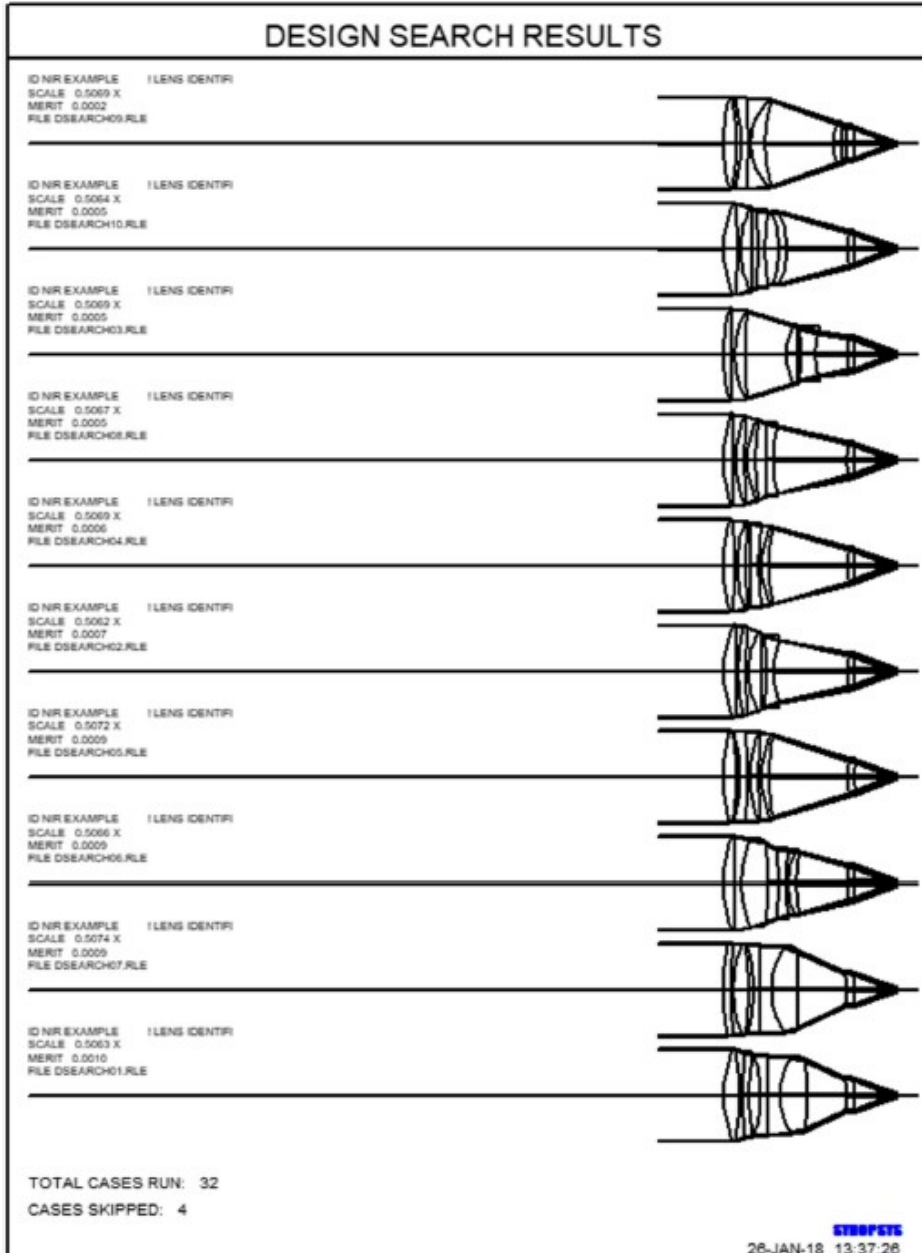
2. Multicore: DSEARCH™ supports multicore operations.

With 32 cores, at one second per optimization, 4096 cases run in minutes.

Note: When the valley in a particular direction is found, the question still remains: is this the best solution in this direction? To overcome this, simulated annealing is used to explore the surrounding optimization hyperspace to determine if a lower valley exists.

Choosing the Winner

After the initial optimization completes, the best 10 trials (ranked lowest in the merit function) will be selected and submitted to a second optimization, and then again ranked accordingly by merit function. The highest ranking one, which is already sitting in or near a deep valley in the optimization space, would be a good starting point for the design projects.



An Example DSEARCH™ Job

This example resulted from a friendly competition between Don Dilworth and his friend, David Shafer, a renowned lens designer.

Dilworth asked Shafer for an example of a difficult lens design job. Shafer suggested an eight-element lens with tight specifications.

Shafer completed the design using a traditional approach, while Dilworth used DSEARCH™ to find good starting points and then optimized each system.

They both came up with excellent designs. But Dilworth's process was faster and returned more excellent systems, using the computer global search methods.

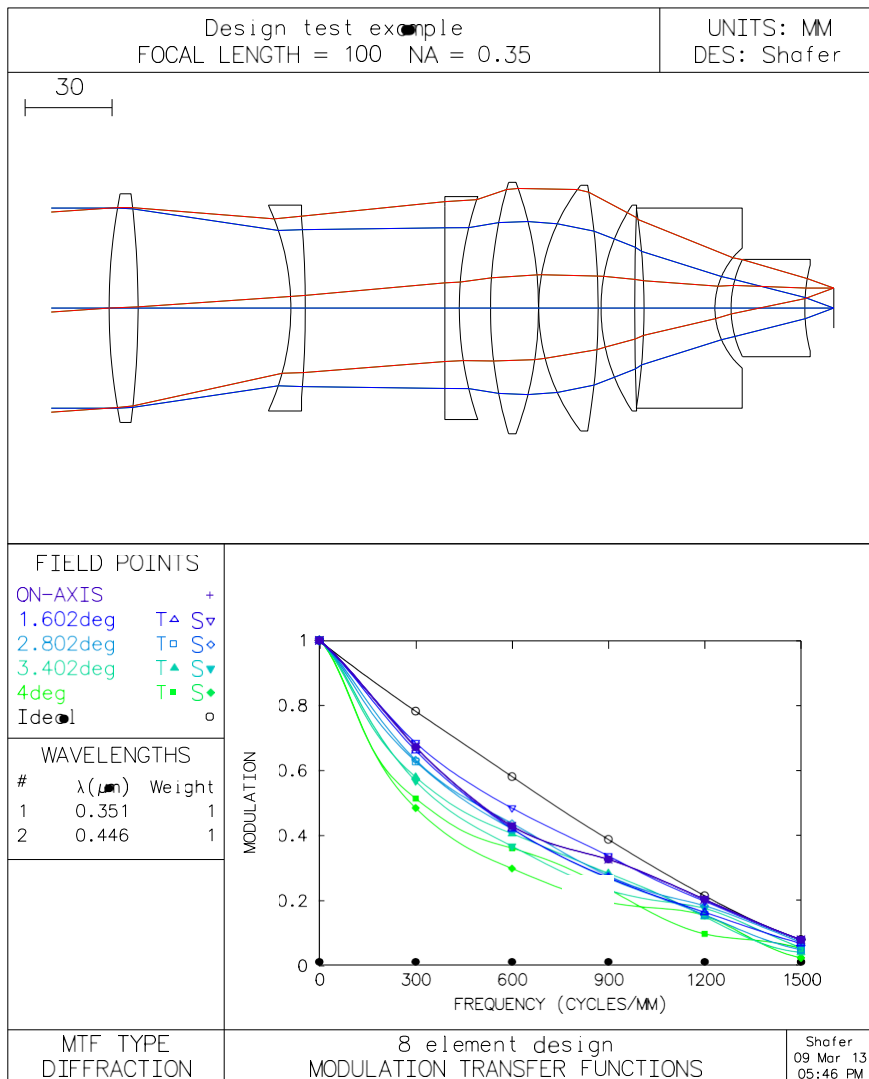
Specifications:

- 0.35 NA (F/1.428)
- 10x10 mm square field.
- 100 mm focal length.
- System length less than 250 mm.
- Back focus at least 10 mm.
- No vignetting.
- Telecentric at image.
- Distortion near zero.

This is a difficult system already...and there are further constrains:

- Two separated wavelengths,
- Only two glass types permitted.

Here is David Shafer's excellent design. Can this be done faster by a Global Search method?



DSEARCH™ Macro with Design Goals

DSEARCH 1 QUIET SYSTEM ID DSEARCH SAMPLE OBB 0 4 35 WA1 .446 .351 WT1 1 1 CORD 2 1 UNITS MM END	System specs
GOALS ELEMENTS 8 FNUM 1.43 BACK 0 0 TOTL 0 0 RSTAR 300 THSTART 5 ASTART 5 STOP FIRST STOP FREE GLASS POSITIVE S UBK7 GLASS NEG S LF5	Design goals
RT 0.75 FOV 0.0 .5 .75 1 FWT 1 1 1 1 NPASS 60 ANNEAL 10 10 RANDOM 5000 END	Options selected (fast/slow)
SPECIAL LLL 10 1 1 A BACK LUL 240 1 1 A TOTL LUL 240 1 1 A TOTL S ENP M 0 2 A P HH 1 M 0 5 A P YA 1 S GIHT END GO	Special requirements: Back focus more than 10 Total length no more than 240 Difference between total length and pupil distance no more than 240 Telecentric at image Distortion corrected at edge of field.

The best search results from DSEARCH™ are then further optimized by a human, first with transverse ray targets, then OPDs, then MTF or GSHEAR aberrations.

DSEARCH™ Results and Final Design

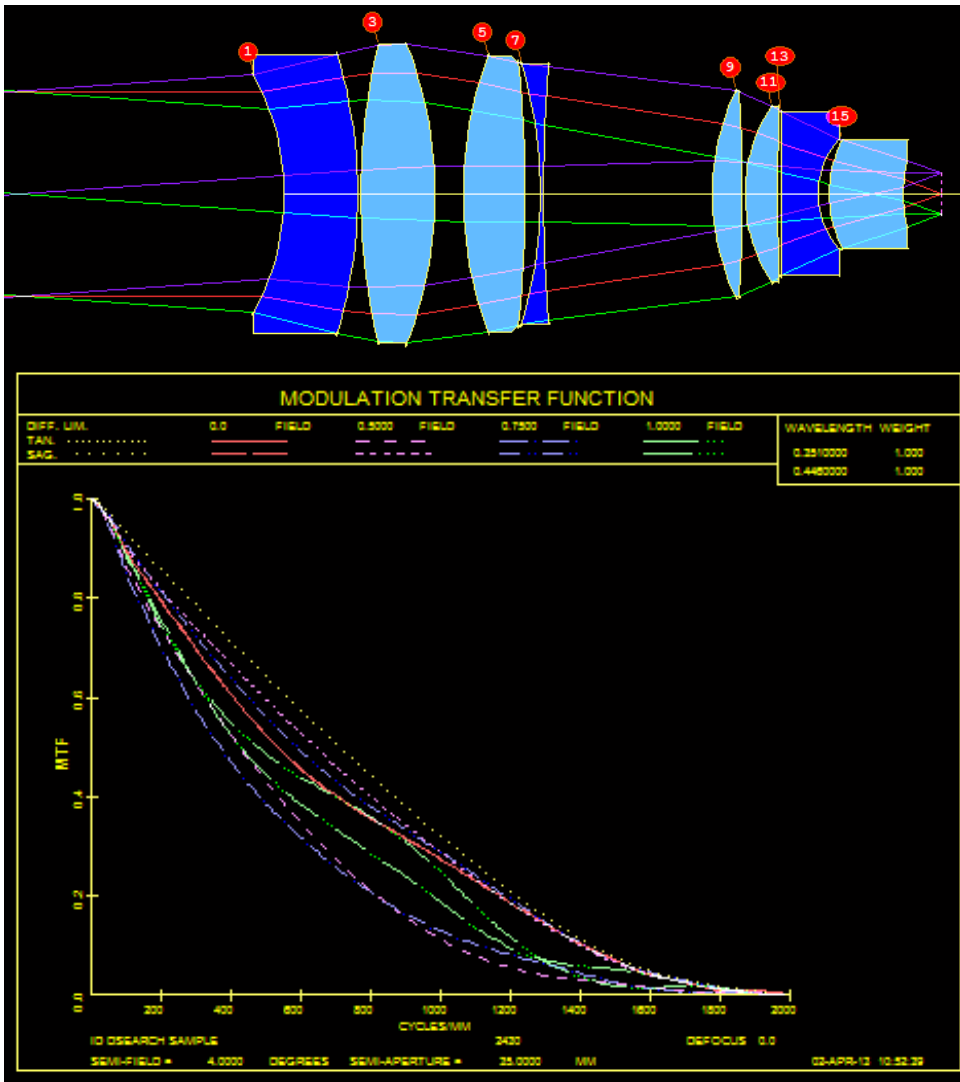
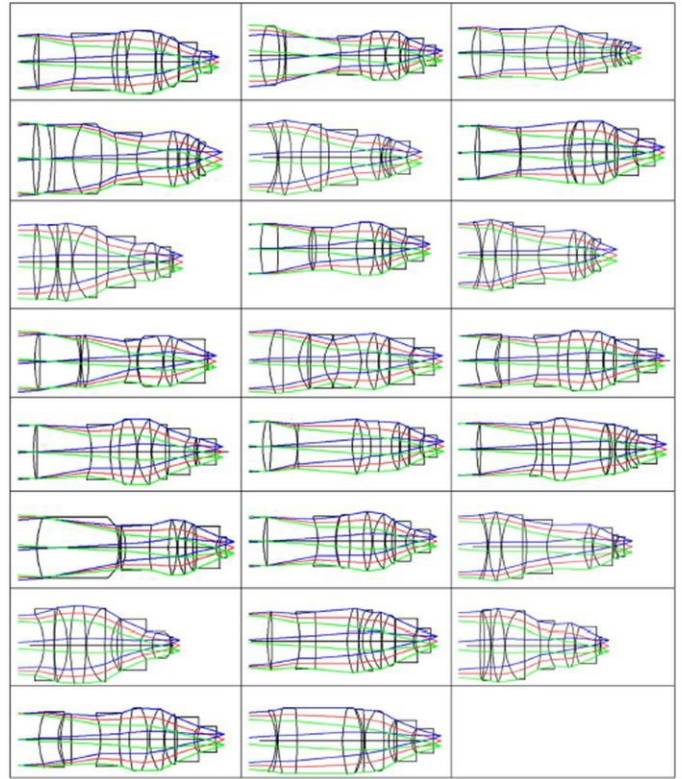
Here are some of the 23 designs found by DSEARCH™.

Every one of these designs is as good as or better than Shafer's.

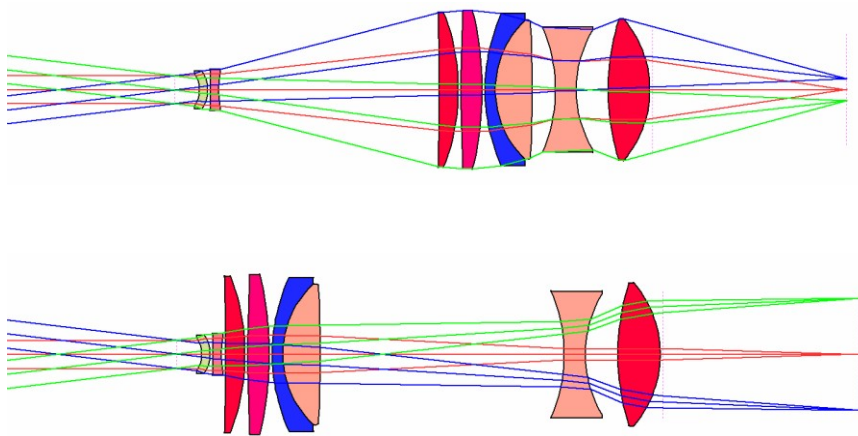
Average search time was 20 minutes on one core, or 2 minutes with 10 cores.

Choosing from one of the 23 designs as the starting point, further optimizing it with transverse ray targets, then OPDs, then MTF or GSHEAR, one can reach a very good final design in a much shorter time than can the conventional method.

One thing needs to be emphasized here: DSEARCH™ is a tool to help designers find good starting points for their projects and thus complete their job faster -- but it is not supposed to replace the designer completely. The refining process and its final result still hinges on the designer's knowledge in optics.



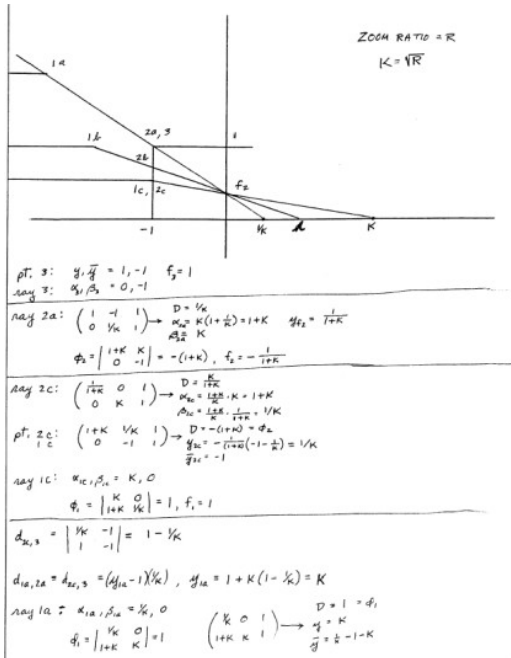
ZSEARCH™ and AEI (Automatic Element Insertion)



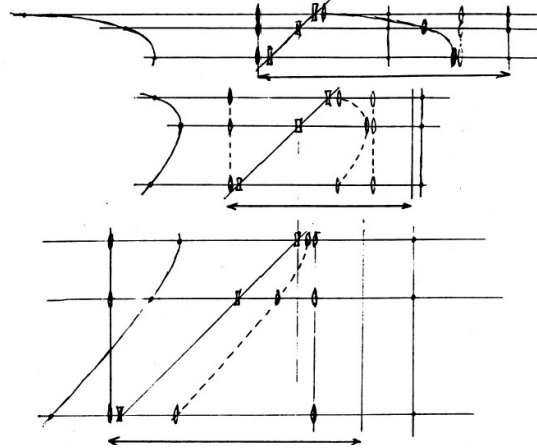
ZSEARCH™

Traditionally, to design a zoom lens, one would produce some initial sketches and calculations that may spread over 10 pages or more...

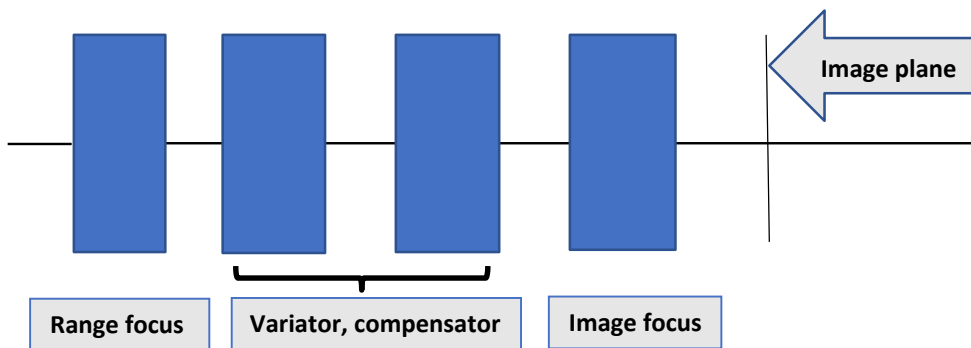
This is an example of the designer doing most of the work. **Can we get the computer to do the work for us?** That question triggered the development of ZSEARCH™ in SYNOPSIS™.



ZSEARCH™ is the Global Search solution for zoom lenses as DSEARCH™ for fixed focus lenses.



Zoom lens design is more complex. Theory tells us, in general, we need four groups:



Let's say (an educated guess) we'll need three elements in each group. Let the program do the rest!

ZSEARCH™ Input Macro

Here is an example input macro to ZSEARCH™:

```
LOG           ! to keep track of things later
TIME          ! to see how long this run took
CORE 12       ! it runs 12 times faster
ZSEARCH 3 QUIET ! save results in library location 3

SYSTEM
ID ZSEARCH TEST
OBB 0 14 2.85 ! infinite object, 14 degrees semi field, 2.85 mm semi aperture. This defines the wide-field object
UNI MM
WAVL CDF
END

GOALS
ZOOMS 10      ! request 10 zoom positions
GROUPS 3 3 3 3 ! lens has four groups with 12 elements altogether

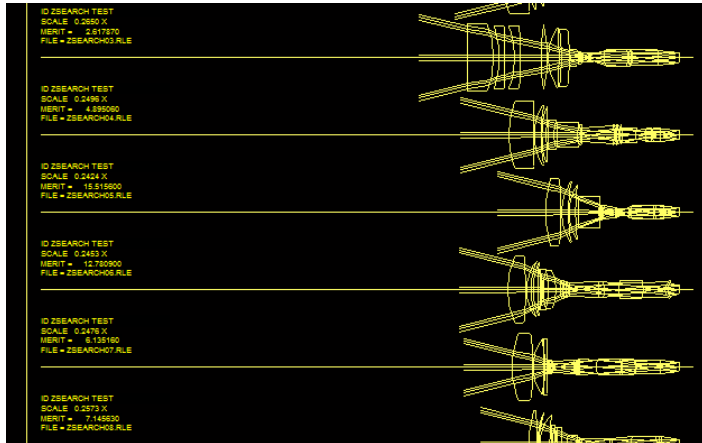
FINAL         ! declare the desired object at the last zoom position, which is the narrow field zoom
OBB 0 1.7545 22.8 ! object is 1.7545 degrees semi field and 22.8 mm semi aperture. That implies an 8X zoom.

ZSPACE LIN    ! other zoom objects will be linearly spaced between the first and last
APS 19        ! put the stop on the first side of the lastgroup
GIHT 5 5 10   ! the image height is 5 mm for all zooms, with a weight of 10.
BACK 20 .01   ! the back focus is 20 mm and will vary. A target will be added to the merit function with a low weight.
COLOR M       ! correct all defined colors
ANNEAL 50 10 ! anneal the lens as it is optimized in real-ray mode
QUICK 15 40   ! 15 passes in quick mode, 40 in real-ray mode
END

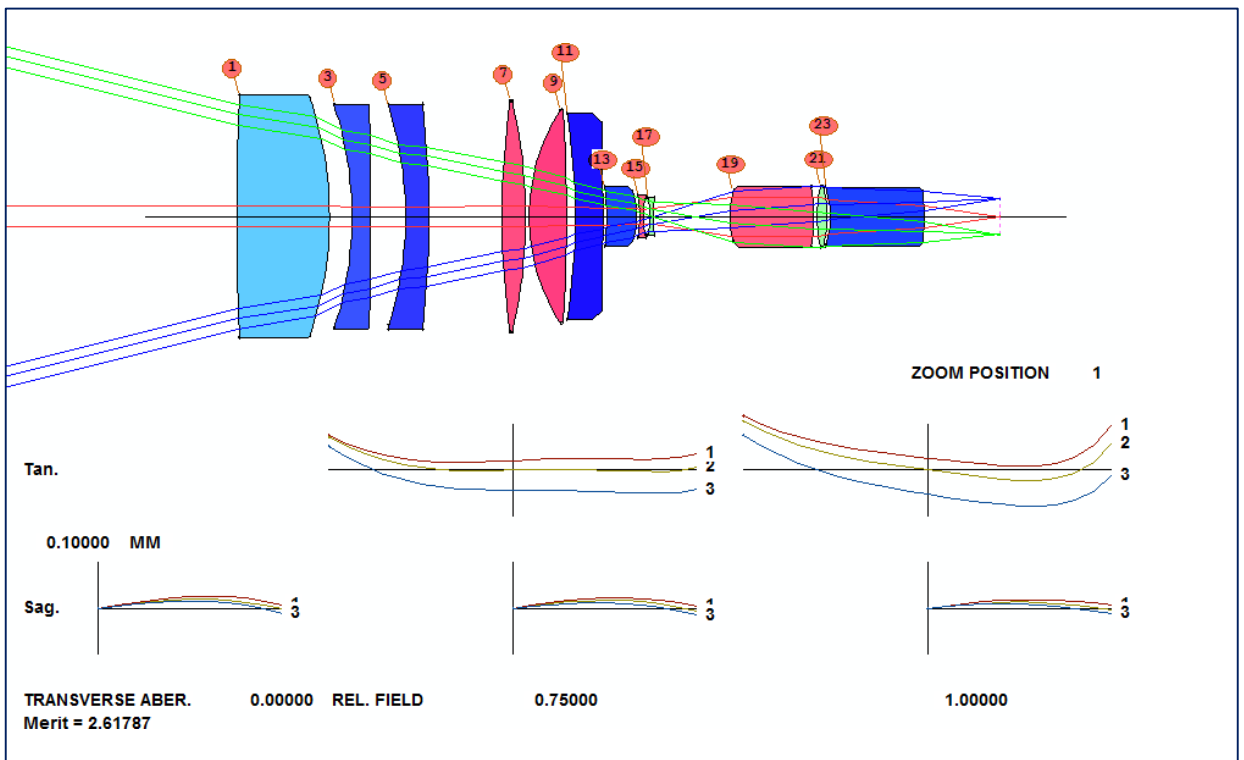
SPECIAL AANT
AAC 30 1 5    ! request a maximum semi aperture on all elements of 30 mm
ACA 50 1 1    ! monitor rays to keep away from the critical angle.
END
GO            ! start ZSEARCH
TIME         ! see how long the run took.
```

ZSEARCH™ Results

ZSEARCH™ comes back with the 10 best lenses it found.



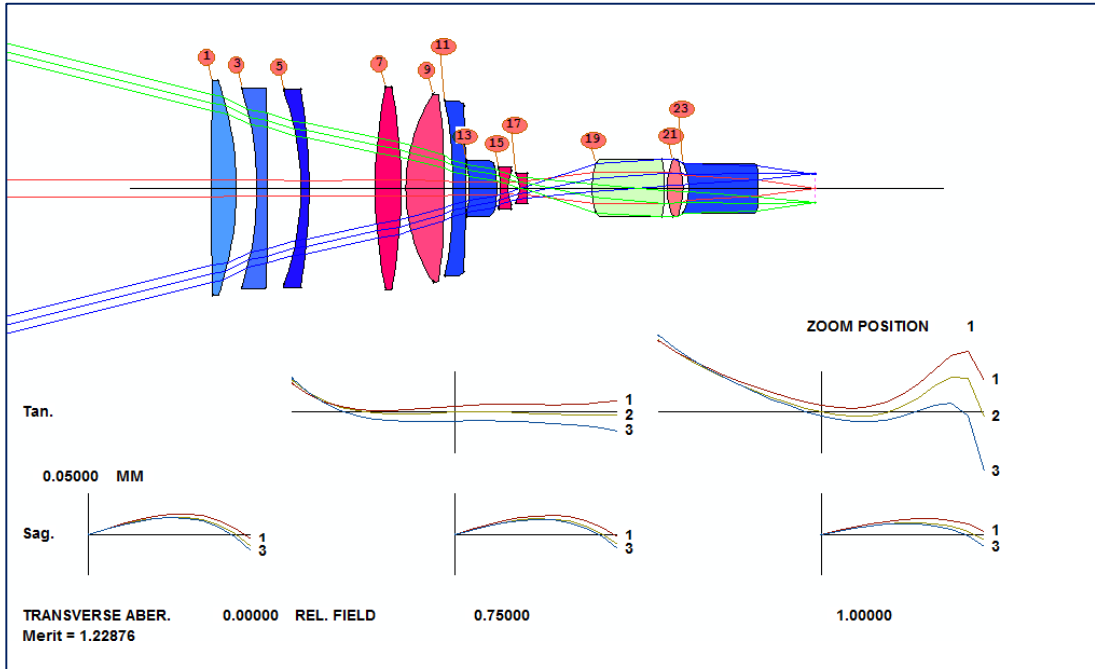
This is the top lens returned by ZSEARCH™ :



Improving the Zoom Lens Design by Optimization

We first optimize the zoom lens using the optimization macro automatically generated by the ZSEARCH™ algorithm:

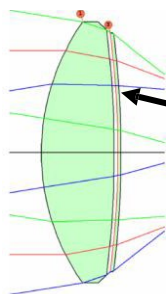
Optimized system:



To further improve the lens system performance, we need more elements. Where should they go?

Automatic Element Insertion/Deletion and Saddle-Point Build

When the best solutions found are not good enough, an automatic element insertion (AEI) tool is available, and the prior solutions can be reprocessed. Should the solutions be 'too good', an automatic element deletion (AED) option can be used to reprocess the lenses to look for adequate solutions having $N-1$ elements.



Thin shell added to side 2

If the power of the shell is zero and its thickness is zero, ray paths do not change. But now there are 6 new degrees of freedom in the design.

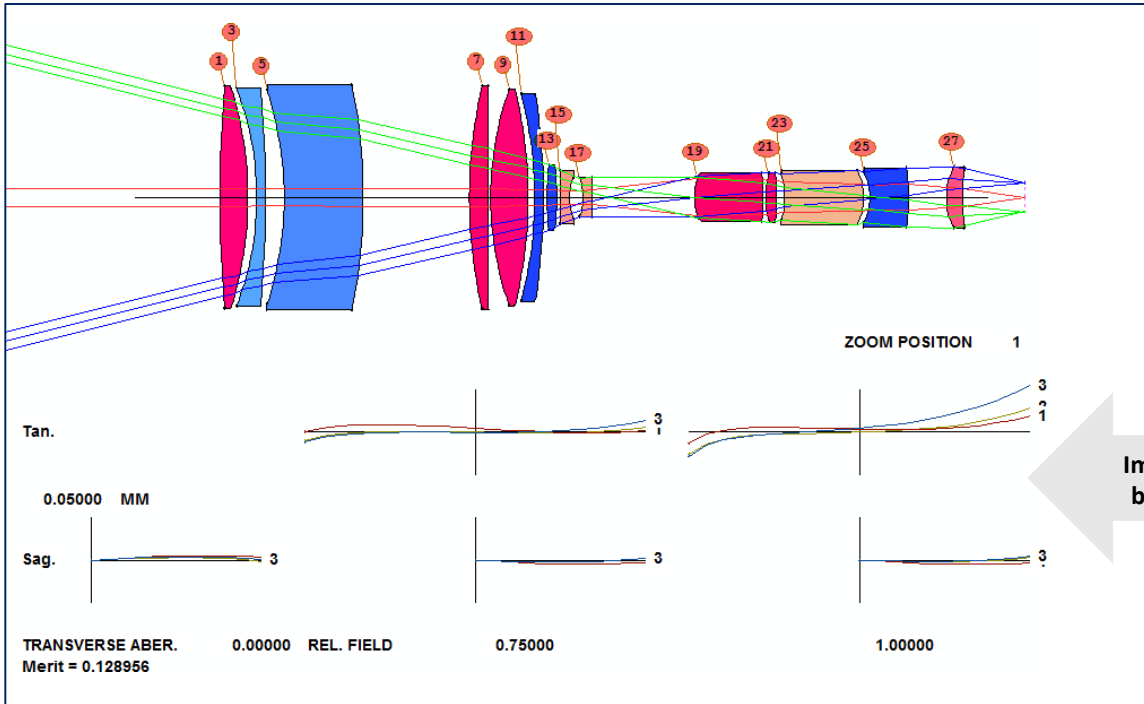
The implementation of these tools is based on the Saddle-Point Build (SPB) Method. You can view a video of SPB in action by clicking the following link to see how SPB can build up an entire 5-element system one element at a time, from nothing:

<https://osdoptics.com/wp-content/uploads/2020/02/spbuild.mp4>

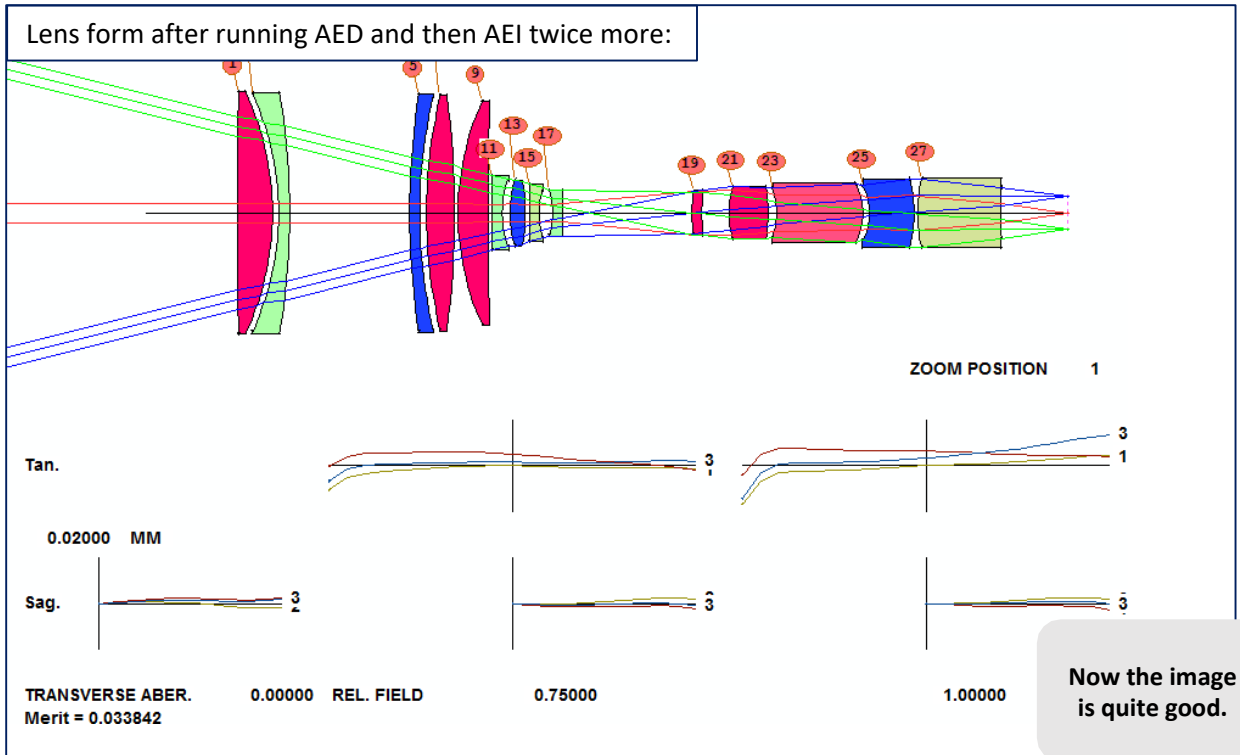
For more information on the AEI, AED, and the Saddle-Point method, please refer to Appendix B, 'Lens Design, Automatic and quasi-autonomous computational methods and techniques', by Donald Dilworth, IOP Publishing

Improving Zoom Lens Design with AEI and AED

Then we use the AEI tool to add elements to the system to improve its performance. Two new elements are added by applying the AEI method twice. Now there are 27 elements in the system:



Sometimes you will wonder whether your system could work as well with fewer elements. The AED (Automatic Element Delete) tool in SYNOPSIS™ can help you make that decision. Combining AED with AEI, you can generate yet new design forms that deliver even better performances.

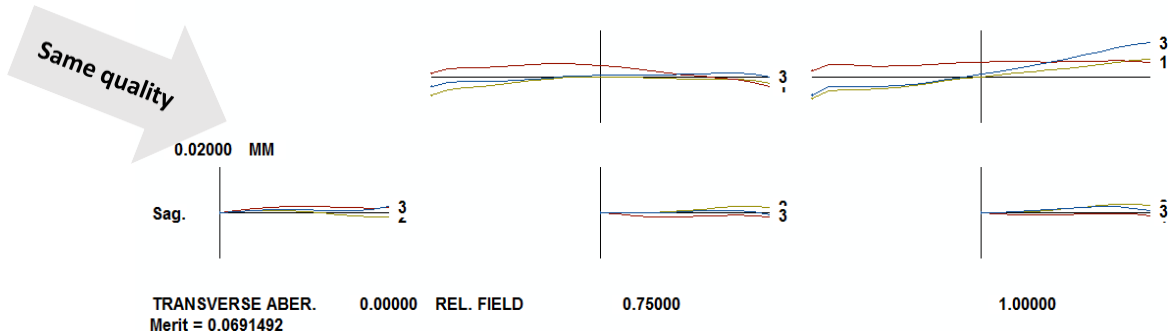
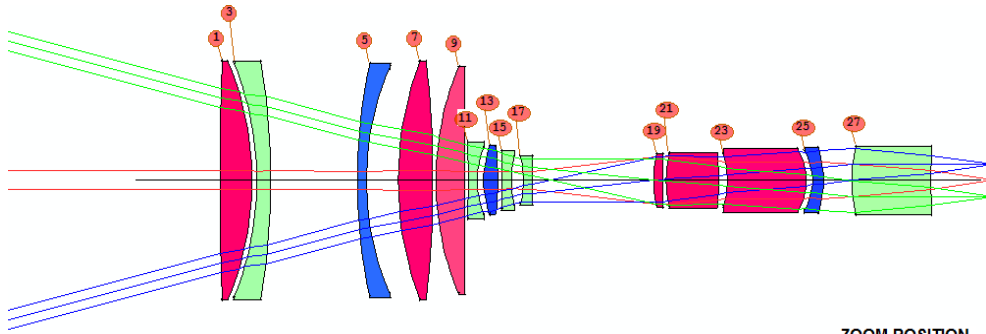


Note that the ray fan plot scale changes 0.05mm to 0.02mm in this design.

Assigning Real Glasses to Replace the Glass Models

When you do the designs, you usually start with Glass Models. When you get a pretty good lens, you will want to use real glasses before handing the design over to the optics shop. In SYNOPSIS™, you can use ARGLASS™ (Automatic Real Glass Insertion) to substitute real glasses for the models.

The lens system with real glasses in place for each element:



To complete the design, we need a CAM curve to define the complete movement of the zoom groups.

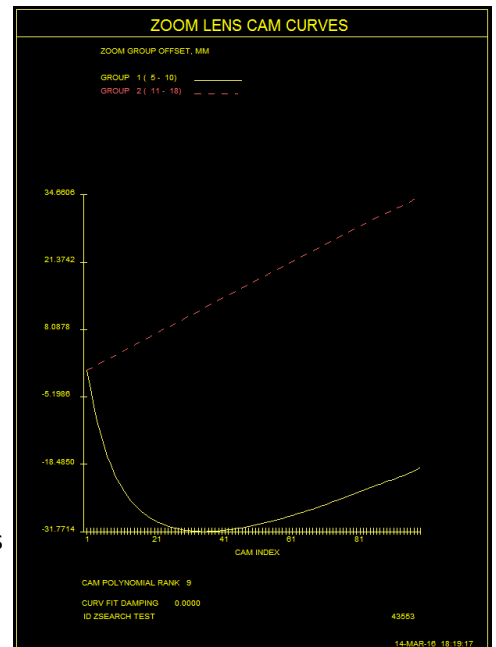
CAM Curve in SYNOPSIS™

When designing zoom lens, we can only design and optimize the system at a limited number of discrete zoom positions, where the lens group placements are determined. For locations between the zoom positions, the lens group placements are interpolated by the CAM curve. There are two types of CAM curves available in SYNOPSIS™:

1. Polynomial that fits all zooms:
 - Power-series polynomial.
 - Number of terms almost equal the number of zooms
2. Piecewise cubic function interpolation (this gives better results).

The video link below shows the continuous movement of the lens groups of a zoom lens designed with 20 zooms, in the ZoomSlider. The intermediate positions of the lens groups are determined using the piecewise cubic function interpolation method. The ZoomSlider is an elegant tool in SYNOPSIS™ that allows the designer to examine their zoom lens in a continuous manner, not just at the discrete zoom positions.

http://osdoptics.com/wp-content/uploads/2020/12/the_lens_is_fit_to_20_zooms_with_cubic_interpolation.mp4



Example 1. Wide-angle Eyepiece design with DSEARCH™

Specifications for the eyepiece:

- Field of view: 90-degrees total at the eye
- Eye relief: 15 mm or greater
- F/number of beam from telescope objective: F/8.
- Visible spectrum: C, d, and F Fraunhofer lines
- Correction to $\frac{1}{4}$ wave or better in d light at 0.58756 μm
- Correction to $\frac{1}{2}$ wave or better in C (0.6563 μm) and F (0.4876 μm) light
- Pupil aberration at eye point no greater than 1 mm
- An internal field stop, where tangential image errors must be no greater than twice the Airy disk at the local F/number of the beam
- The telescope objective to be 2000 mm away
- The eyepiece must have no more than 10 elements
- Total length of the eyepiece no more than 200 mm.

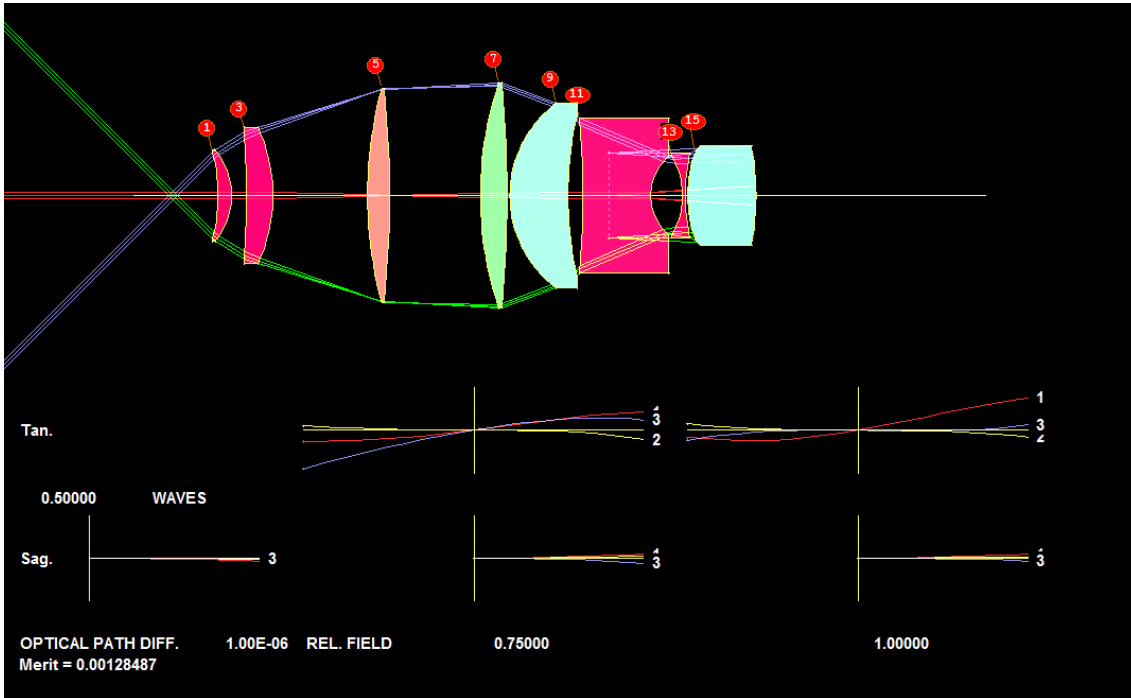
Input for DSEARCH™:

```
LOG
CORE 8
DSEARCH 5 QUIET
SYSTEM
ID TEST DSEARCH EYEPIECE
OBD 1.0E9 45 1.27
UNI MM
WAVL CDF
WAP 1
END

GOALS
ELEMENTS 8
TOTL 200 .01
FNUM 8.0 10
THSTART 10
RSTART 1250
NPASS 80
ANNEAL 0 0
SNAP 10
STOP FIRST           ! keep the stop at the eye point
STOP FREE
QUICK 50 100
FOV 0 .3 .6 .8 1.   ! correct over five field points
FWT 2 1 1 1
END
SPECIAL AANT
ACA 50 1 1
M 15 1 A P YA 1 0 0 0 1   ! control eye relief
M -.01 1 A P HH 1       ! aim light at objective to right
M -.005 1 A P HH .5     ! and control pupil aberrations
M 0 1 A P YA 1
S GIHT
END
GO
```

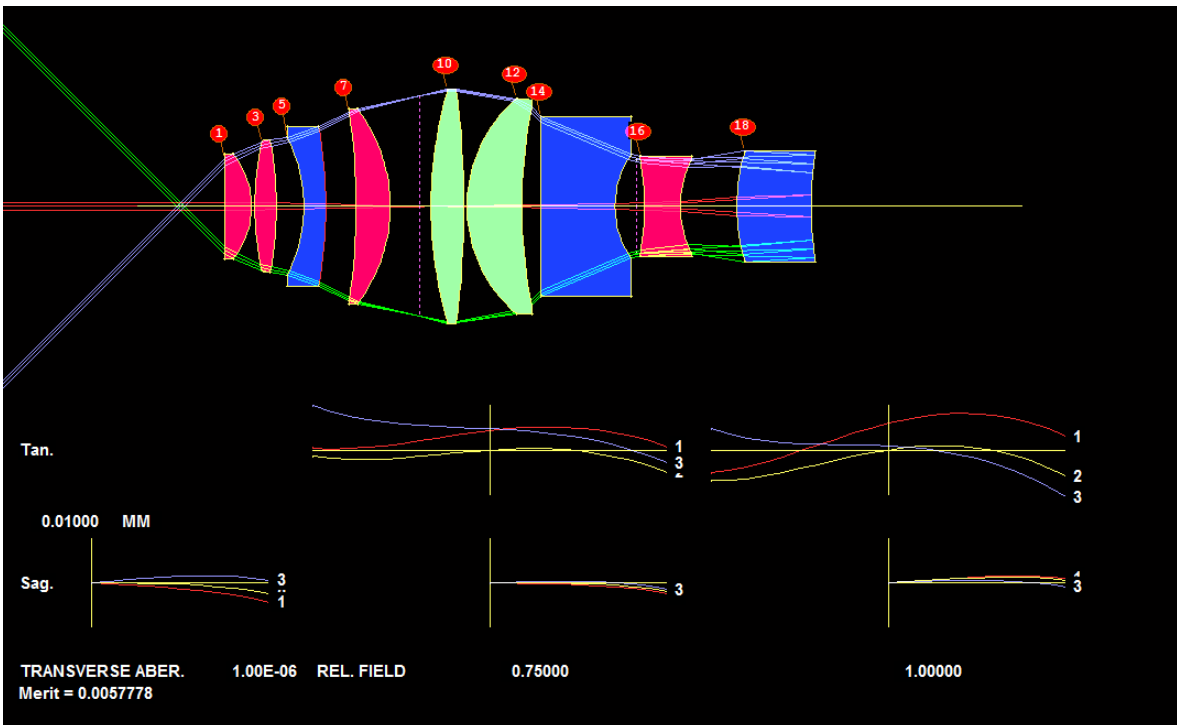
Best Lens Returned by DSEARCH™

DSEARCH™ returns a pretty good design starting point.



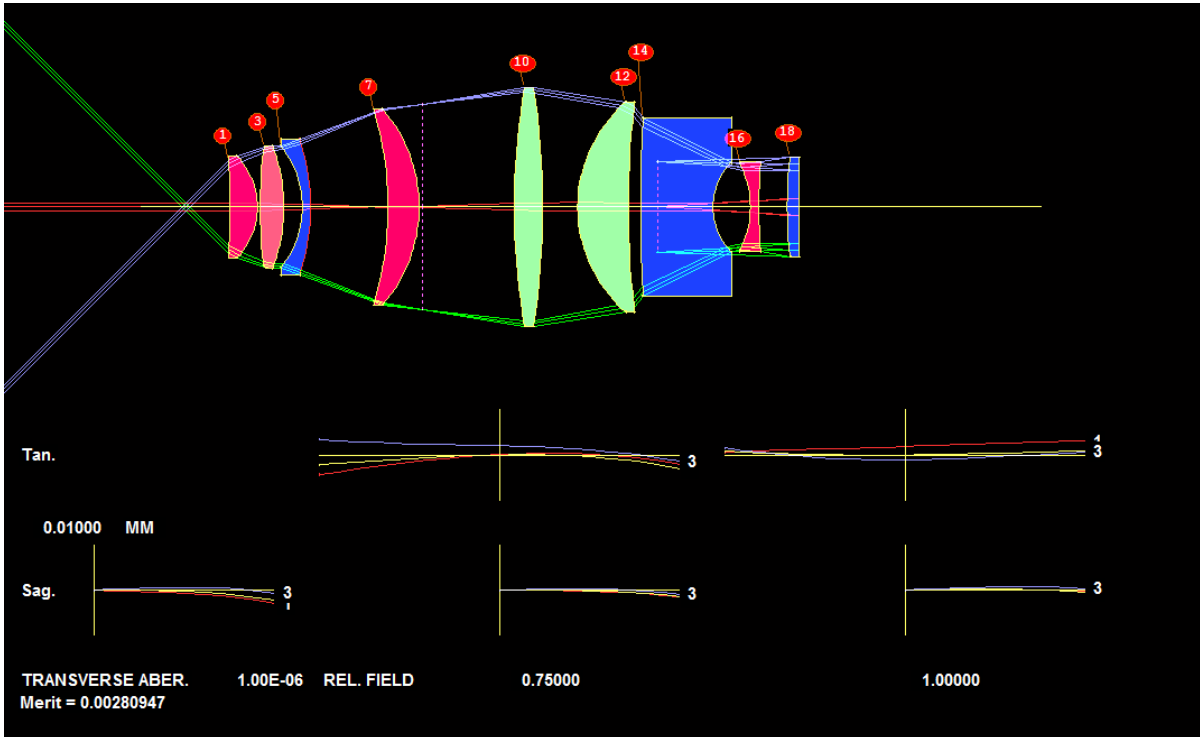
To make it better,

- Add a field stop and requirement for sharp tangential focus at that location
- Then use AEI (Automatic Element Insertion) to obtain this design

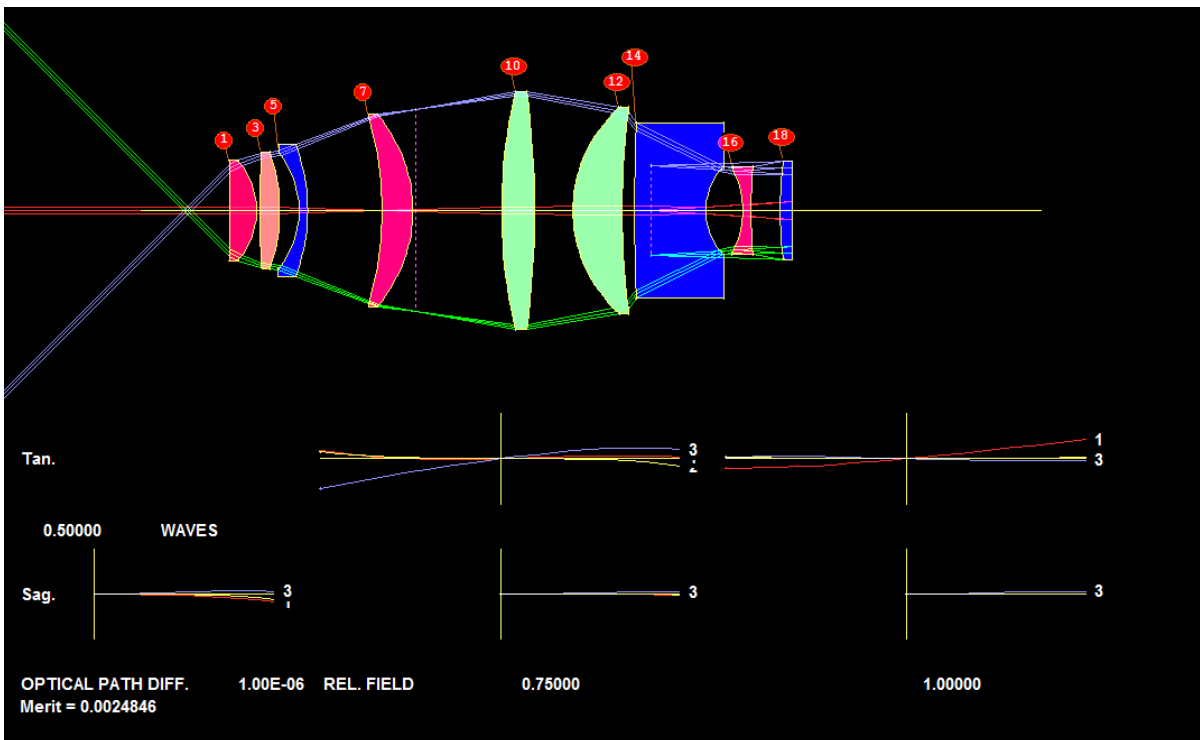


Final Design

With some more optimization, we arrive at this pretty good lens.

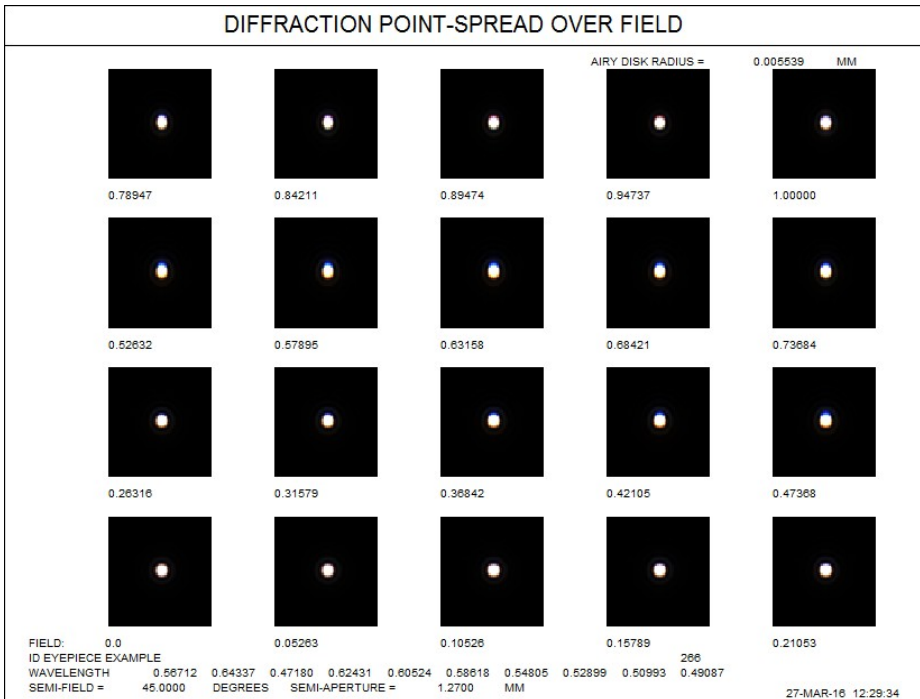


We are now ready to replace the model glass with real glass. The lens is even better after inserting real glasses.

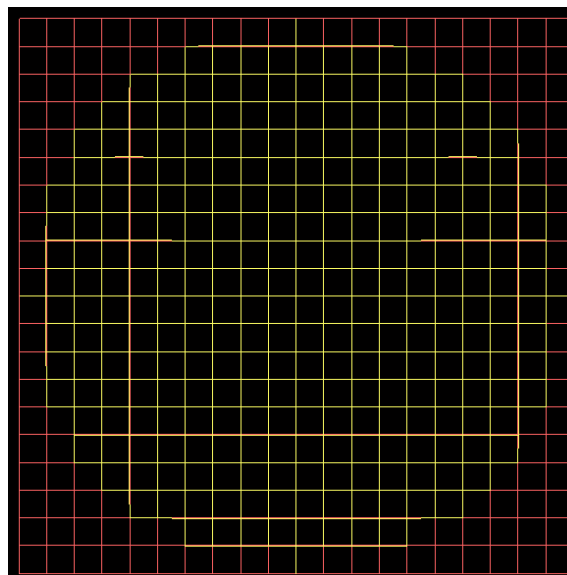


Some Image Analysis

Here is the diffraction point-spread image at 20 points in the field.



Here is the Grid Distortion analysis for the lens. To the eye, essentially perfect.



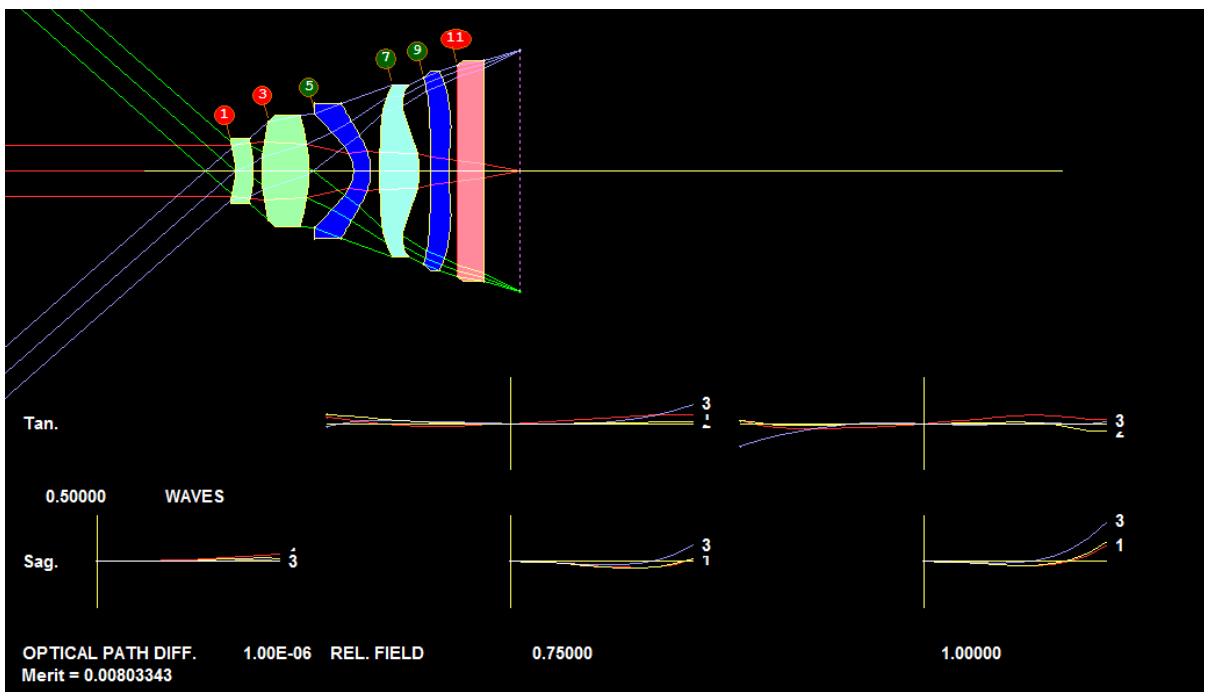
Example 2: A Cell-phone Camera Lens with DSEARCH™

Some specifications for the camera lens:

- Five elements plus cover glass
- First two elements of glass
- Next three elements of plastic
- Aspheric, up to 10th power of aperture

We set up a DSEARCH™ macro for the cell-phone camera. In just over three minutes, DSEARCH™ returns a good starting point for the design. You can click at the following link to view part of the DSEARCH™ process:

http://osdoptics.com/wp-content/uploads/2020/12/DSEARCH_for_cell_phone_camera.mp4

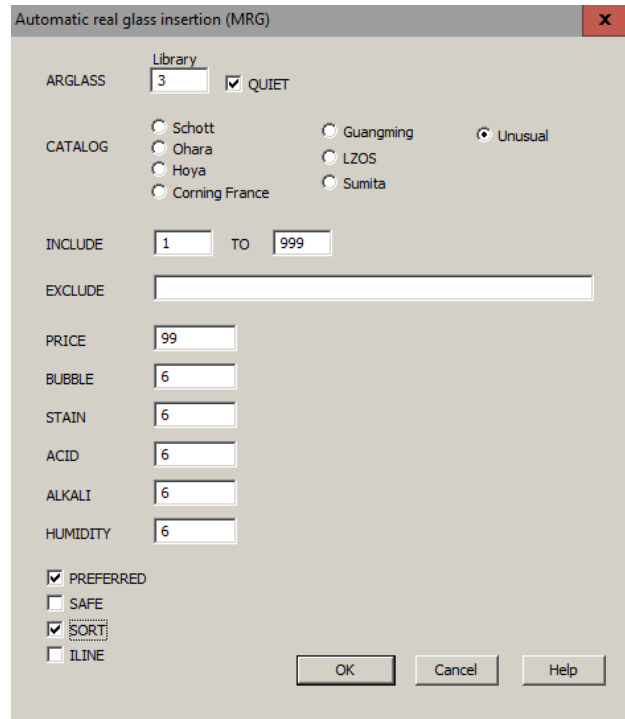


Assigning Real Glasses and Plastics

Next, we run the Automatic real glass insertion program, selecting the Unusual glass catalog.

That replaces all plastic elements that have a glass model with a real plastic.

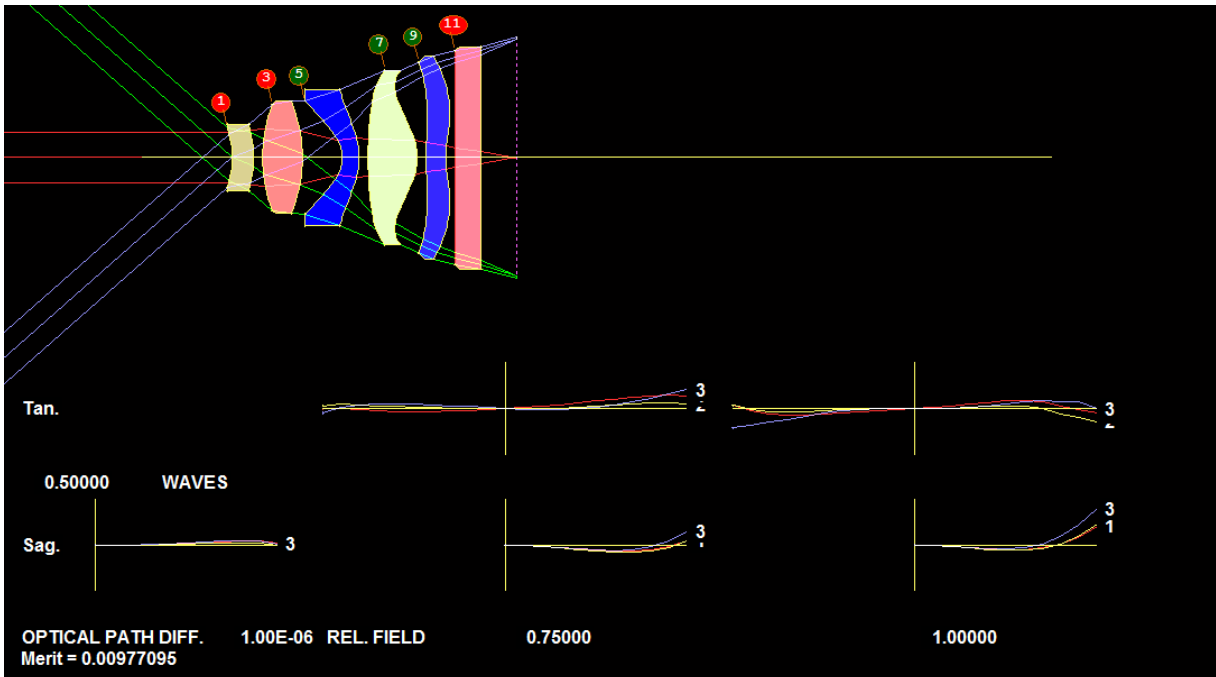
Then we run it again, selecting the Ohara catalog. That replaces the first two elements, which are not plastic.



The final result is a very good cell-phone camera lens.

- Diffraction limited.
- No distortion.

All is done without the hassle of finding a starting point manually. The Global Search algorithm can do it for you.



Summary

The DSEARCH™ and other Automatic Design tool in SYNOPSIS™ provide an effective, fast, and practical solution for optical designers.

1. They can ease the burdens on the designers in finding good starting points for their design projects.
2. They help the designers explore the design space efficiently and to discover alternative design forms that may deliver better performances

With the automatic design tools in SYNOPSIS™

- No need for paraxial or third-order designs.
- No need for a starting design.
- Just tell the computer what you want.
- And automatic design algorithms do the work.

To submit a trial request, navigate to
<https://osdoptics.com/accessinstallation/>

For any questions or inquiries, please contact us at
info@osdoptics.com