# SYNOPSYS™ *(SYNthesis of OPtical SYStems)*

Lens Design Software

Automatic Design Tools

DSEARCH™ (Design Search)
ZSEARCH™ (Zoom Search)
AEI/AED (Automatic Element Insertion/Deletion)
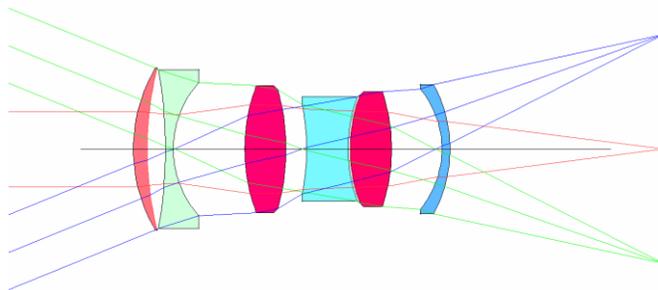
Design search: 7 element system (F2.8) built in seconds

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

Optical Systems Design

SYNOPSYS™
Lens Design Software

Table of Content

Introduction

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

- DSEARCH™ (Design SEARCH),
- ZSEARCH™ (Zoom SEARCH) for zoom lens,
- AEI (Automatic Element Insert)

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

After identifying the design candidates with DSEARCH™ or ZSEARCH™ , you can use other Automatic Design tools such as AEI (Automatic Element Insert) to refine the system. On the other hand, AED (Automatic Element Deletion), can help you decide whether you can 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 (SYNOPSYS™) 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 SYNOPSYS™ Lens Design Software
Lens Design, Automatic and quasi-autonomous computational methods and techniques

SYNOPSYS™ Lens Design Software
Essential Tool for Optical Design

DSEARCH™

## SEARCH and OPTIMIZE in a breeze
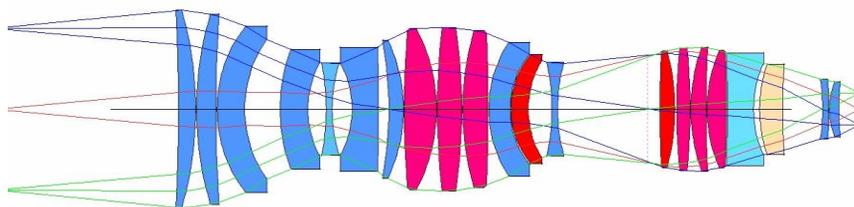
**21-element microlithography objective designed by SYNOPSYS™
automatic design search (DSEARCH™) in 44 minutes.**

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 closed enough to the desired system. He/she then defines a merit function that sufficiently models the system specifications (or design goals). The optimization algorithm of the design software varies randomly the selected lens data (the optimization parameters) to drive the

system from its current state (the starting point) into optimized configurations that minimize 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 analogy to a mountain range, with many minima. Like skiing 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 for landing at the lowest valley in the design space (point A in the illustration). However, it is difficult to reach; especially in the traditional approach where the designer usually starts with certain configuration that is closed 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 drive the system into some nearby local minimum (for example, point B) and stop there, and thus misses the other design forms that can deliver yet better performances (for example, points C and D).
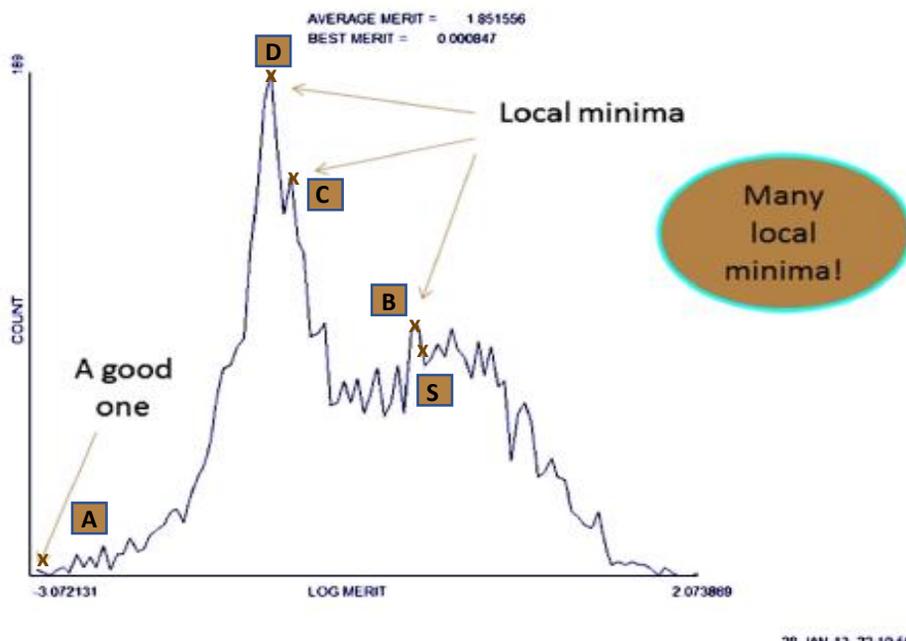
DSEARCH™ (Design Search) and the Design Space

The DSEARCH™ in SYNOPSYS™ is an Automatic Design tool created to provide an effective, fast, and practical solution for optical design. It is created
1. To ease the burdens on the designers 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 lower valleys, 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-select starting point (as in the traditional approach), this method is also referred to as the Global Search method.

Standing at the mountain top (Plane-parallel plates)

Descends in this direction and you go here

In this directions… you go here

The distance you jump downhill is an input parameter in the optimization.
How fast you can go depends on the speed of the optimization process.
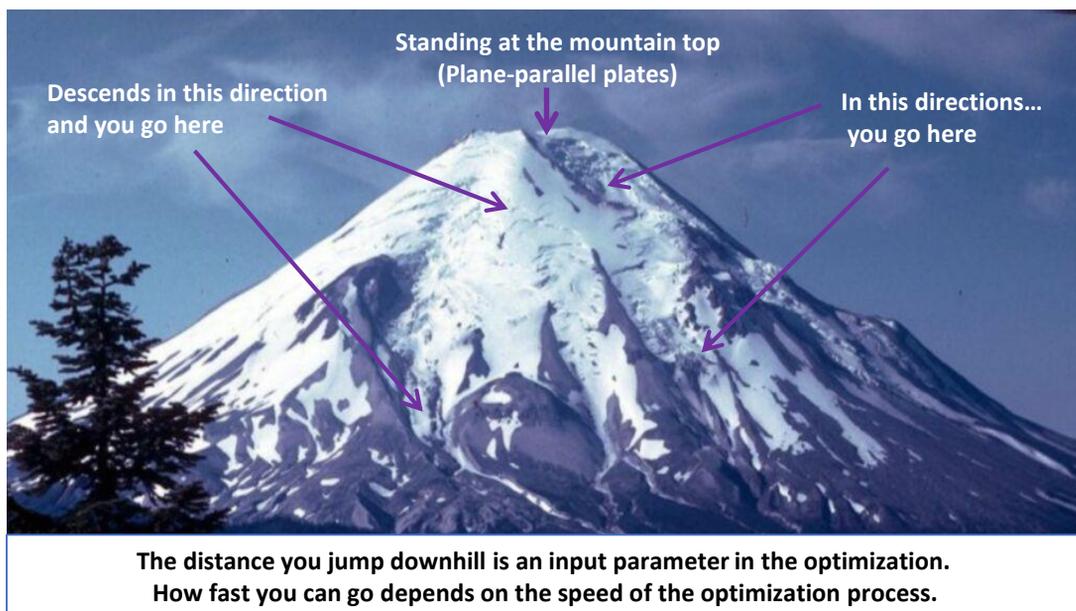
To implement the DSEARCH™ method, we
a. Start with a system consists of flat plates (standing at the mountain top)
> By starting with the flat plate systems and then modifying the optical power of the plates, we can probe the massive design space in an effective way to reach corners that are less visited by the conventional design method. Such exploration of the optical design space can lead to design forms that are not seen before and can only be done efficiently with modern computers.

b. Generates enough trial designs (descend directions) to sample the design space effectively (to scout out other valleys)
> Before descending from the merit function mountain top, the question one would ask is, 'which directions will bring the system to the deep minima?'. Trying each direction is too time consuming and not practical. In SYNOPSYS™, 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 process.

c. Equip the search process with fast optimization algorithm
> The PSD III optimization algorithm in SYNOPSYS™ is fast and effective.

d. Settle with good or better designs, not the holy grail of the 'absolute best'

Binary Search in DSEARCH™

We start DSEARCH™ with the declaration of 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 descend directions).

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

Bit 1	Bit 2	Bit 3	Bit 4	Bit 5	Bit 6	Bit 7	Bit 8

There are totally $2^8 = 256$ 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 descend 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 trail systems represent some very lousy systems with high merit functions 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 refine the prescription of the design trials.

The PSD method, was first developed by Don Dilworth, the creator of the SYNOPSYS™ 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 and faster.

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 SYNOPSYS™ is fast and powerful. It can do each optimization in less than one second. 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 SYNOPSYS™

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

The following link shows a video demonstrate the speed of PSD III in optimizing a very lousy 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.
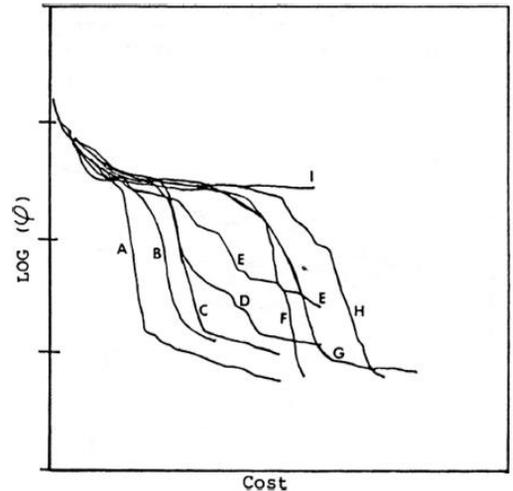
http://www.osdoptics.com/video/optimization_of_7_lenses.mp4

Accelerators in DSEARCH™ : Quick mode and Multicore

For most practical modern optical systems, we have large number of trials to evaluate. Therefore, we want to speed things up furthermore. There are two mechanisms in SYNOPSYS™ that help accelerate the DSEARCH™ 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 differentiate 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 process, the best 10 trials (ranked lowest in the merit function) will be retained and go through stricter optimizations and ranked accordingly again by their final merit functions. 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.
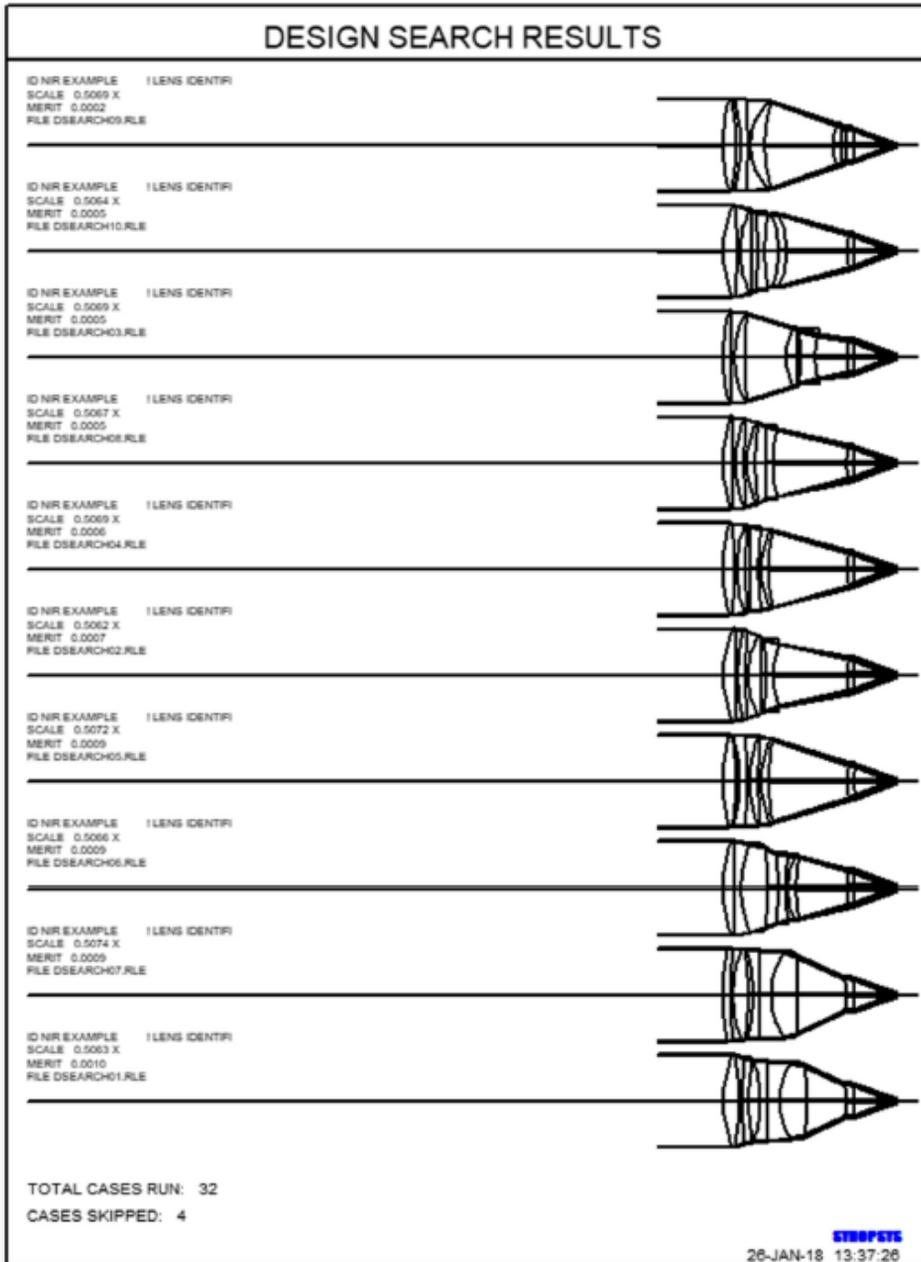
An Example DSEARCH™ Job

This example is 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 with the traditional approach from scratch. Dilworth use DSEARCH™ to find good starting points and then refined the system.

They both came to excellent final designs. But Dilworth's process was faster with the help of the computer global search.

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 Global Search method?
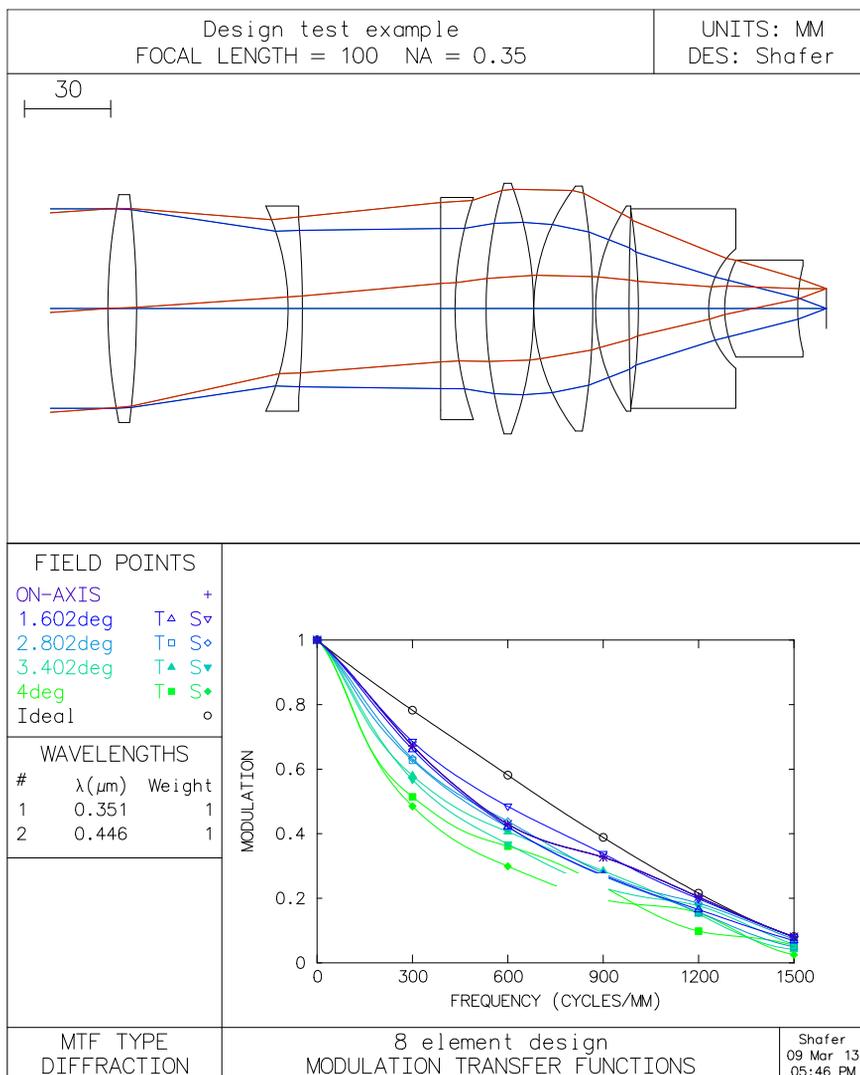
DSEARCH™ Macro with Design Goals

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 is 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.

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, one can reach a very good final design, in a much shorter time than 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.
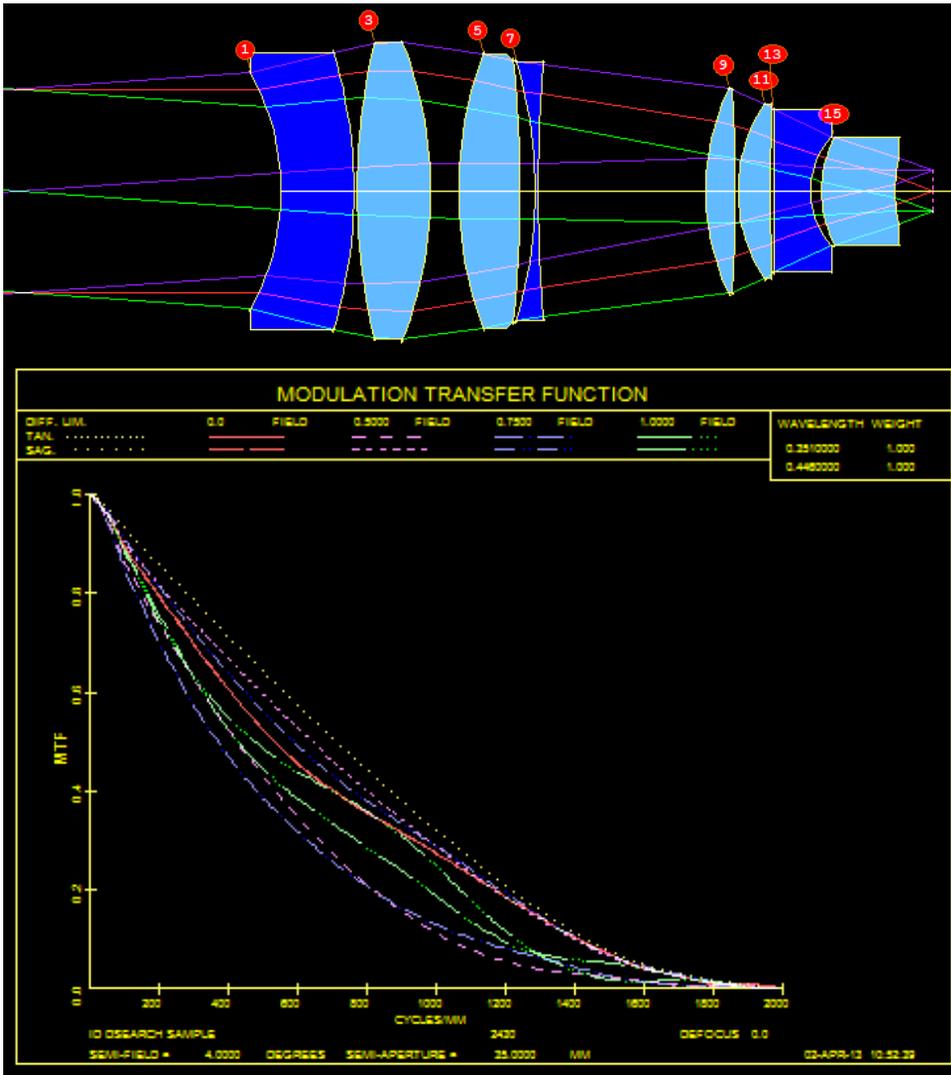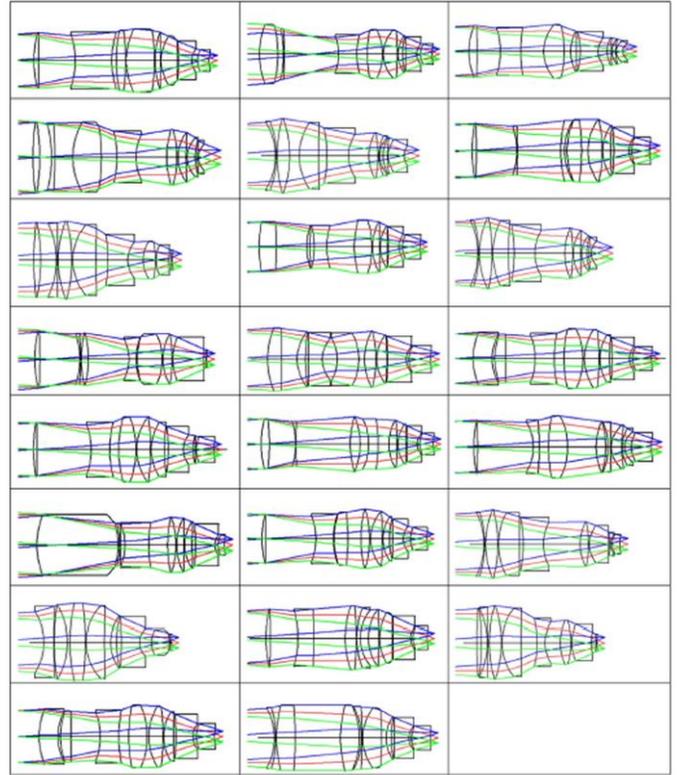
# ZSEARCH™
and
AEI (Automatic Element Insert)
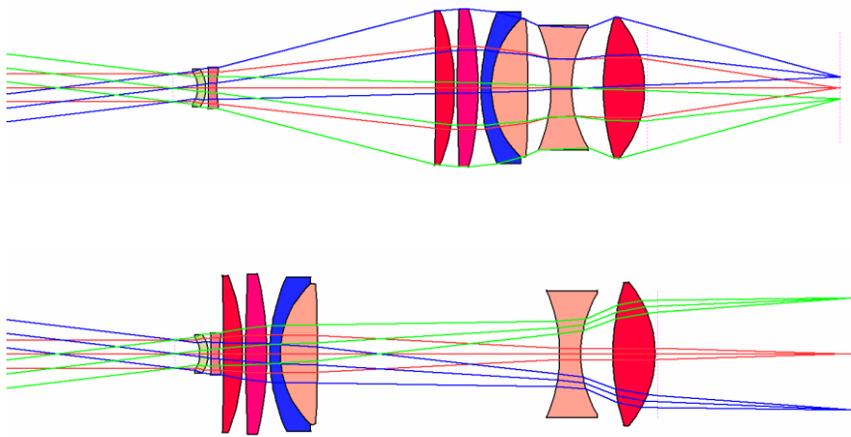
ZSEARCH™

Traditionally, to design a zoom lens, one will produce some initial sketches and calculations that may spread over 10 pages or more…
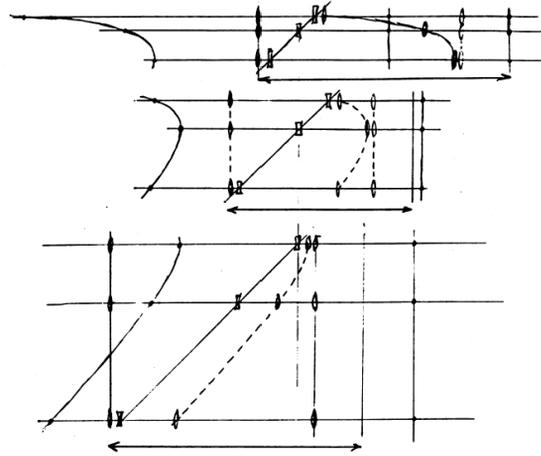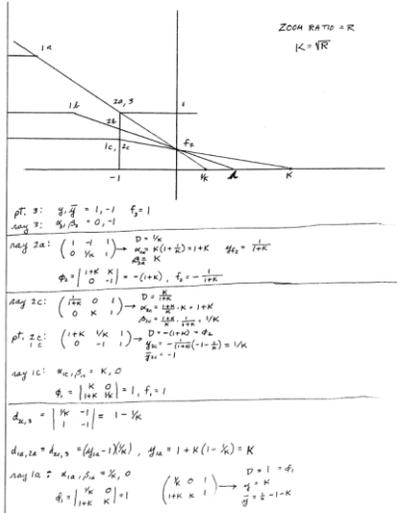
This is an example of the designer doing most of the work. **Can we get the computer to do the more for us?** That triggered the development of ZSEARCH™ in SYNOPSYS™.

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:

Image plane

Range focus

Variator, compensator

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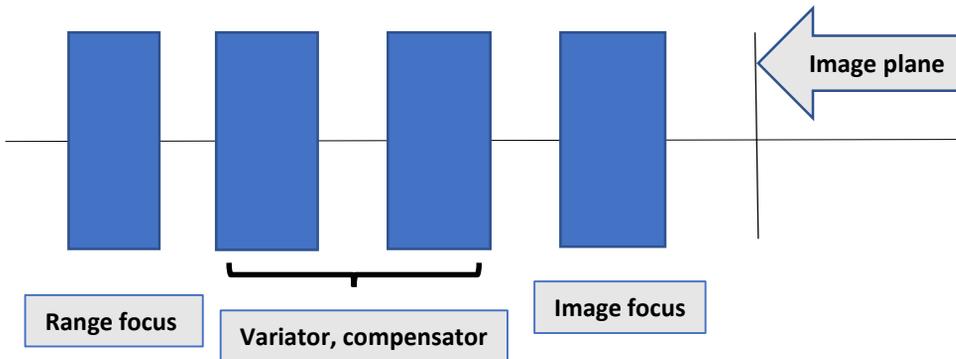
Let's say (an educated guess) we'll need three elements in each group.
Let the program do the rest!

ZSEARCH™ Input Macro

Here is an exemplary input macro to ZSEARCH ™:

```
LOG              ! to keep track of things later
PROJ             ! 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 last group
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
PROJ            ! see how long the run took.
```

ZSEARCH™ Results

ZSEARCH™ comes back with the 10 best lenses it found.
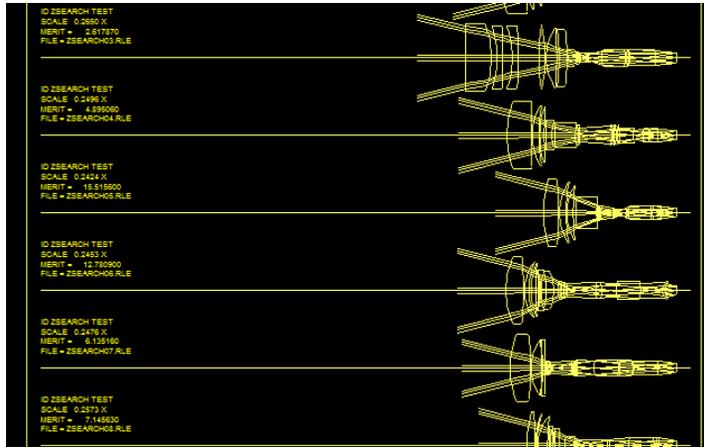
This is the top lens returned by ZSEARCH™ :
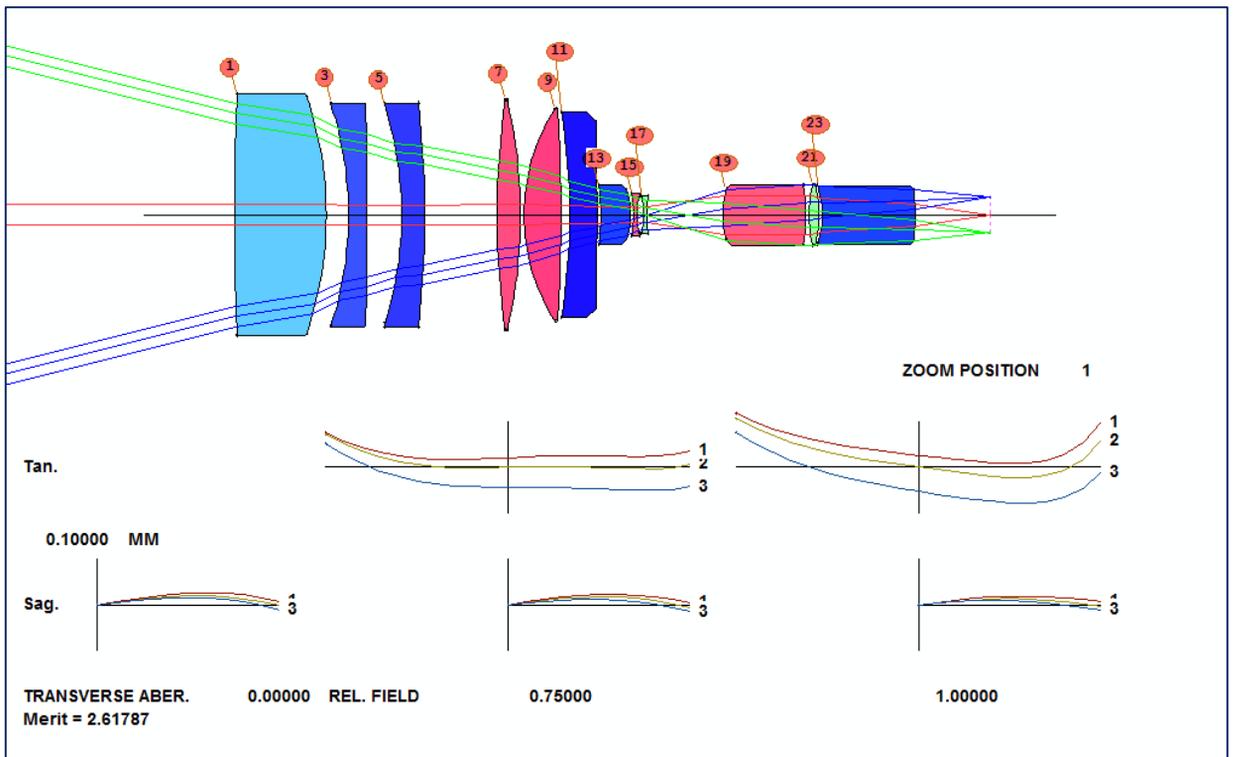
Improving the Zoom Lens Design with Optimization

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

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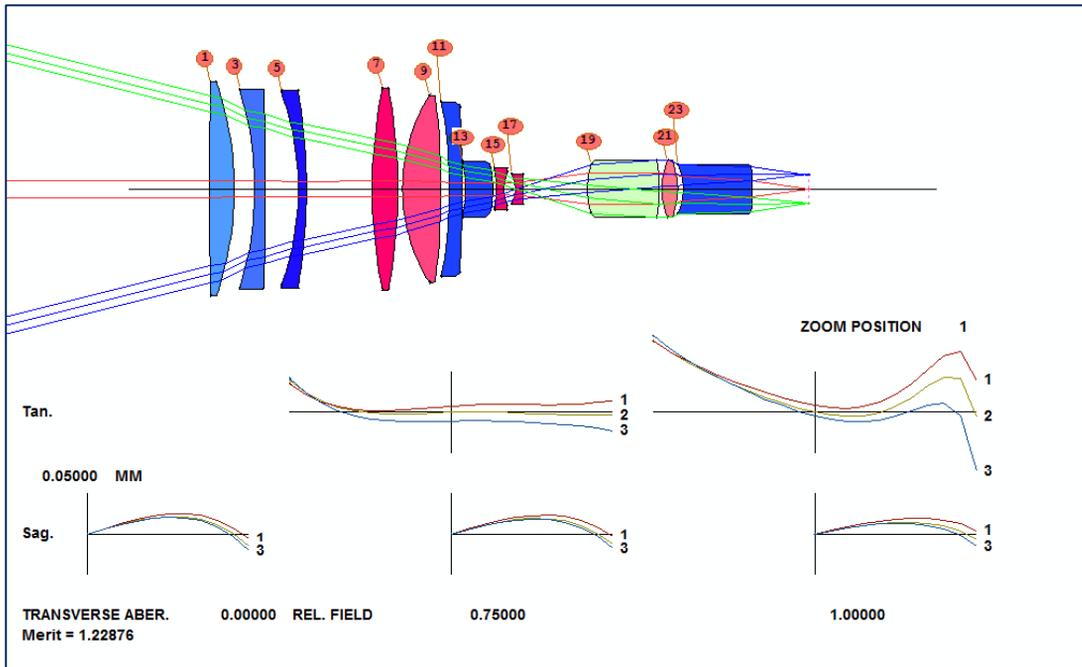
To further improve the lens system performance, we need more elements. Where should they go?

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 solution lenses 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.
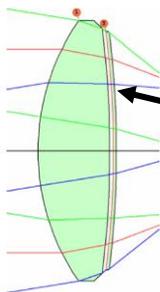
Thin shell added to side 2

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 for design.

The implantation of these tools are 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 build up an entire 5-element system one element at a time from nothing:

http://www.osdoptics.com/video/an_example_of_SPB_in_action.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. Now there are 27 elements in the system:
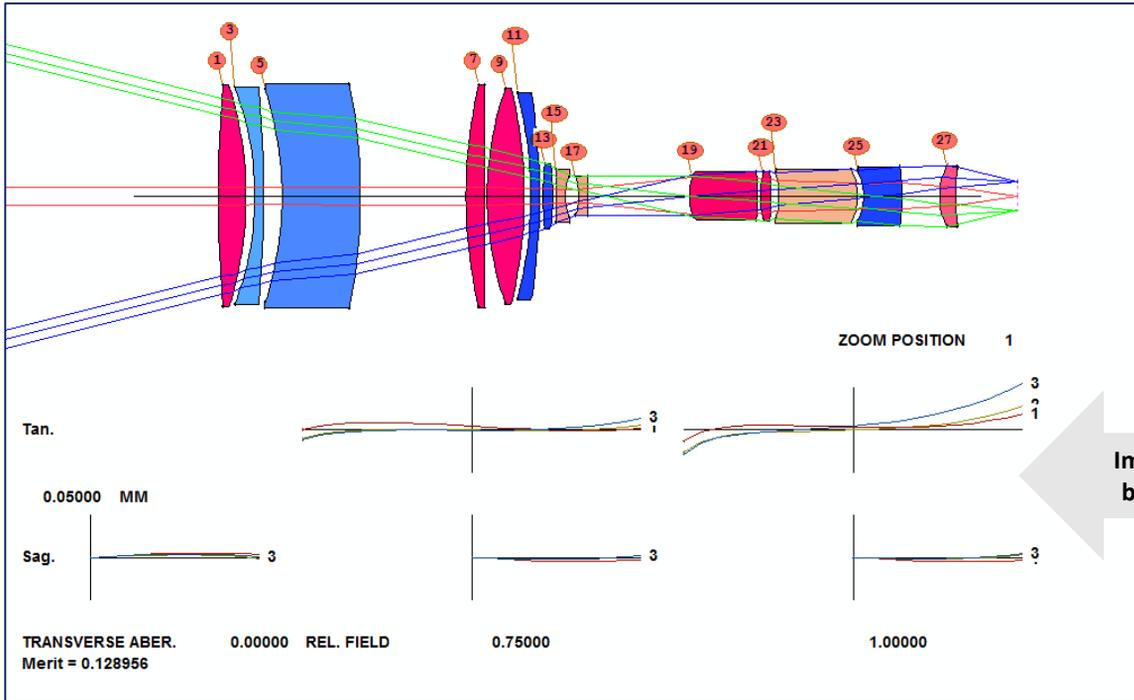
Sometimes, you would wonder whether your system can work as well with less elements. The AED (Automatic Element Delete) tool is SYNOPSYS™ can help you make that decision.
Combining AED with AEI, you can generate yet new design form that delivers even better performances.
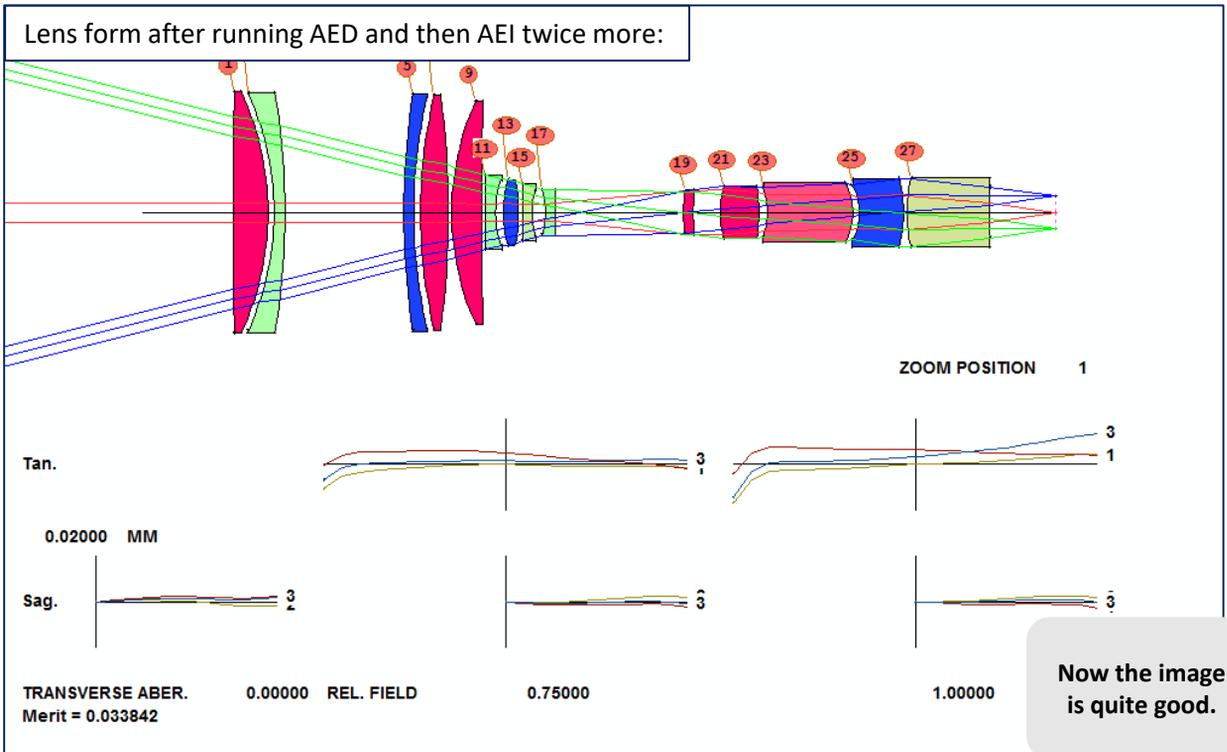
Note that the ray fan plot scale changes 0.05mm to 0.02mm in this design.

Assigning Real Glasses to Replace the Glass Models

When you do the designs, you usually start with Glass Models. Now when you get a pretty good lens, you would want to use real glasses in your design before handing it over to the optics shop. In SYNOPOSYS™, you can use ARGLASS™ (Automatic Real Glass Program) to substitute real glass for the models.

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

ZOOM POSITION   1

Same quality

0.02000   MM

Sag.

TRANSVERSE ABER.   0.00000   REL. FIELD   0.75000   1.00000
Merit = 0.0691492
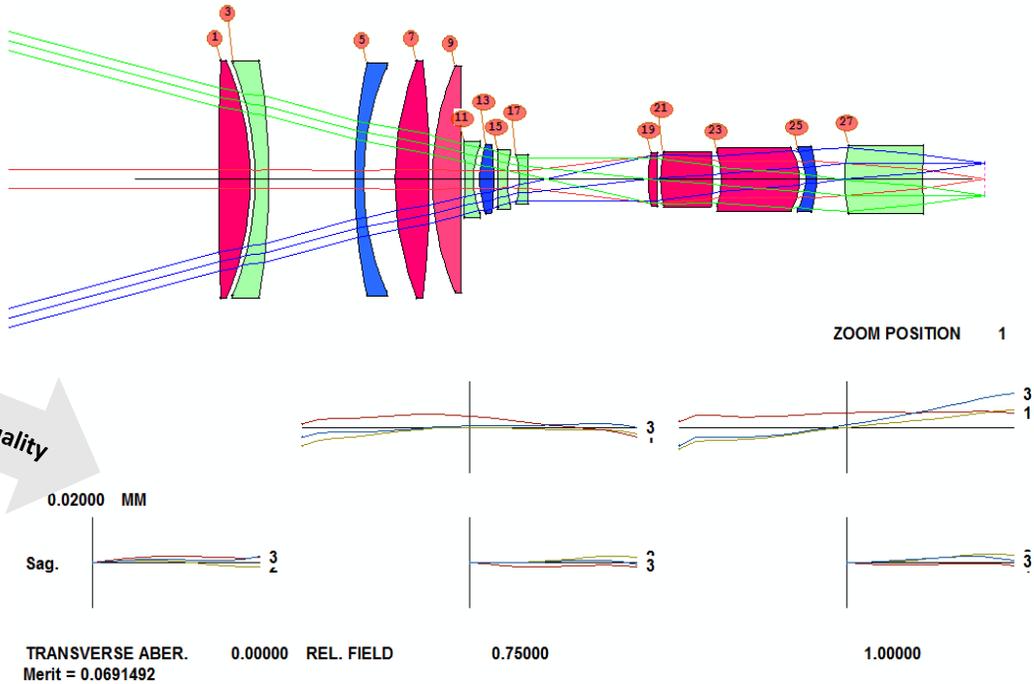
To complete the design, we need a CAM curve to define the complete movement of the zoom groups.

CAM Curve in SYNOPSYS™

When designing zoom lens, we can only design and optimize the system at limited discrete zoom positions where the lens groups placement 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 SYNOPSYS™:

1. Polynomial that fit 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 zoom position 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 SYNOPSYS™ that allows the designer to examine their zoom lens in a continuous manner, not just at the discrete zoom positions.

http://www.osdoptics.com/video/the_lens_is_fit_to_20_zooms_with_cubic_interpolation.mp4
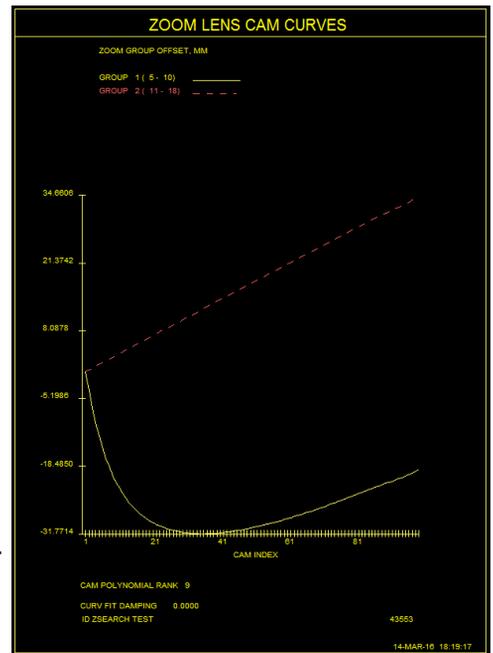
Example 1. Wide-angle Eyepiece design with DSEARCH™

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 ¼ wave or better in d light at 0.58756 um
- Correction to ½ wave or better in C (0.6563 um) and F (0.4876 um) 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.
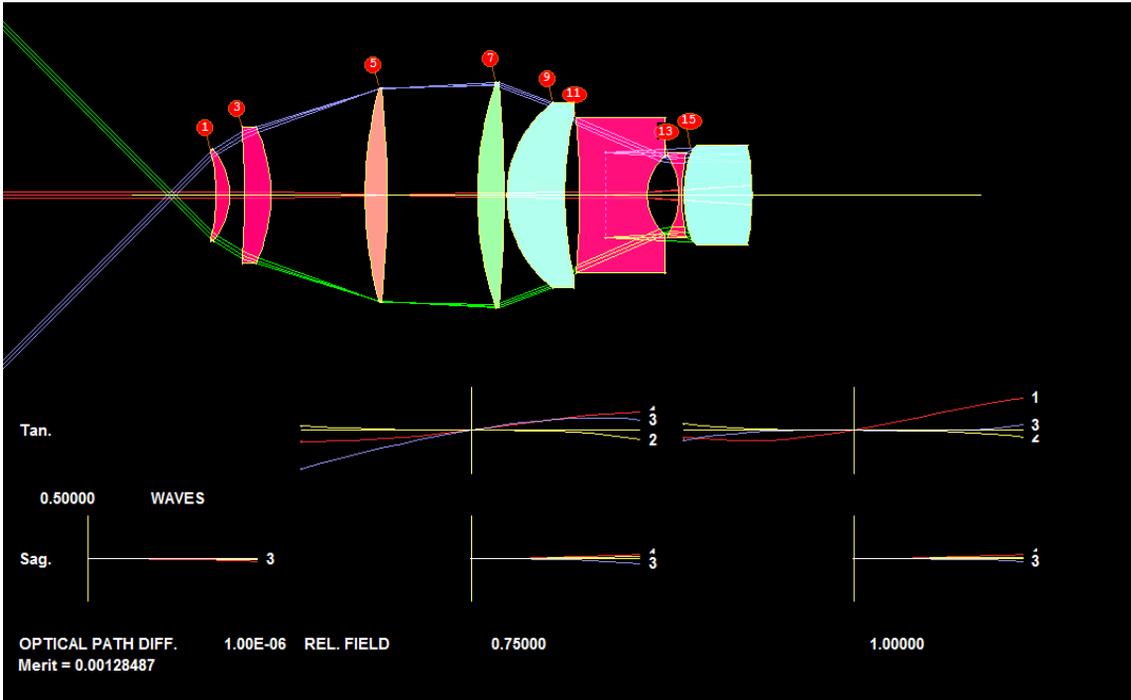
To make it better,

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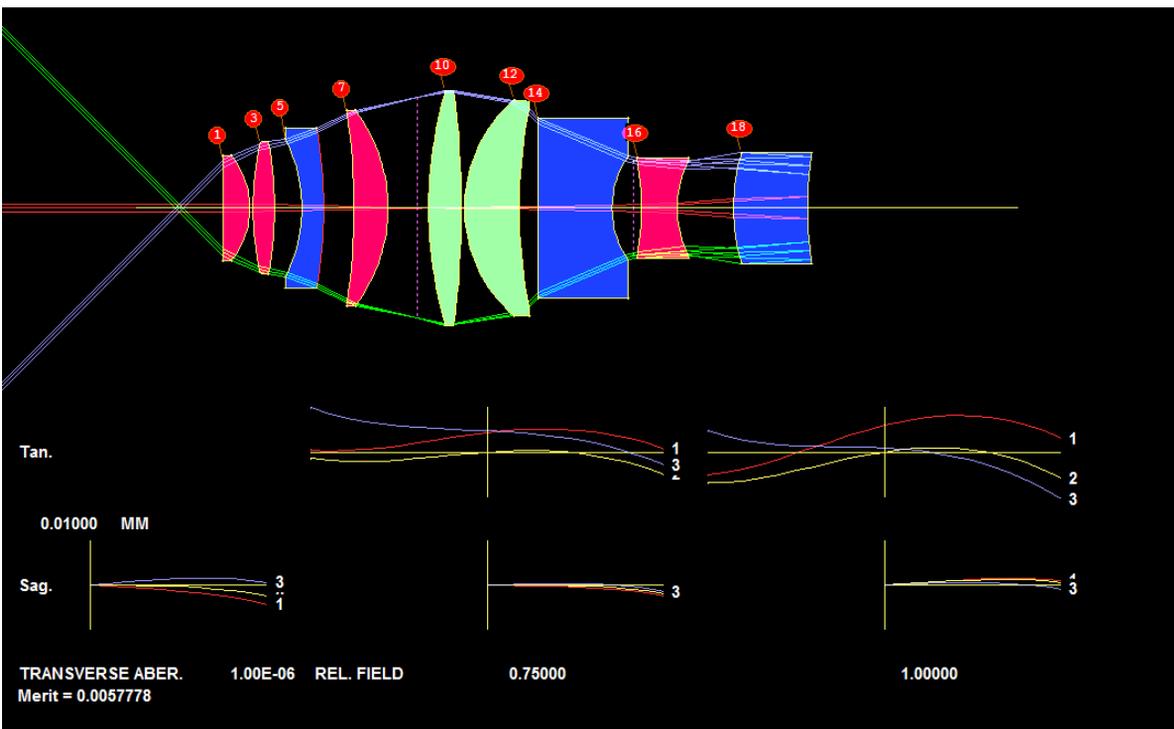
Final Design

With some more optimization, we arrive at this pretty good lens.
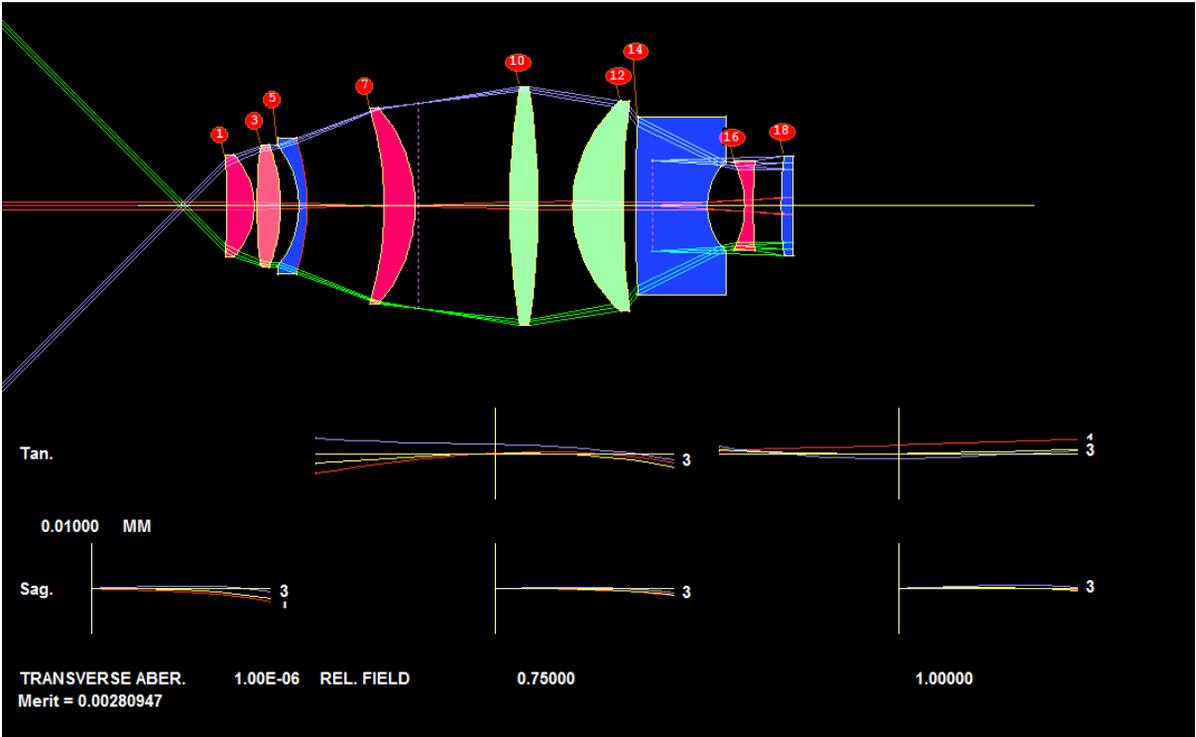
We are now ready to replace the model glass with real glass. The lens is even better after inserting real glasses.
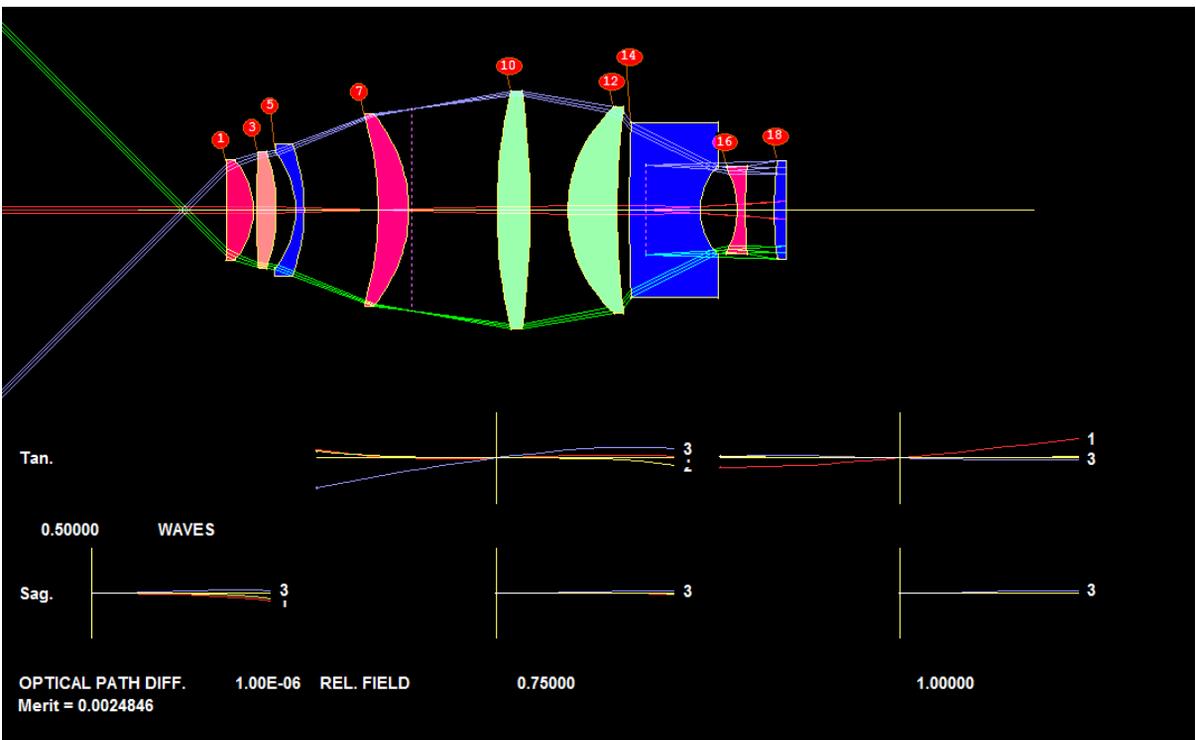
Some Image Analysis

Here is the diffraction point-spread image at 20 points in the field.
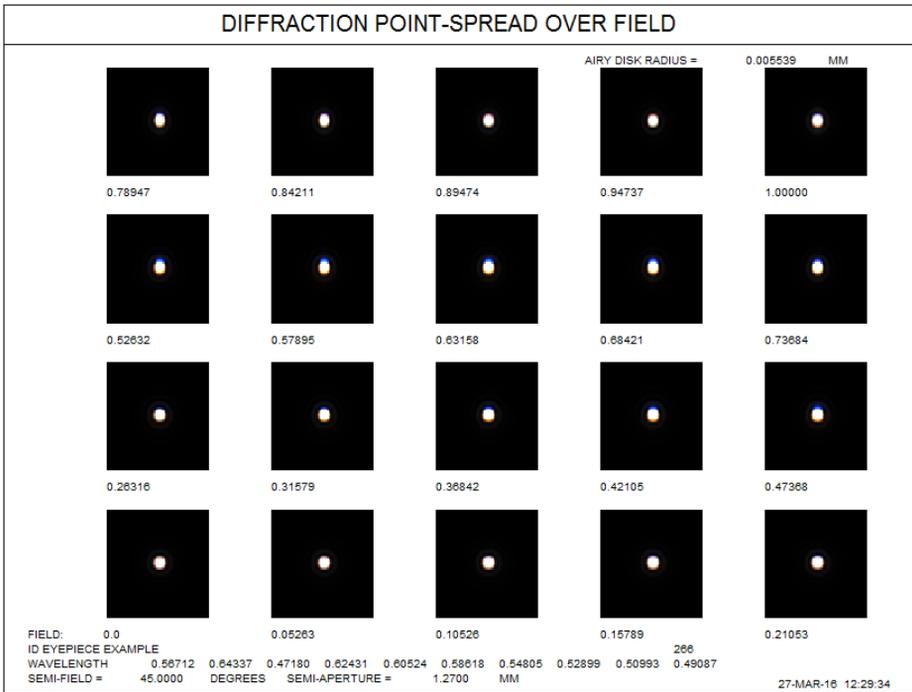
Here is the Grid Distortion analysis for the lens. To the eye, essentially perfect.
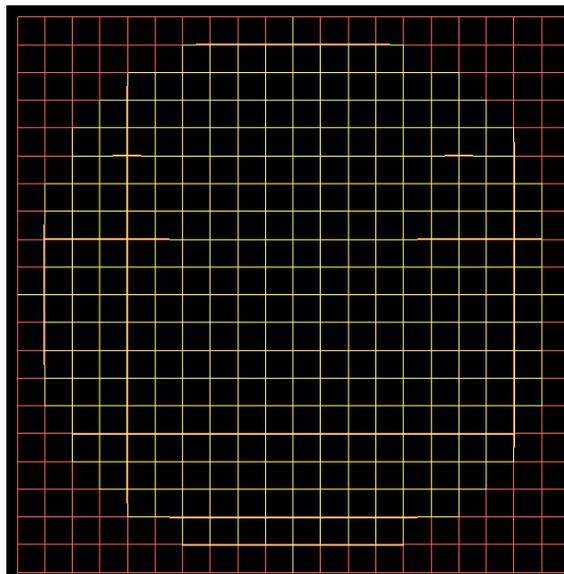
Example 2: A Cell-phone Camera Lens with DSEARCH™

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™ return a good starting point for the design. You can click at the following link to view part of the DSEARCH™ process:

http://www.osdoptics.com/video/DSEARCH_for_cell_phone_camera.mp4
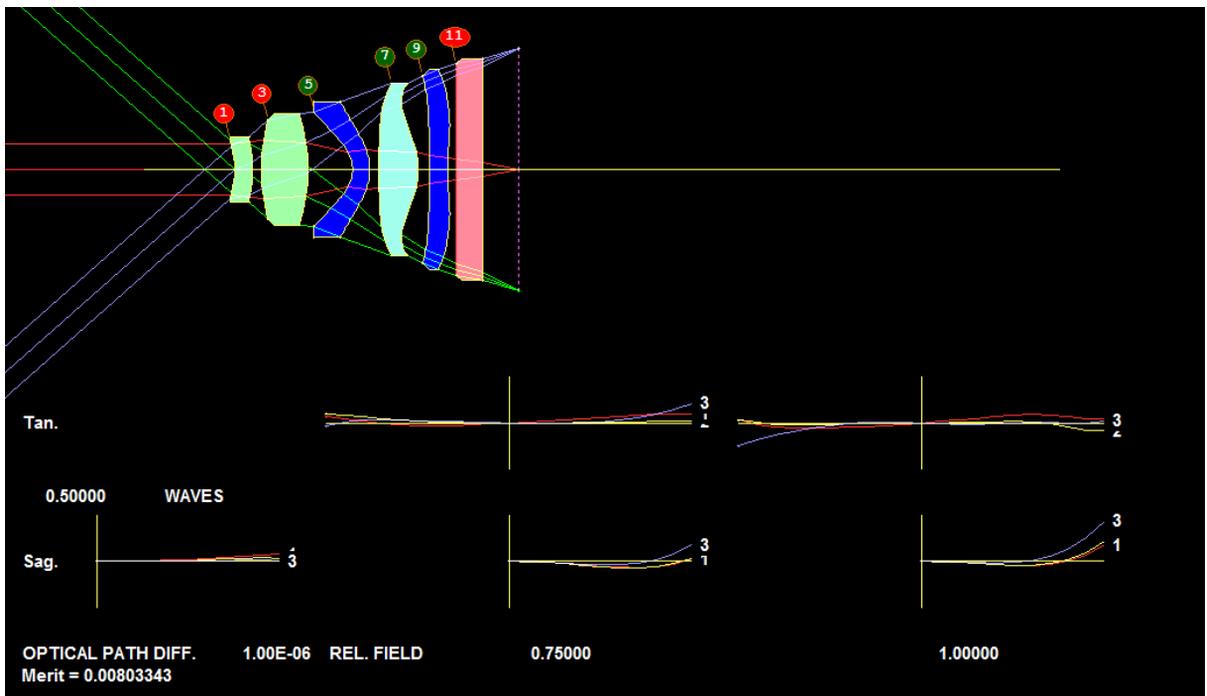
Assigning Real Glasses and Plastics

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.
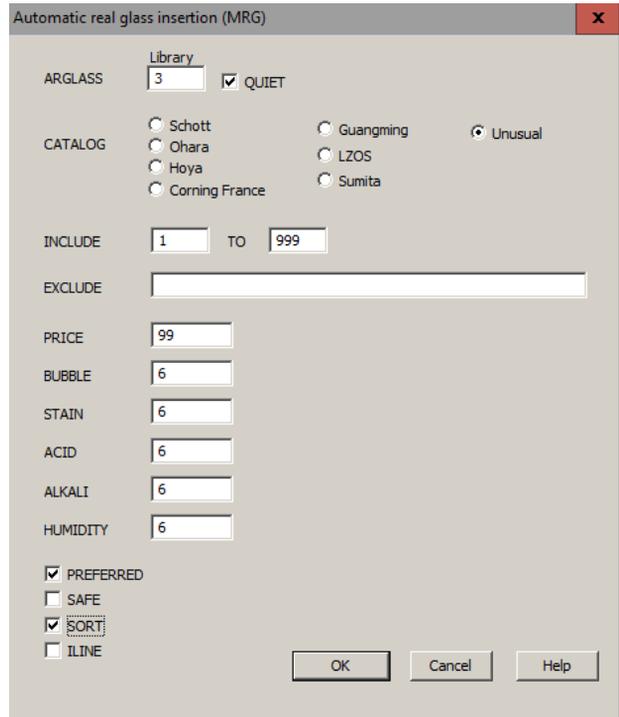
The final result is a very good cell-phone camera lens.
- Diffraction limited.
- No distortion.

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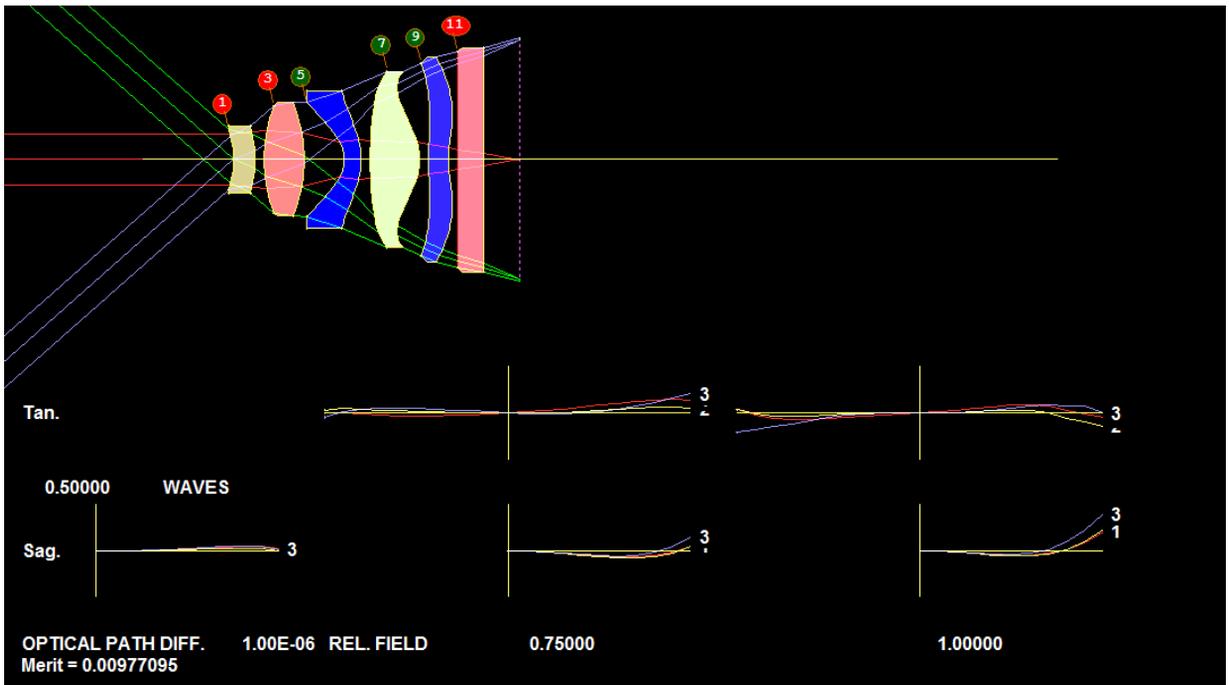
Summary

The DSEARCH™ and other Automatic Design tool in SYNOPSYS™ are created to 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 to discover alternative design forms that may deliver better performances

With the automatic design tools in SYNOPSYS™
- No need for paraxial or third-order design.
- No need for starting design.
- Just tell the computer what you want.
- And automatic design algorithms do the work.

Download a free trial version at the following link:
http://osdoptics.com/installation.php

For any questions or inquiries, please contact us at
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