

Lesson 38: A Zoom Lens from Scratch

It's noon on Friday. Your boss runs in. "The customer wants a proposal for an 8x zoom lens by 8:00 AM Monday". You've never designed a zoom lens in your life. Your job hangs in the balance. He gives you a list of requirements and heads out. What now?

You might go to a patent database and try to find a lens that resembles what you need. That would probably take all afternoon -- but you have a better plan.

First, be glad you chose SYNOPSIS™ for your optics design code. You have a great assistant helping you. Here's what you do.

1. Start the program.
2. Type **HELP ZSEARCH** in the Command Window. Open that chapter, which is 10.7.3.
3. Read the *whole chapter*. Yes, read it. To be a professional lens designer you have to know what you are doing. But if you already know how to do other tasks on SYNOPSIS you are almost there. So it's an easy read. And now you know something about zoom lenses, so it's time well spent.
4. Set up your input to ZSEARCH. The lens is to be F/3.5 with a semi field angle of 14 degrees in the wide setting and a GIHT of 5 mm.

Here is what will be in your MACro: (L38M1)

```
LOG                ! to keep track of things later
PROJ               ! to see how long this run took
CORE 16           ! on our 8-core hyperthreaded PC, it runs 8 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
NOVIG
END

GOALS
ZOOMS 5
GROUPS 3 3 3 3   ! lens has four groups with 12 elements altogether
ZGROUP 0 Z Z 0   ! and groups 2 and 3 will zoom

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
RT 0.5
DELAY OFF         ! don't ask to abort other cores
GIHT 5 5 10       ! the image height is 5 mm for all zooms, with a weight of 10.
BACK 20 .02       ! the back focus is 20 mm and will vary. A target will be added to the
! merit function with a low weight.
FOV 0 .4 .6 .85 1 ! correct five field points
FWT 5 4 3 3 3
```

```

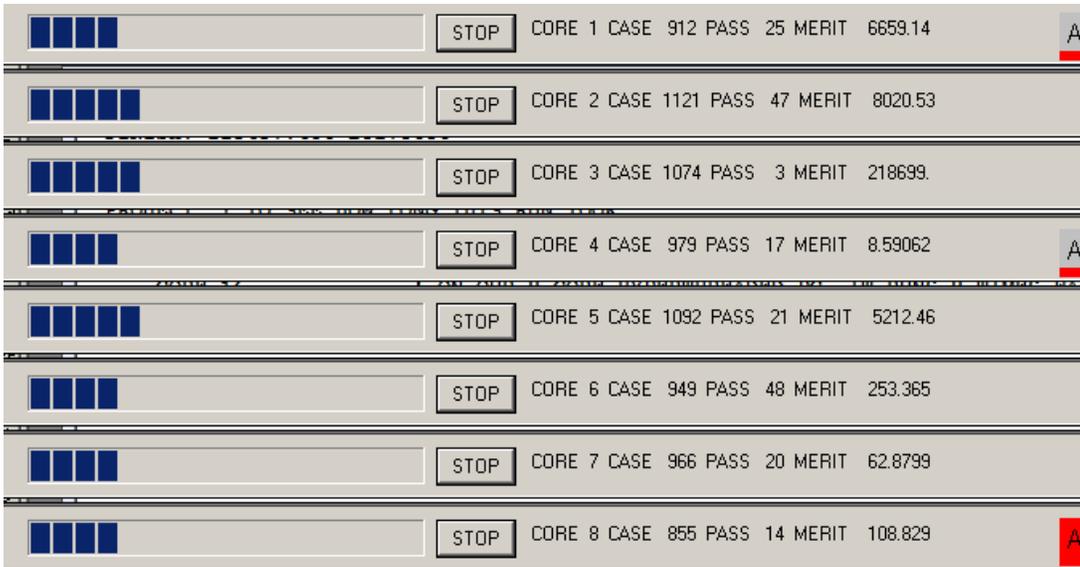
COLOR M           ! correct all defined colors
ANNEAL 50 10 Q    ! anneal the lens as it is optimized in real-ray mode
QUICK 50 100      ! 30 passes in quick mode, 40 in real-ray mode
END

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

```

The zoom lens will consist of four groups, each with three elements. The first group will be used for range focus in the final design, and the last is fixed to provide a constant F/number over the zoom range. It is likely we will need more than 12 elements -- and we can ask ZSEARCH for more if we want to -- but it will run faster if we start here and then add elements later where needed. It will probably require more than five zoom positions too -- but we start with a simple system (which runs faster) and can easily add things later when the need arises.

We run this MACro and watch the progress on 16 windows that monitor each of the cores we authorized.



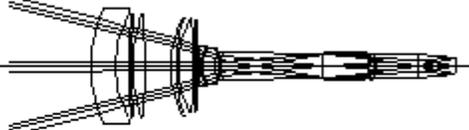
When the quick mode is finished, the program optimizes each of the best 10. After about 44 minutes we see these results:

ZOOM DESIGN SEARCH RESULTS

ID ZSEARCH TEST
SCALE = 0.2763 X
MERIT = 0.617007
FILE = ZSEARCH06.RLE



ID ZSEARCH TEST
SCALE = 0.2727 X
MERIT = 0.869036
FILE = ZSEARCH04.RLE



ID ZSEARCH TEST
SCALE = 0.2784 X
MERIT = 1.326140
FILE = ZSEARCH03.RLE



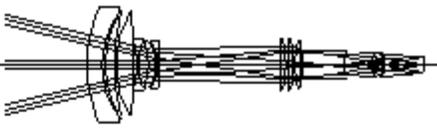
ID ZSEARCH TEST
SCALE = 0.2634 X
MERIT = 1.545610
FILE = ZSEARCH01.RLE



ID ZSEARCH TEST
SCALE = 0.2717 X
MERIT = 1.626360
FILE = ZSEARCH09.RLE



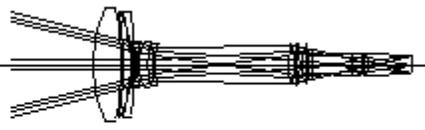
ID ZSEARCH TEST
SCALE = 0.2636 X
MERIT = 2.066730
FILE = ZSEARCH05.RLE



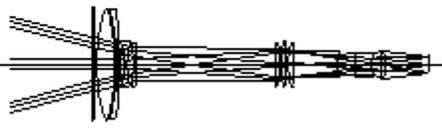
ID ZSEARCH TEST
SCALE = 0.2601 X
MERIT = 2.115210
FILE = ZSEARCH08.RLE



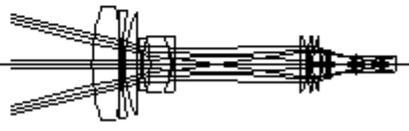
ID ZSEARCH TEST
SCALE = 0.2616 X
MERIT = 2.237070
FILE = ZSEARCH07.RLE



ID ZSEARCH TEST
SCALE = 0.2673 X
MERIT = 2.291080
FILE = ZSEARCH10.RLE



ID ZSEARCH TEST
SCALE = 0.2605 X
MERIT = 3.236770
FILE = ZSEARCH02.RLE



TOTAL CASES RUN: 4096

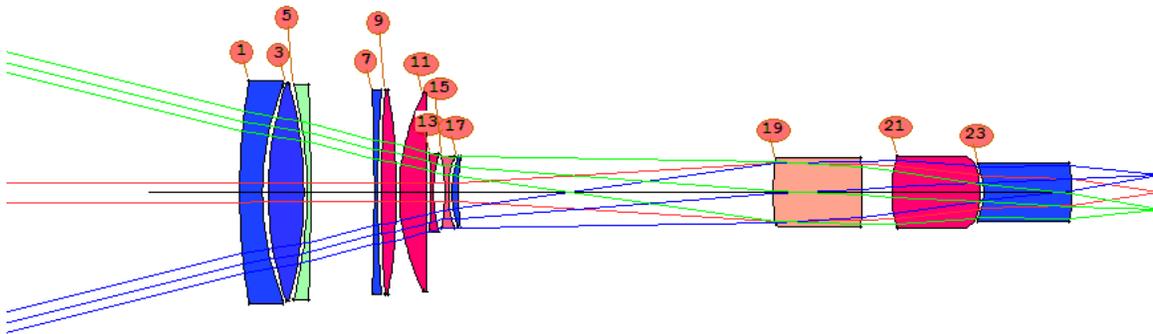
CASES SKIPPED: 0

SYMPST

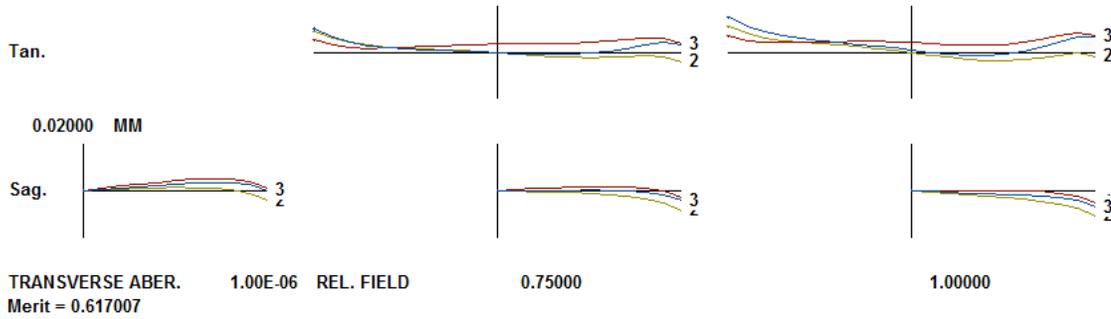
06-JUN-17 12:39:15

A glance at the merit function values shows that most of these are promising candidates. The program has loaded the best one into the PAD display.

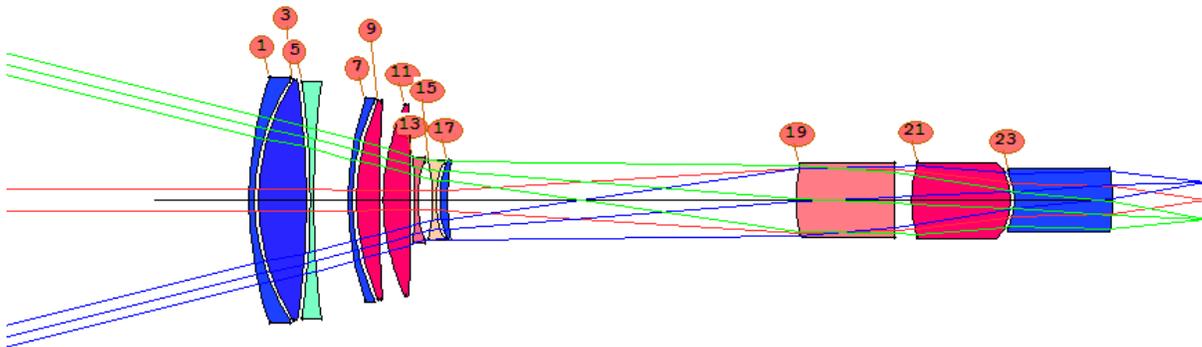
We run the MACro **ZSS**, which ZSEARCH has created, to look at all 10 of the matches, and decide that this one is indeed the best starting point. Not perfect yet, to be sure -- but not bad considering we gave the program nothing but a list of goals and constraints. This will be our starting lens.



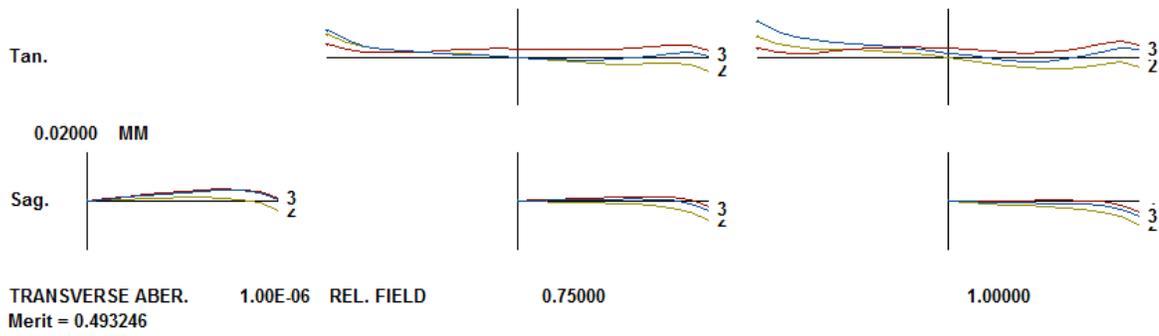
ZOOM POSITION 1



The program has created an optimization MACro for us, already loaded with a starting merit function definition and a set of variables. We run this, and the MF barely moves. Then we click the Anneal button, change the starting temperature to 50, request 100 passes, and click OK. (A higher temperature is often called for when the lens is stuck in a deep minimum, but when you're starting a new design, that would probably just slow things down.) The MF now has come down to 0.493



ZOOM POSITION 1



Often one wants to know why the MF won't go any lower. A great way to check is to type **FINAL 5** (or the AI symbol FF, which we have defined to equal that command). That shows the five largest items in the MF.

SYNOPTSYS AI>FF

FINAL 5

ABERRATION LIST

	NAME	TARGET	WEIGHT	RAW VAL.	FINAL ERROR	R. EFFECT
5	A BACK	20.0000000	0.0200000	24.2573	0.851455E-01	0.014629
6	AAC	30.0000000	1.0000000	-----	0.157788	0.050240
342	A 1 YC	0.0000000	15.4402596 SR	0.0040	0.624556E-01	0.007871
		0.85000 0.12500	-0.12500 0.00000			
498	A 1 YC	0.0000000	15.4402596 SR	0.0044	0.674752E-01	0.009187
		1.00000 0.12500	-0.12500 0.00000			
3046	A 1 YC	0.0000000	15.4402596 SR	-0.0042	-0.646104E-01	0.008424
		1.00000 0.12500	-0.12500 0.00000		ZOOM 5	



Here we notice that the **AAC** wants an aperture larger than 30 mm. That aberration is much bigger than the others, so maybe we should increase the target.

Here's a useful trick: When we get to a stage that we might want to come back to later (if some of our ideas do not work out as well as we hope) we click the **ACON copy** button  in the top toolbar. If the lens we started with is in configuration 1, as it is by default, this puts a copy in alternate configuration 2, or ACON 2. Then we make a checkpoint in that ACON and develop the design further, and can instantly go back to ACON 1 with the "1" button



should we want to. We use all six configurations in this way quite often.

In the AANT file, change the line

AAC 30 1 1

to

AAC 35 1 1

Also, we want the real chief ray to go exactly to the center of surface 19, the stop, so we change the declaration to

APS -19

in a CHG file or with the WorkSheet™. That calls for a real pupil, which means that every real chief ray is found by iteration and will go where we want.

Make a new checkpoint and run the MACro and anneal again. The MF comes down to 0.386. The ray fans look great, but many elements are too thin. We have to change the MF again. While we're at it, we delete all the sections that define aberrations in each zoom group higher than zoom 1.

```
ZOOM          1
M 0.500000E+01 0.100000E+02 A GIHT
GSR 0.500000 5.000000 4 M 0.000000
GNR 0.500000 4.000000 4 M 0.400000
```

```

GNR 0.500000 3.000000 4 M 0.600000
GNR 0.500000 3.000000 4 M 0.850000
GNR 0.500000 3.000000 4 M 1.000000
  ZOOM 2
M 0.500000E+01 0.100000E+02 A GIHT
GSR 0.500000 5.000000 4 M 0.000000
GNR 0.500000 4.000000 4 M 0.400000
GNR 0.500000 3.000000 4 M 0.600000
GNR 0.500000 3.000000 4 M 0.850000
GNR 0.500000 3.000000 4 M 1.000000

```

...

Then we modify the zoom 1 requirements so they apply to all zooms. Now, if we want to change a weight somewhere, it will apply to all zooms.

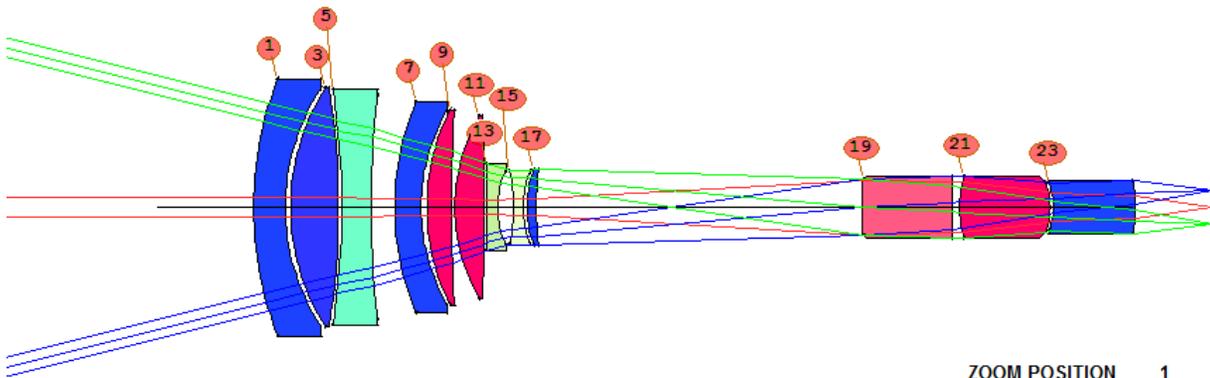
```

ZGROUP ALL
M 0.500000E+01 0.100000E+02 A GIHT
GSR 0.500000 5.000000 4 M 0.000000
GNR 0.500000 4.000000 4 M 0.400000
GNR 0.500000 3.000000 4 M 0.600000
GNR 0.500000 3.000000 4 M 0.850000
GNR 0.500000 3.000000 4 M 1.000000
END

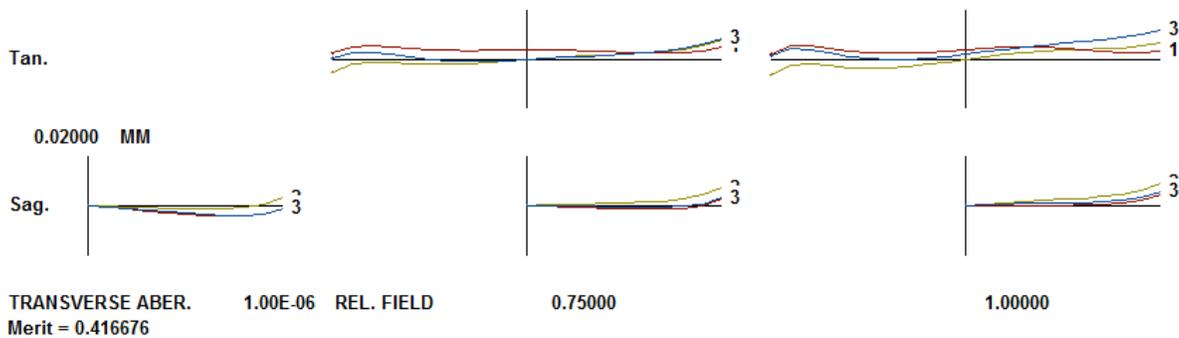
```

END

The ZGROUP directive requires its own **END** to terminate the group, in addition to the **END** that terminates the AANT file. Lastly, we add a new monitor **ADT 8 1 1** before the ZGROUP line, to control element thicknesses, and reoptimize and anneal.



ZOOM POSITION 1



Right now we have a tolerably good lens with 12 elements, and that's about as good as this lens will get.

But, wait! We suspect that the elements at 1 and 3 might be combined into a single element. We have to find out.

Make a checkpoint, then add, before the PANT directive,

```
AED 9 QUIET 1 24
```

and run the MACro again, and ... What? The program wants to delete the element at surface 7! We change the PANT file, commenting out the AED line, deleting all the GLM variables and replacing them with a single line

```
VLIST GLM ALL
```

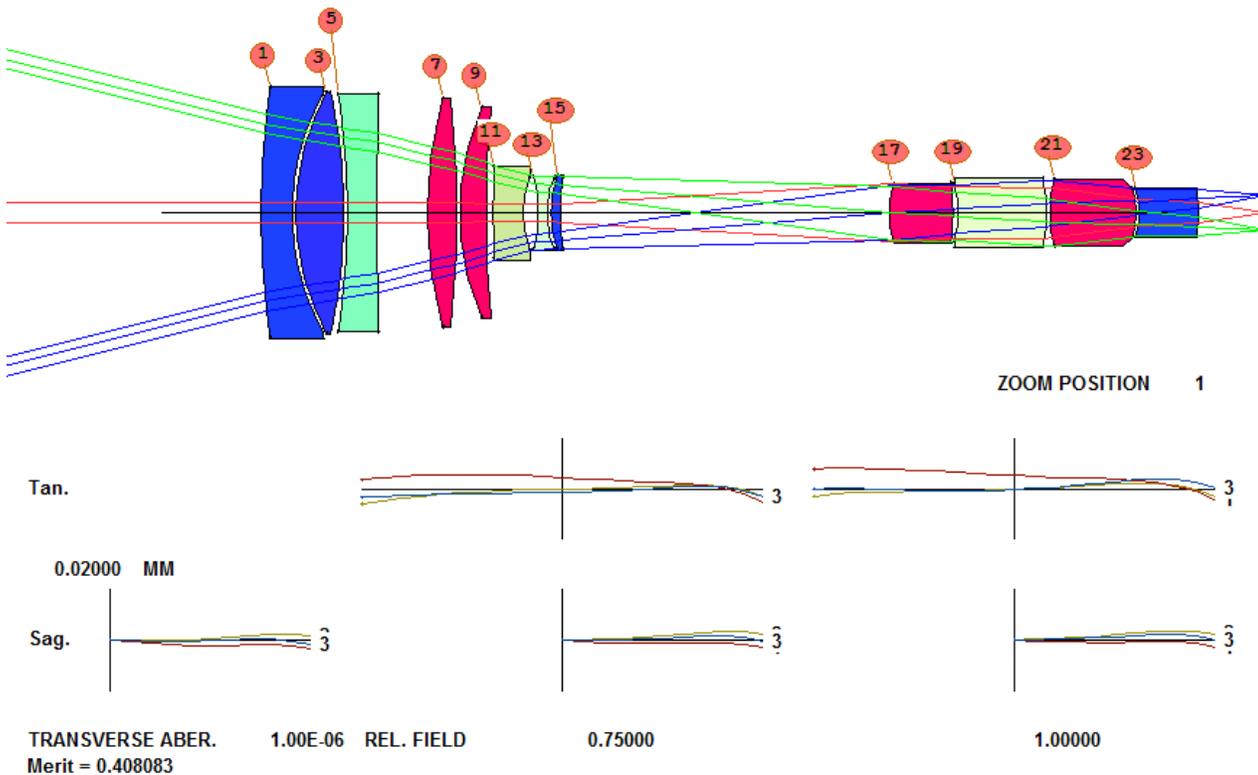
and then reoptimize and anneal. The MF is larger now, at 0.585. Let's see if adding an element with **AEI** will improve it.

AEI honors the **CORE** directive, and since this is a lengthy process we enjoy almost 16^1 times faster speed once they're all authorized. It first optimizes and does some annealing of its own, because you want to start with the best that this lens will do. Then it tries inserting elements. You can watch them come and go in the PAD display, but since we have activated 16 cores you only see 1/16 of the trials (the other cores do not update the display except for the small status windows).

Add this line before the PANT directive and run it again.

```
AEI 9 1 123 0 0 0 50 10
```

The program has added an element at surface 19. Comment out the AEI line and keep optimizing. The MF comes down to 0.408. Here is our lens now:



We notice that some of the edges are rather thin; we change the AEC line to

¹ This assumes you either have 16 real cores or 8 hyperthreaded cores.

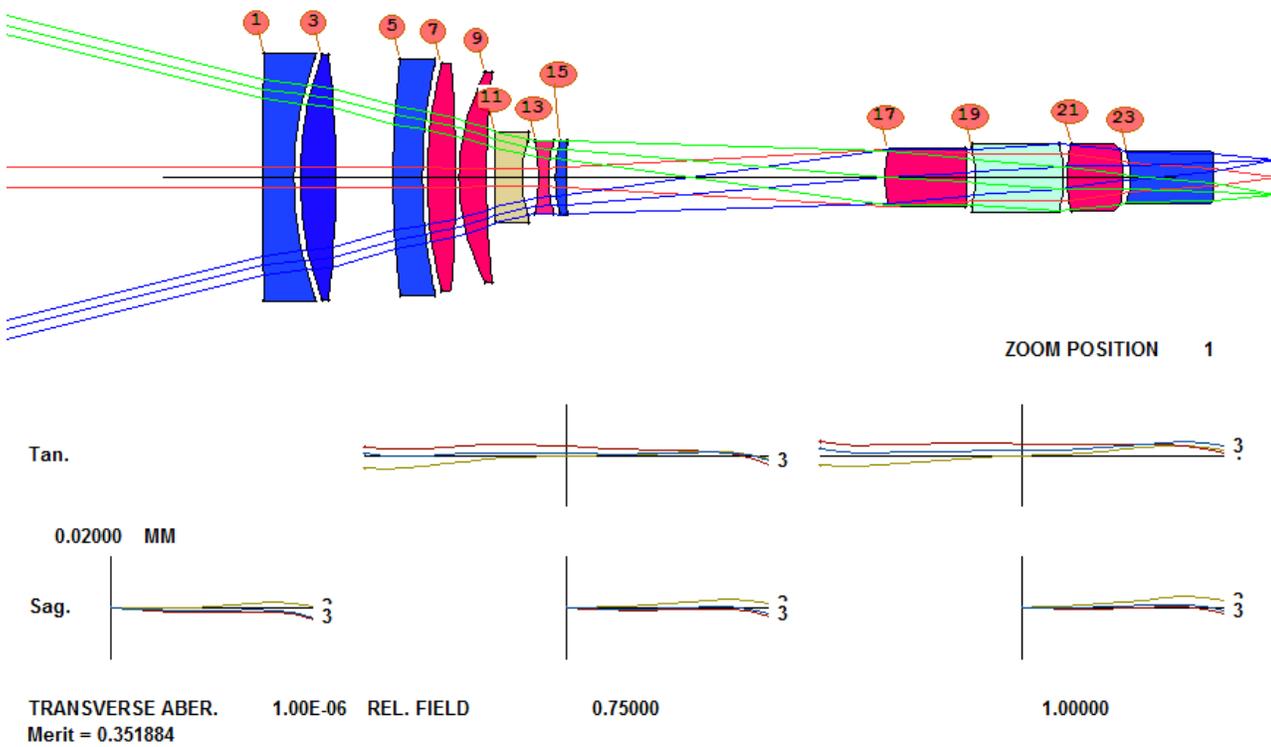
AEC 2 1 1.

This will penalize any edges less than 2 mm thick.

Also, since some of the elements are rather thin, add a line to the AANT file:

ACM 3 1 1

This will penalize any varying thickness less than 3 mm. Optimize and anneal once more, and the MF is now 0.434. (Adding anything new to the MF usually makes the value go up.) That seems to be as far as this configuration wants to go. We still suspect that element 1 can be removed, so we run AED once more. The best place comes back at surface 5. So we let it delete that element and optimize again. Now the MF is at 0.451, and we run AEI again. The program adds an element at surface 7 and the MF comes down to 0.35. This looks like a remarkably good lens.



It's time to take stock. We click each of the Zoombar² buttons on the right to examine the image quality at each of our 5 zooms...



² ZoomBar is a trademark of Optical Systems Design, Inc., a Maine USA corporation.

... and see that things are well under control. Lenses do not collide when you zoom the lens, and there are no feathered edges. The **AZA** monitor that ZSEARCH added to the MACro takes care of both of these automatically.

This is a good zoom lens at five zoom positions. What happens in between those zooms? We have to find out. Very likely the lens will be poorly corrected somewhere and we will have to add more zooms. First we need a cam curve, which will let us interpolate the defined zooms at in-between points. Type

CAM OPT

The program finds the optimum exponent for a power-series expansion of the zoom data that smoothly interpolates between the defined zooms. But the curve only produces an in-focus image at the five defined zooms, since it has no other information yet.

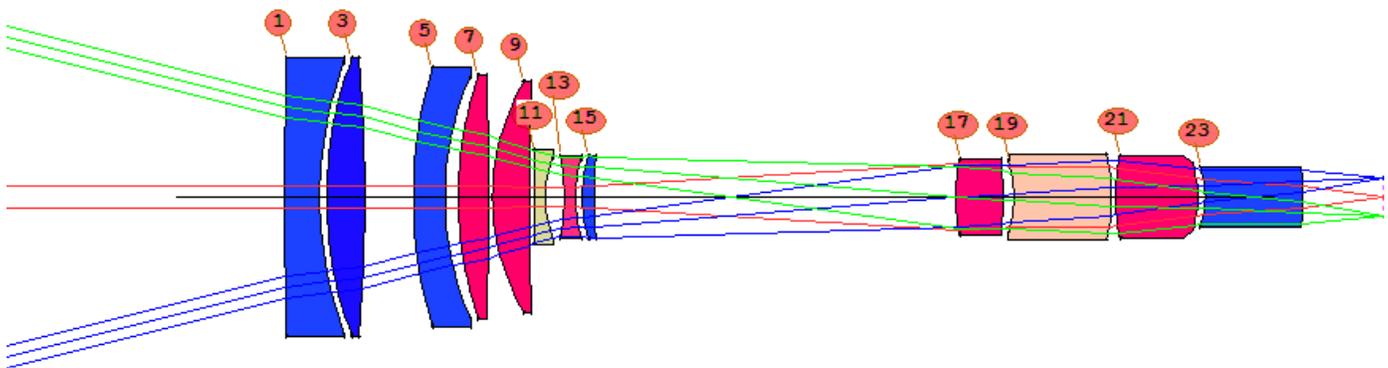


To see this, run the zoom slider (click on the button at the bottom of the ZoomBar™). You see the image going out of focus in several places. We need more zooms. Type

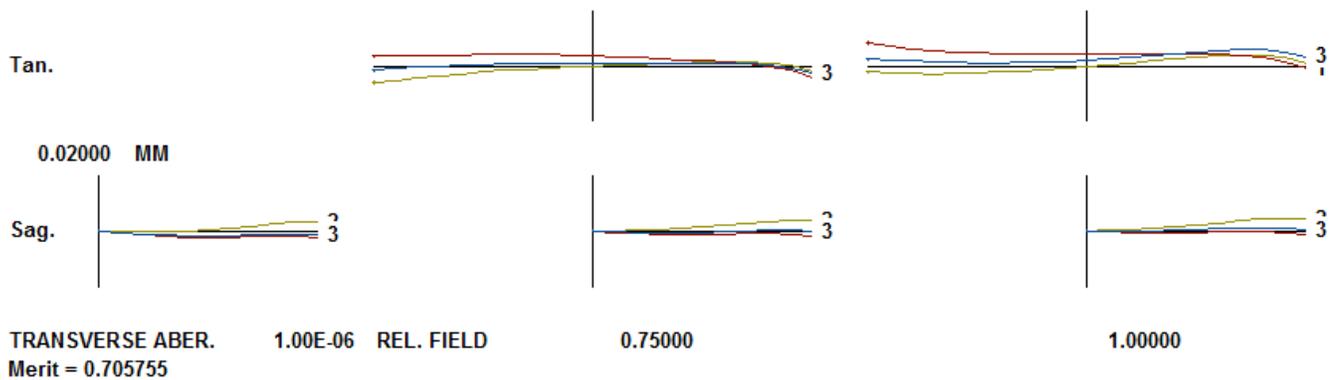
CAM 10 SET.

Now 10 zooms are defined, and our MACro will automatically vary and control all of them. (That is why we changed to the ZGROUP designation: now we don't have to declare ray sets in the new zooms.)

Make a new checkpoint, then run the MACro again and anneal. (Be sure to comment out the AEI line first.) Zoom 1 looks much the same.



ZOOM POSITION 1



Run **CAM OPT** again, , and then run the zoom slider again. Looks great, except just before it gets to zoom 10, where there is a sudden change in focus. Looks like we need more zooms. Type

CAM 15 SET

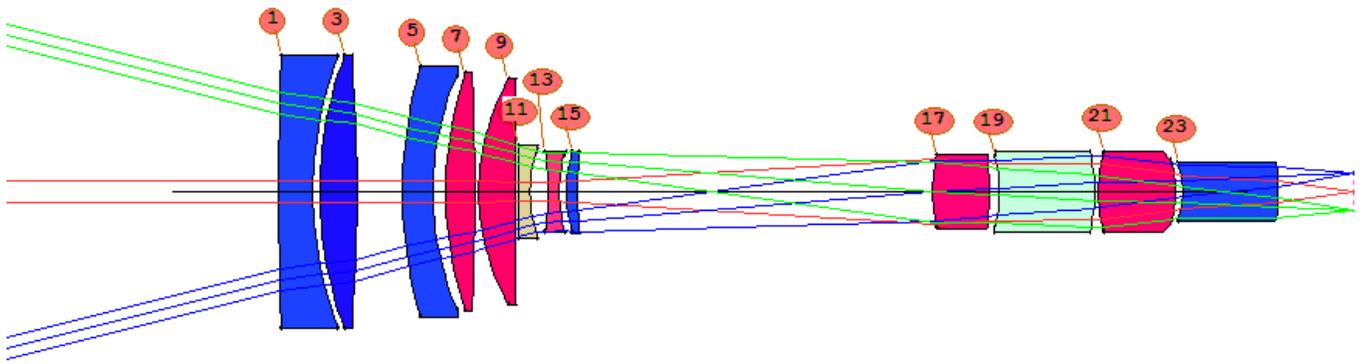
And reoptimize. Then run CAM OPT again. The program will again find the best-fitting polynomial expansion of all the zooming parameters, to be used for generating intermediate positions when you run the zoom slider. Often this gives a smooth zoom over the range. But one sometimes one gets better results by requesting a piecewise-cubic expansion.

Open WS and click on the **ZFILE** button **Z**. This loads the zoom definitions into the edit pane. Type **CUBIC** where shown and click the Update button. Now try the slider again.

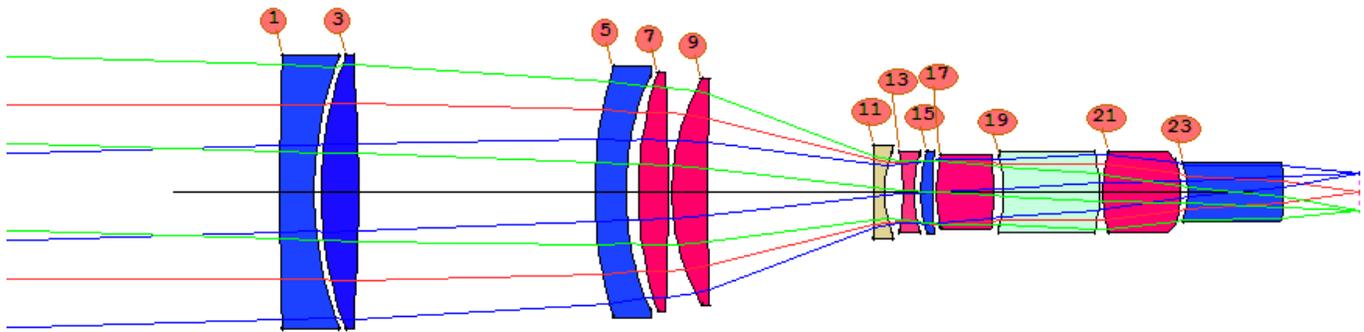
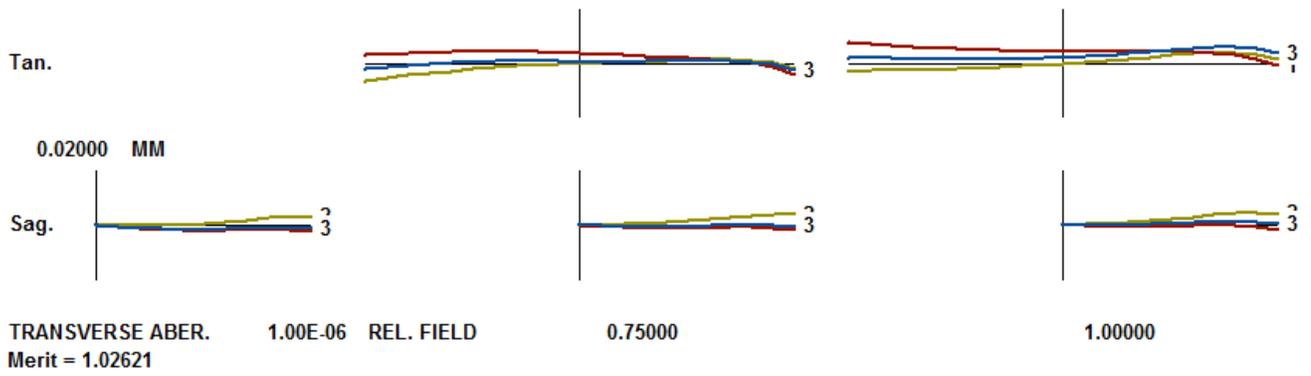
```
WS -- WorkSheet Lens-Edit Window
OBB 0.000000 14.00000 2.85000 -2
ZFILE 2
CAM RANK 9
CAM EXPONENT 1.47000
5 10 DFOCUS
11 16
RSOLVES
CUBIC
ZOOM 2
OBB 0.174689E-09 13.17380 3.24048 -23
ZDATA -2.2352750E+00 9.2171569E-01
```

One can also declare a given zoom group as a focusing group for the polynomial expansion, and it is wise to try it both ways. (This is what zoom lens makers do in practice: move one group and refocus with another, then mark the locations and cut the cam curves accordingly.) See the help file under ZFILE for details.

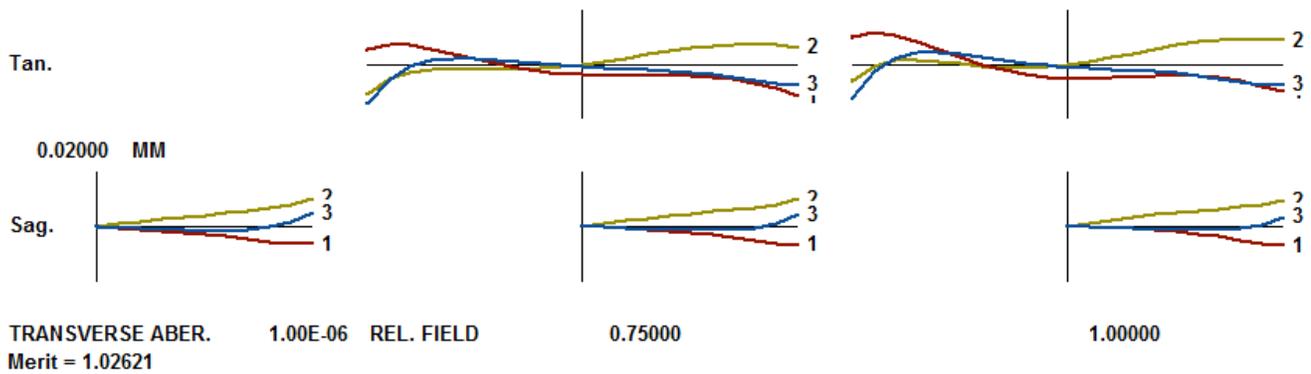
Viola! Performance is very smooth over the zoom range. And here we are:



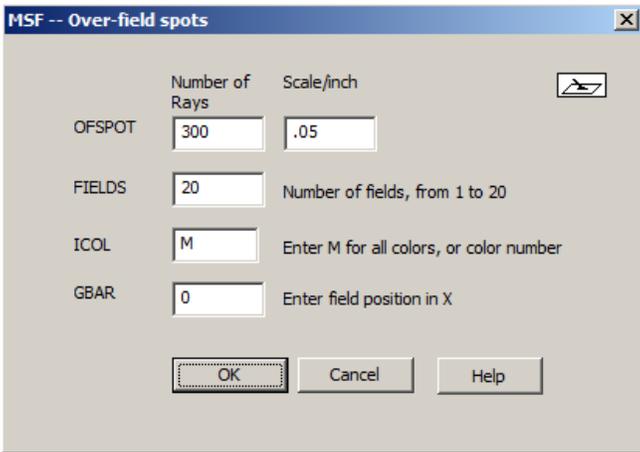
ZOOM POSITION 1



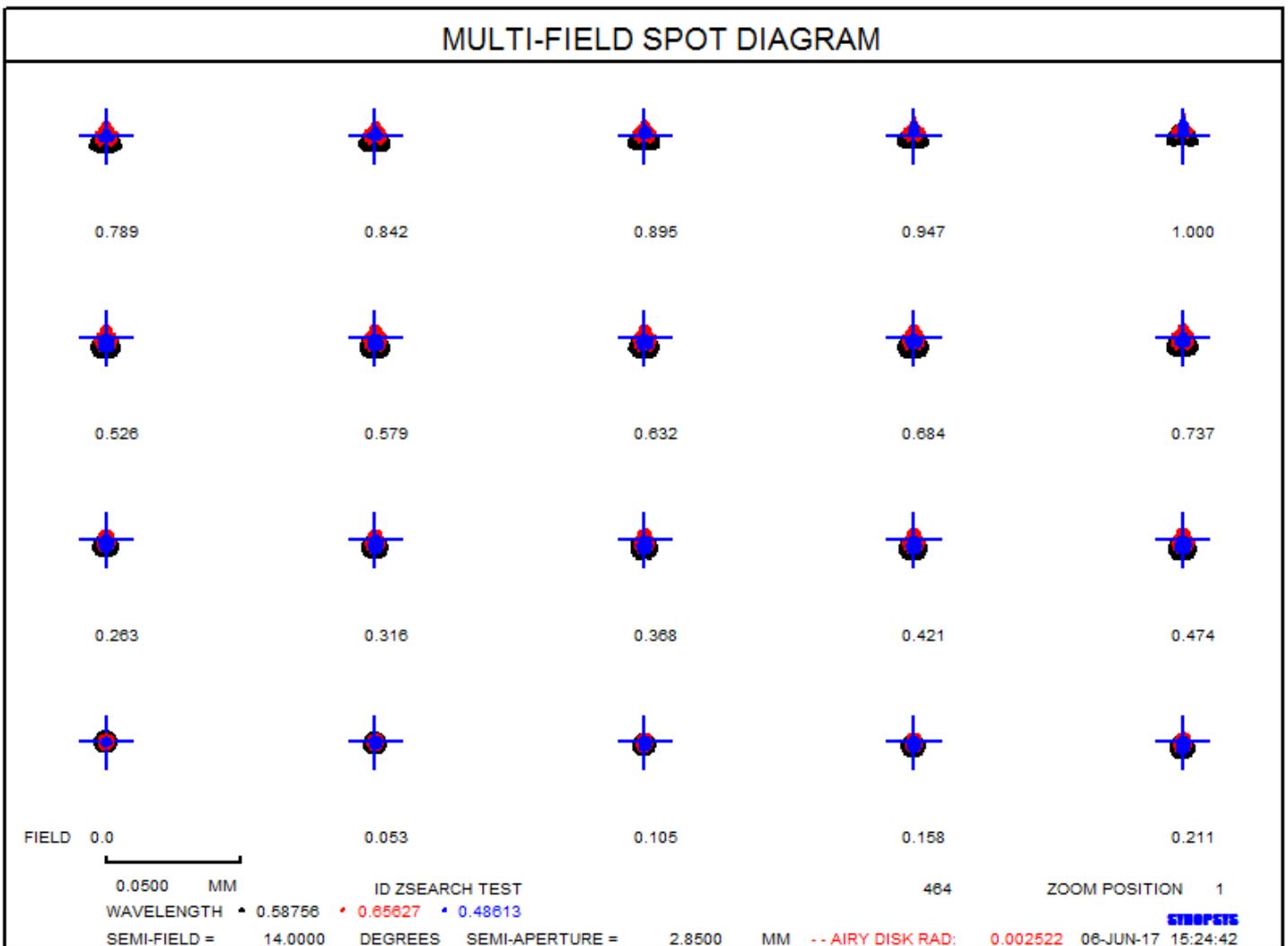
ZOOM POSITION 15



We can check the spot sizes with the MSF dialog.



Change the scale to 50 um and click OK. The image is excellent. (If you need even better quality, you could run AEI once more.) But you quickly learn that the benefit of adding yet another element goes down as the number of elements gets larger. That makes sense: adding an element to a doublet increases the variable count by 50%. Adding one to a 10-element lens increases that count by 10%, and so on.



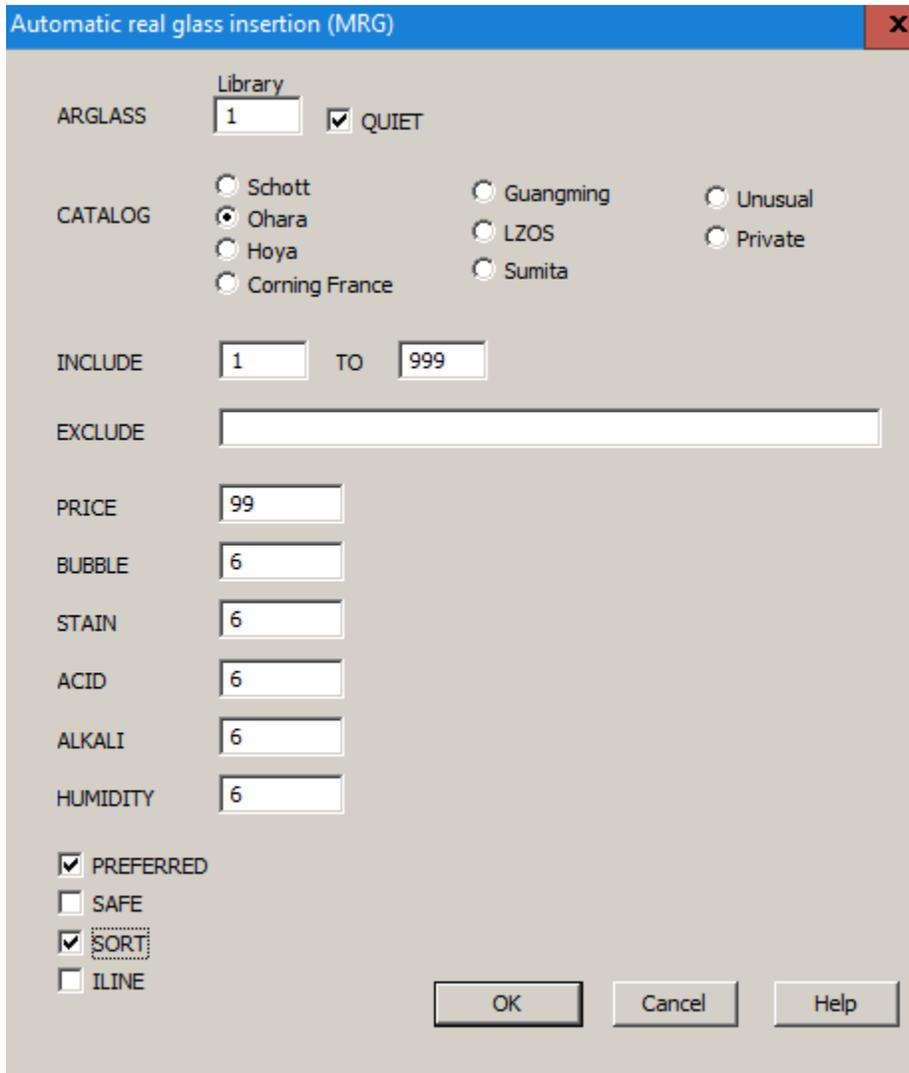
It's time for some finishing touches.

We have to replace the model glasses with real glass. Type **HELP ARGLASS** and read about that feature.

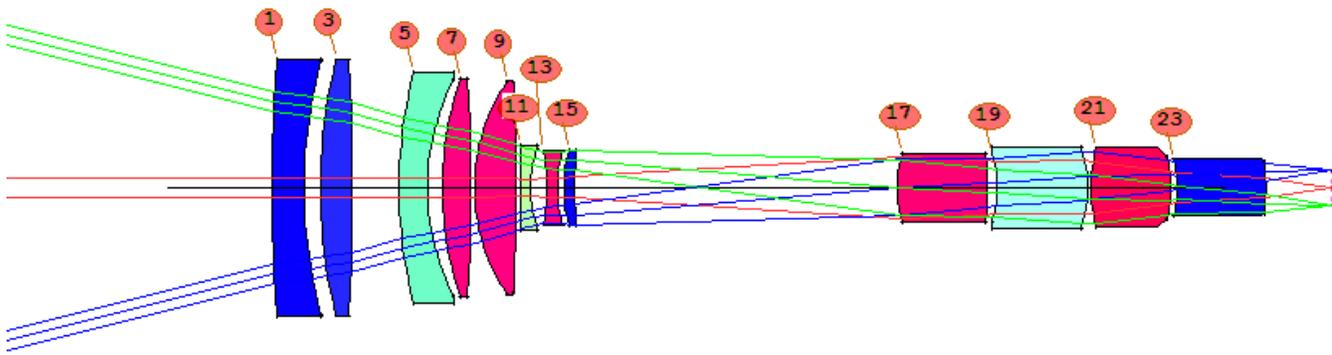
Since we have come a long way, it's time to save this lens so we can easily get back to it if necessary. Click the button

 in the top toolbar, and the lens is saved with a name taken from the current log number. ZSEARCH has already added a LOG command to your MACro, so each run increases this number. That way, whenever you get a version that you might want to go back to, you just click that button and it's saved.

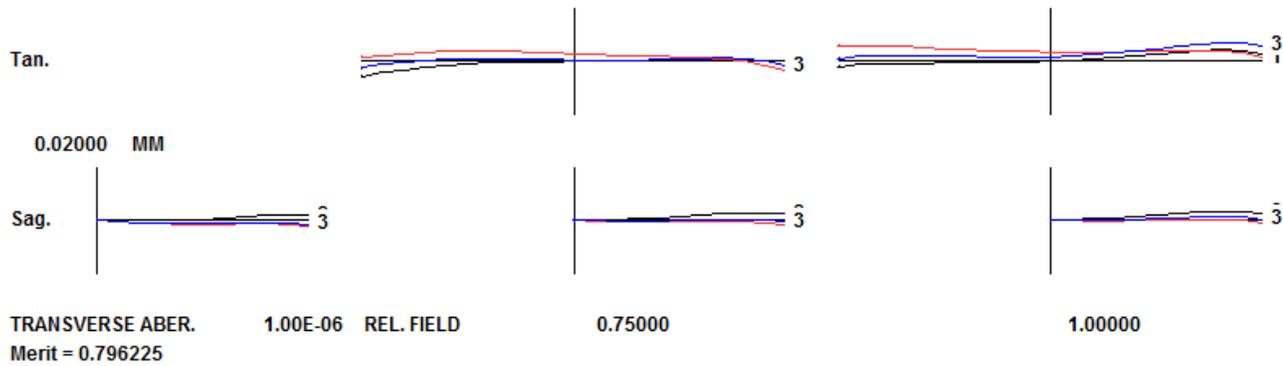
You can easily run the ARGLASS feature from the dialog **MRG**. (If you changed ACONs, be sure to run the optimization again in the current one; ARGLASS uses the same setup.) Type that command and fill in some data:



Select the Ohara catalog, QUIET, PREFERRED, SORT, click OK, and ... wow! The MF actually came *down* as the glasses were inserted! This seems surprising -- and it does not happen all the time -- but it makes sense since the repeated optimizations have an effect similar to annealing. Here is our lens now:



ZOOM POSITION 1



One more task before we call it a day. Here are the steps:

1. Run **CAM ZMAG 0.125**. When you change the number of zooms, the program respaces all the data according to the previous cam curve, which is only an approximation; the respaced object definitions may not correspond exactly to the original zoom ratio specification. This will clean it up.
2. Reoptimize.

Now the lens has changed only slightly, and the slider shows a beautiful image all across the range.

If this were a real-world lens, we'd have to ensure that adjusting the positions of elements 1 and 2 would work for range focusing. We ignored that for this lesson, but it's not hard to do. First, estimate the focal length you need for that group. For example, to focus at one meter by moving the group by, say, 20 mm, the focal length of that group would have to be about 141 mm. How to get this figure? Well, using the Newtonian form of the lens equation,

$$S_1 S_2 = F^2$$

And inserting 1000 for S_1 and 20 for S_2 , F works out to 141.42mm. So add a requirement in the ZSEARCH SPECIAL AANT section

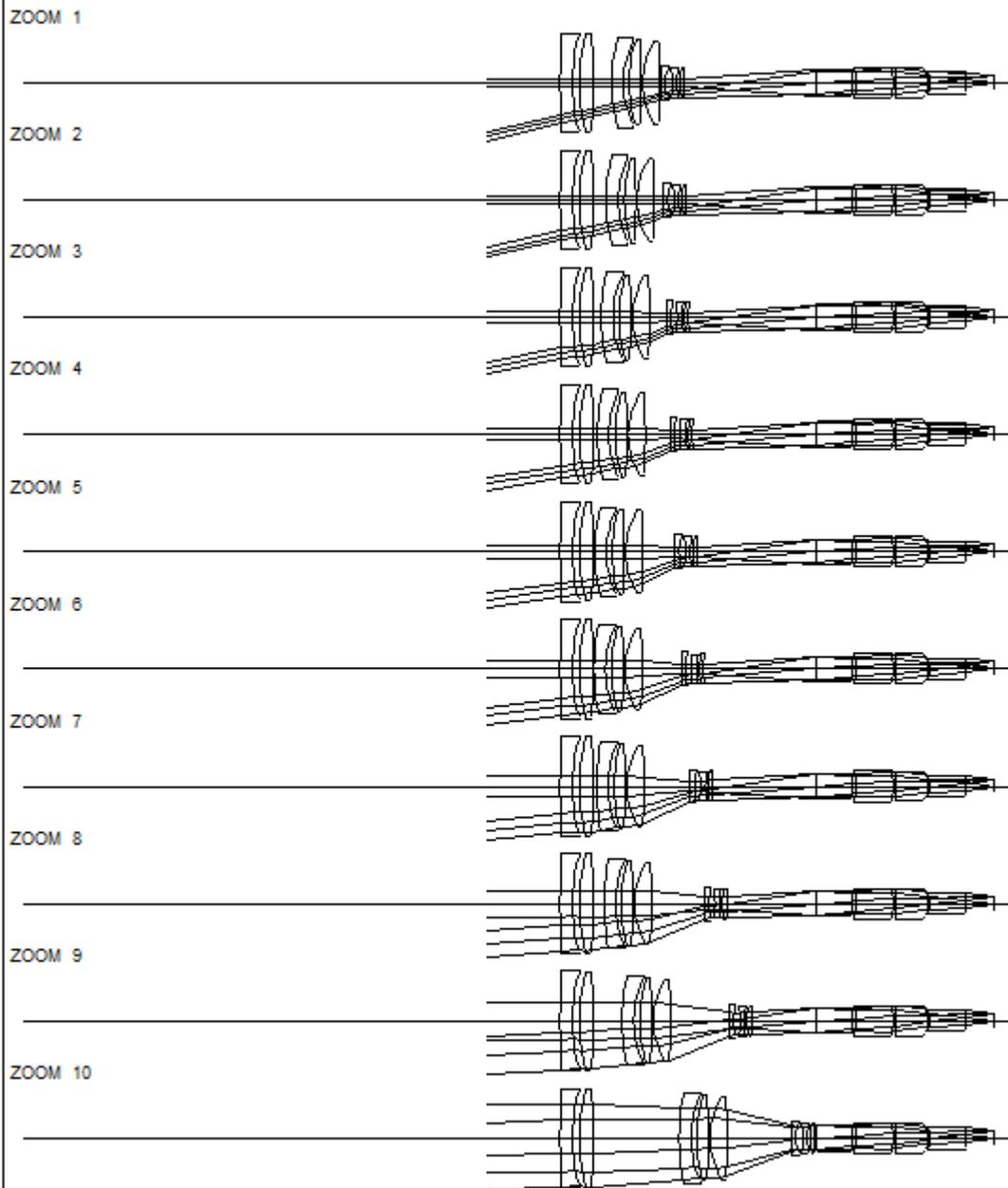
M 141 .01 A SECTION FOCL 1 6.

Then set up an alternate configuration with the best match where the object is at 1000 mm and thickness 6 is free to vary, and optimize both at the same time. Read about ACON in the manual for details.

Save this lens, and then change to 10 zooms (with CAM 10 SET) so the next drawing fits on a single page.

Type **ZDWG .25** to see a picture of the lens at all 10 zooms.

ZOOM LENS PROFILE



SCALE 0.2500 X
ID ZSEARCH TEST

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SYNOPTIS
07-JUN-17 12:27:08

That's enough for this lesson. You get the idea. If the lens is still not good enough, another run with AEI should help. Your boss will be delighted to learn that you have a good design -- and it's still only 2:00 on Friday afternoon. You can head out to the golf course, grateful that you chose SYNOPTIS™.

Try this with any other program and you'll be at your desk all weekend, if you don't lose your job.