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 SYNOPSYS™ 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 SYNOPSYS 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:

```
LOG                     ! to keep track of things later
TIME                    ! to see how long this run took
CORE 14                 ! 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 2 3 3 3          ! lens has four groups with 11 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 APERT            ! other zoom objects will be linearly spaced between the first and
last
ZFOCUS 4000 4 15
APS 17                  ! put the stop on the first side of the last group
RT 0.25
DELAY OFF               ! don't ask to abort other cores
```

1

```
GIHT 5 5 10          ! the image height is 5 mm for all zooms, with a weight of 10.
BACK 5 .01           ! 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 40   ! 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
TIME
```
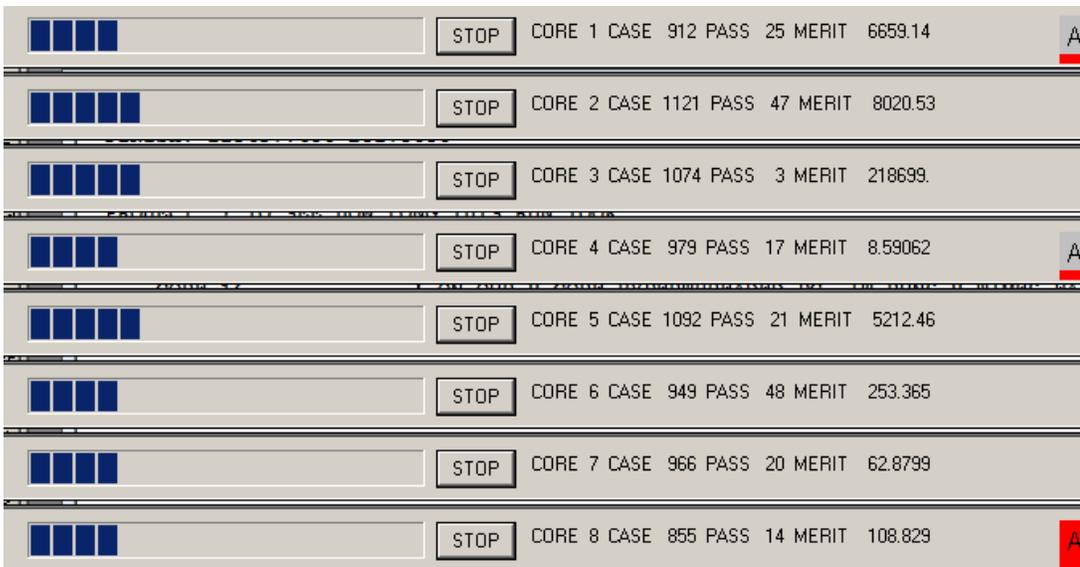
The zoom lens will consist of four groups, the first with two elements and the others with three. The first group will be used for range focus, and the last is fixed to provide a constant F/number over the zoom range. The ZFOCUS request says that the lens must also work when the object is four meters away and the first group has been moved out by 15 mm.

It is likely we will need more than 11 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 a set of windows that monitor each of the cores we authorized.

	STOP	CORE 1 CASE 912 PASS 25 MERIT 6659.14	A
	STOP	CORE 2 CASE 1121 PASS 47 MERIT 8020.53	
	STOP	CORE 3 CASE 1074 PASS 3 MERIT 218699.	
	STOP	CORE 4 CASE 979 PASS 17 MERIT 8.59062	A
	STOP	CORE 5 CASE 1092 PASS 21 MERIT 5212.46	
	STOP	CORE 6 CASE 949 PASS 48 MERIT 253.365	
	STOP	CORE 7 CASE 966 PASS 20 MERIT 62.8799	
	STOP	CORE 8 CASE 855 PASS 14 MERIT 108.829	A

…

When the quick mode is finished, the program optimizes each of the best 10. After about 24 minutes we see these results:

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ZOOM DESIGN SEARCH RESULTS

ID ZSEARCH TEST
SCALE   0.2768 X
MERIT =   0.603375
FILE = ZSEARCH08.RLE

ID ZSEARCH TEST
SCALE   0.2742 X
MERIT =   0.756304
FILE = ZSEARCH01.RLE

ID ZSEARCH TEST
SCALE   0.2775 X
MERIT =   0.845023
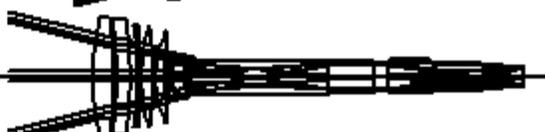FILE = ZSEARCH03.RLE

ID ZSEARCH TEST
SCALE   0.2768 X
MERIT =   0.987246
FILE = ZSEARCH10.RLE

ID ZSEARCH TEST
SCALE   0.2772 X
MERIT =   0.988594
FILE = ZSEARCH09.RLE

ID ZSEARCH TEST
SCALE   0.2763 X
MERIT =   1.061270
FILE = ZSEARCH02.RLE

ID ZSEARCH TEST
SCALE   0.2772 X
MERIT =   1.066500
FILE = ZSEARCH07.RLE

ID ZSEARCH TEST
SCALE   0.2753 X
MERIT =   1.079280
FILE = ZSEARCH06.RLE

ID ZSEARCH TEST
SCALE   0.2735 X
MERIT =   1.283380
FILE = ZSEARCH05.RLE

ID ZSEARCH TEST
SCALE   0.2756 X
MERIT =   1.536970
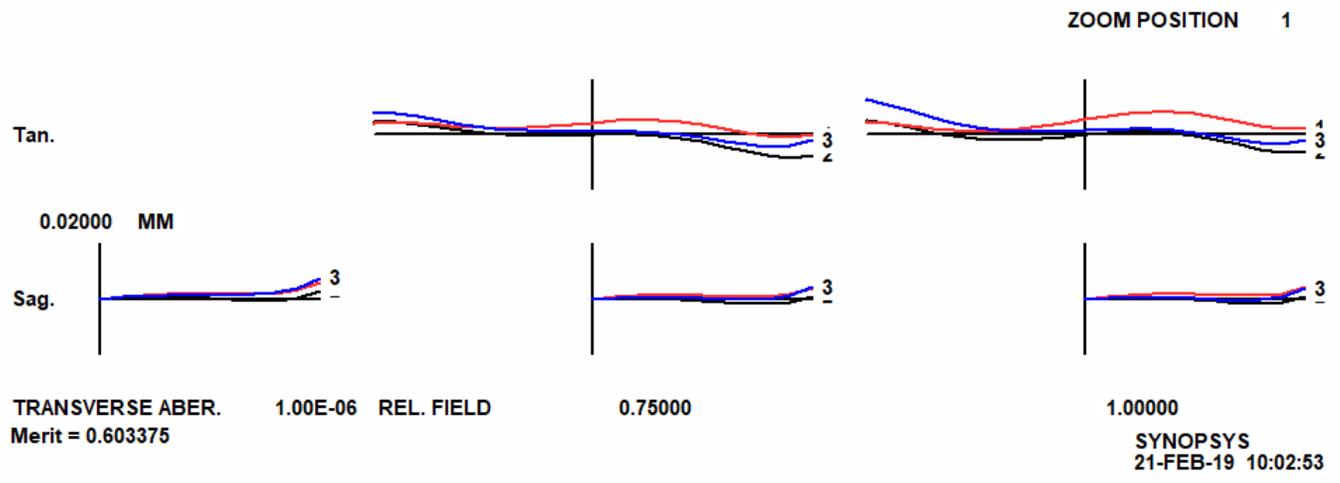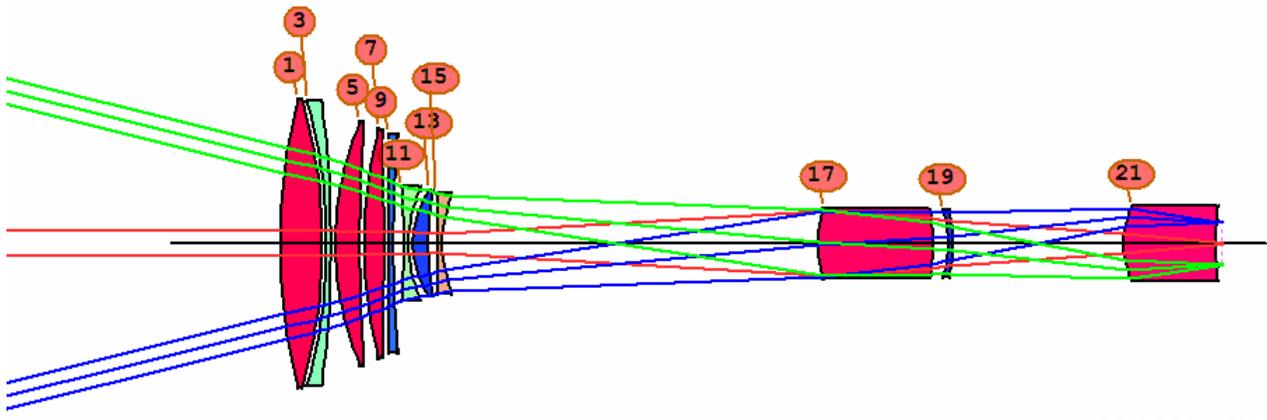FILE = ZSEARCH04.RLE

TOTAL CASES RUN: 2048

CASES SKIPPED: 54

SYNOPSYS
21-FEB-19 09:59:05

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

TRANSVERSE ABER.   1.00E-06   REL. FIELD   0.75000   1.00000
Merit = 0.603375
                                                                                             SYNOPSYS
                                                                                             21-FEB-19 10:02:53
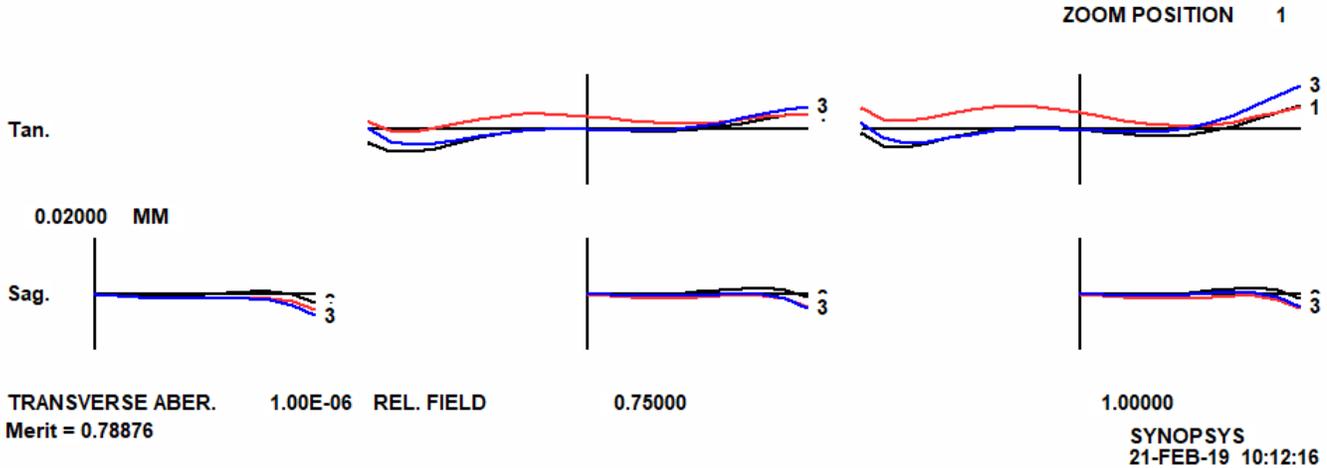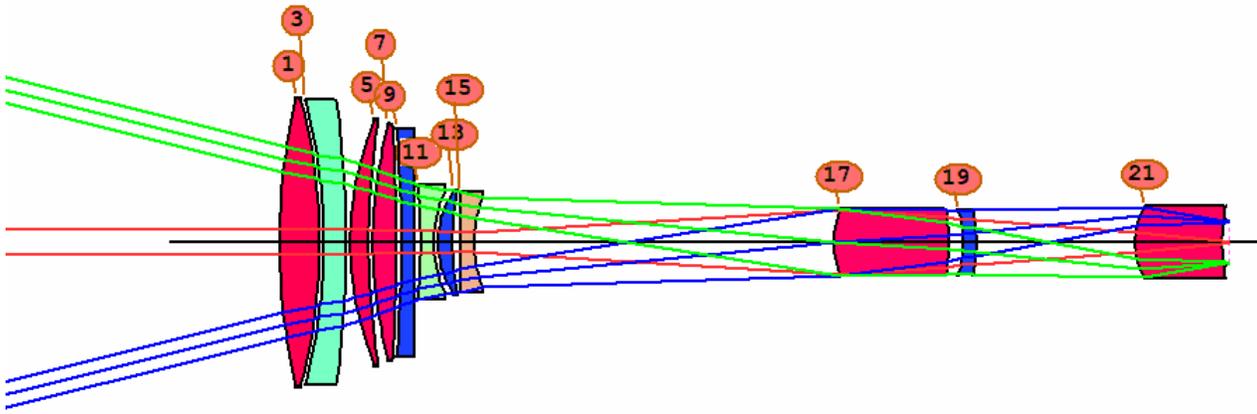
The program has created an optimization MACro for us, already loaded with a starting merit function definition and a set of variables. Some elements are too thin, and others too thick, so we add two more monitors to the AANT file

```
ACM 3 1 1
ADT 7 .1 10
```

We also change the APS designation to APS -17, to better model the stop on surface 17.

We run this, and then click the Anneal button, change the starting temperature to 20, request 50 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 is now 0.789.

ZOOM POSITION   1

Tan.

0.02000   MM

Sag.

TRANSVERSE ABER.   1.00E-06   REL. FIELD   0.75000   1.00000
Merit = 0.78876   SYNOPSYS
                                                                                            21-FEB-19 10:12:16

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.

```
SYNOPSYS AI>FF

FINAL 5
ABERRATION LIST
         NAME              TARGET          WEIGHT            RAW VAL.   FINAL ERROR    R. EFFECT

     1 AEC              1.0000000        1.0000000          ------       0.125740       0.020045

     3 AZA              1.0000000        1.0000000          ------       0.715616E-01   0.006493

     6 AAC             30.0000000        1.0000000          ------       0.305600       0.118403

     9 ADT              7.0000000        0.1000000          ------       0.124060       0.019513
*** ZFOCUS CHANGED TO     4000.00      4   15.0000       0.00000        ***

   6341                  0.0000000        3.0541452 SR      -0.0236   -0.722227E-01     0.006613
     A    3  YC    1.00000   0.37500    0.87500   0.00000     ACON 2       ZOOM 5
SYNOPSYS AI>
```

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

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in that ACON and develop the design further, and can instantly go back to ACON 1 with the "1" button

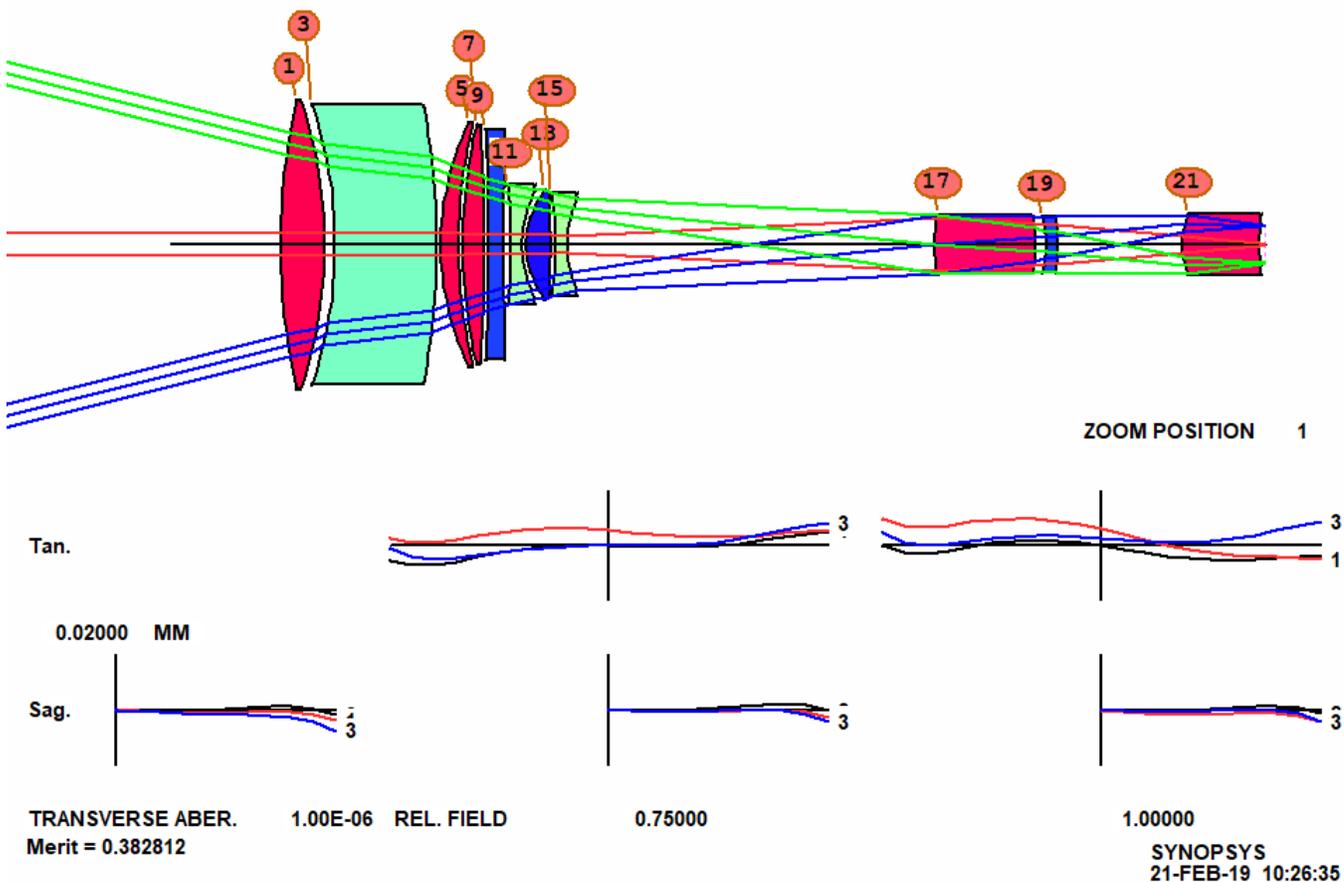 should we want to. We use all six configurations in this way quite often.

In the AANT file, change the line

    AAC 30 1 1

to

    AAC 35 1 1

Make a new checkpoint and run the MACro and anneal again. The MF comes down to 0.383. The ray fans look great.

Now we want to check how well the range focus works. Make a checkpoint, and then open a new MACro editor with the command AEE. Type the following:

```
CHG
VIG
END
ACON BUMP
ZFOCUS 4000 4 15 5
PAD/U
```

Run this, and indeed we see that the ray fans are essentially unchanged at the near focus position. The optimization MACro is controlling that and the infinity focus at the same time.

Now we modify the MF, deleting 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. Right now we have a tolerably good lens with 11 elements, and that's about as good as this lens will get.

But, wait! We suspect that the third element might be unnecessary. We have to find out. Make a checkpoint, then add, before the PANT command,

    AED 9 QUIET 1 22

and run the MACro again. Yes, the program wants to delete that element. Change the MACro, commenting out the AED line, and then reoptimize and anneal. The MF is even better now, at 0.133. Let's see if adding an element with **AEI** will improve it even more.

AEI honors the **CORE** directive, and since this is a lengthy process, we enjoy almost 14[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 14 cores you only see 1/14 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

---

[1] This assumes you either have 14 real cores or 8 hyperthreaded cores.

The program has added an element at surface 13. Comment out the AEI line, keep optimizing, and anneal. The MF comes down to 0.099. Here is our lens now:
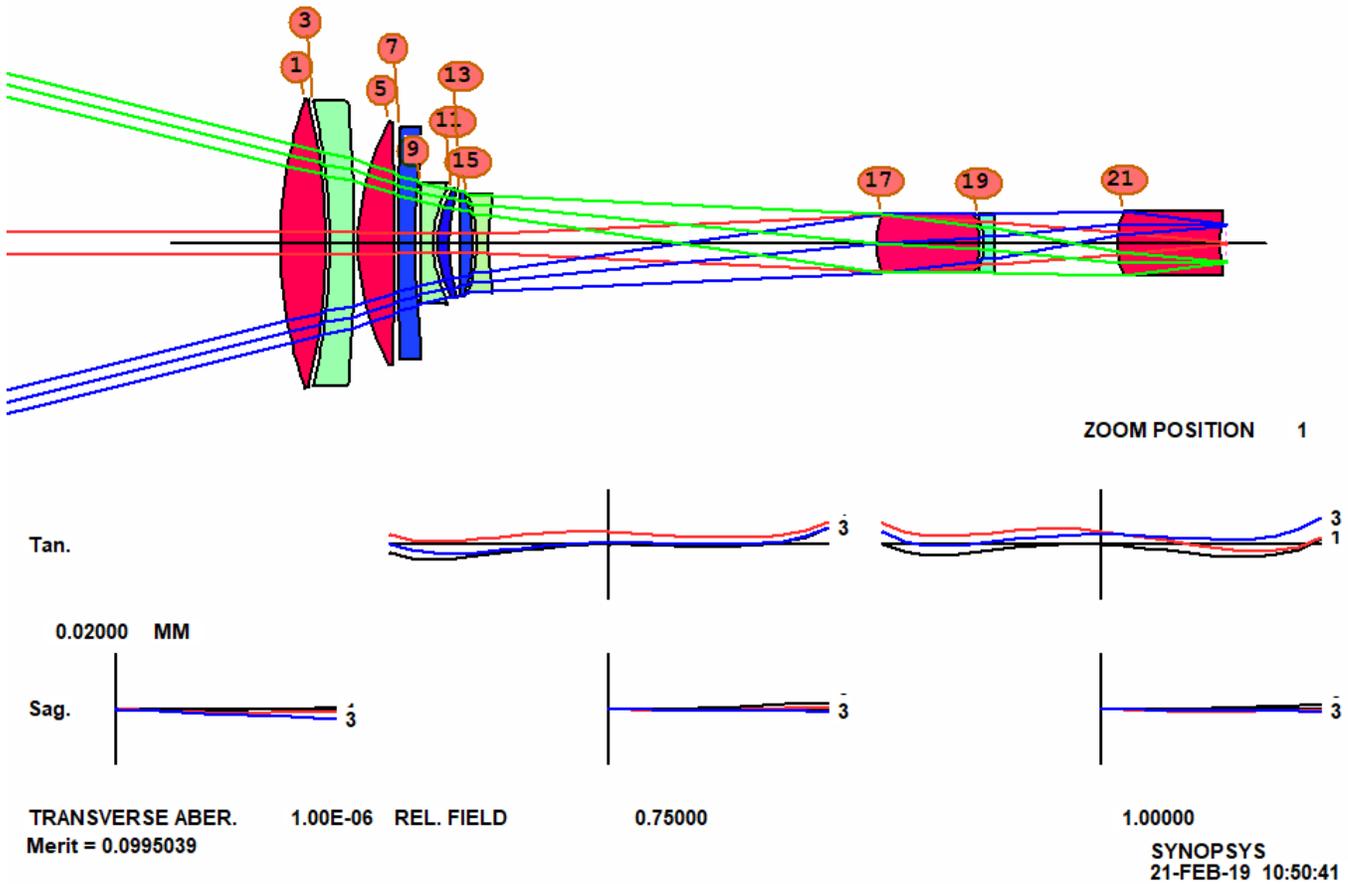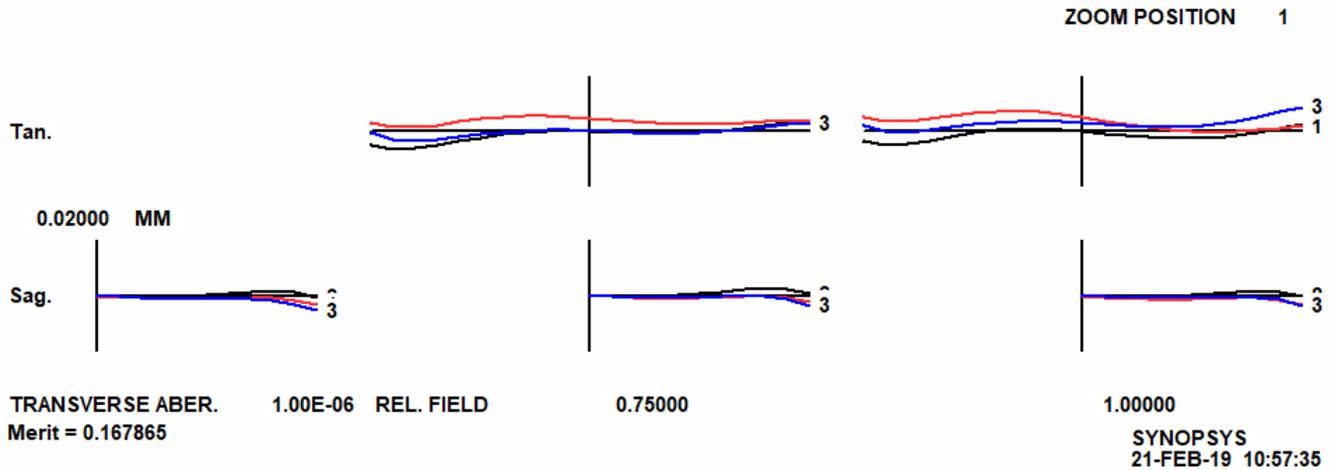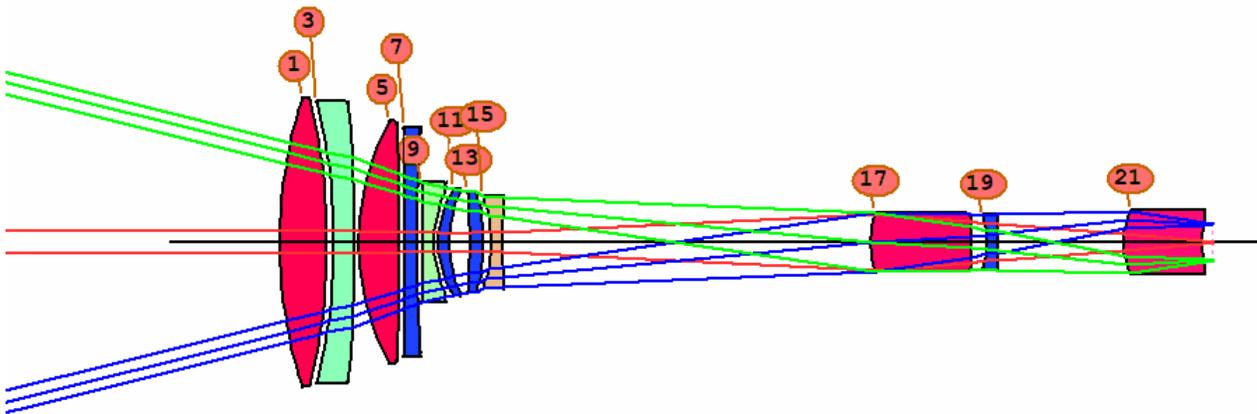

We notice that some of the edges are rather thin; we change the AEC line to

AEC 2 1 1.

This will penalize any edges less than 2 mm thick.

Optimize and anneal once more, and the MF is now 0.1698 (Adding anything new to the MF usually makes the value go up.) That seems to be as far as this configuration wants to go. This looks like a remarkably good lens.

ZOOM POSITION   1

Tan.

0.02000   MM

Sag.

TRANSVERSE ABER.   1.00E-06   REL. FIELD   0.75000   1.00000

Merit = 0.167865   SYNOPSYS
                                                                                     21-FEB-19 10:57:35

It's time to take stock. We click each of the Zoombar[2] buttons on the right to examine the image quality at each of our 5 zooms…

… 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.

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[2] ZoomBar is a trademark of Optical Systems Design, Inc., a Maine USA corporation.
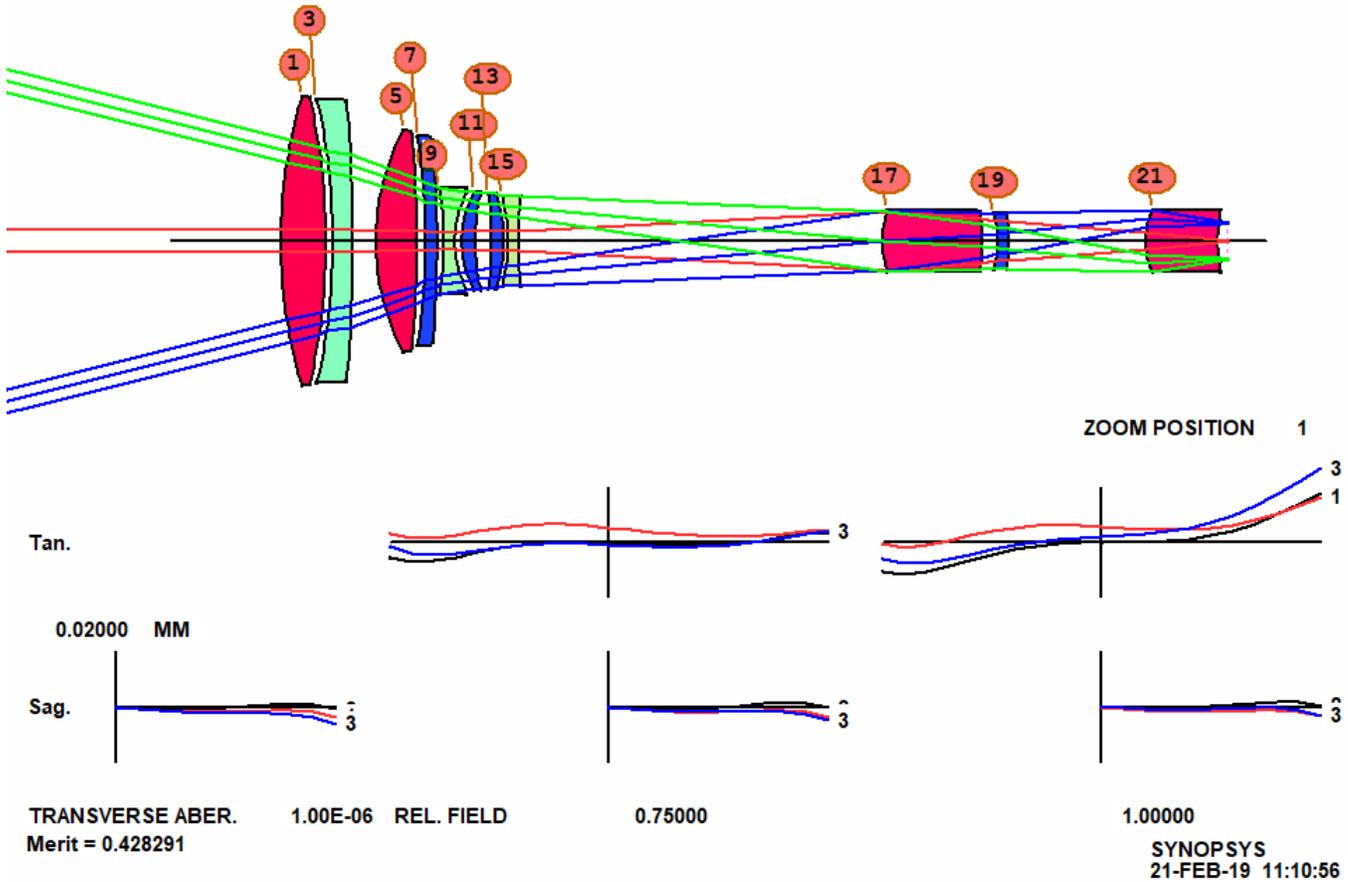
To see this, run the zoom slider (click on the button [icon] at the bottom of the ZoomBar™). You see the image going out of focus in several places, and lenses overlap slightly in one place. We need more zooms. Type
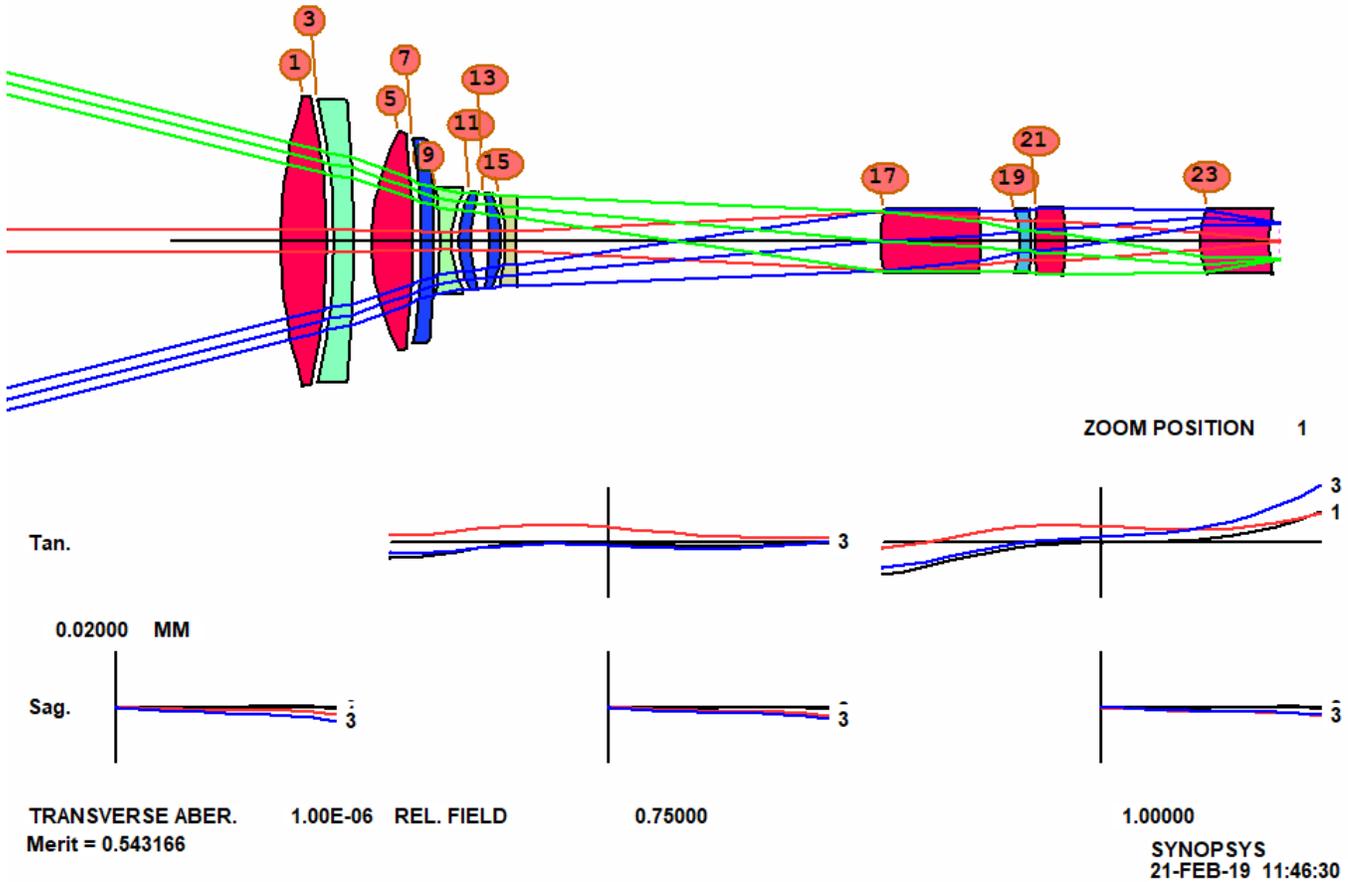
    CAM 10 SET.

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: so we don't have to declare ray sets in all the new zooms.)

Make a new checkpoint, then run the MACro again and anneal. The MF goes up, and the full-field TFAN is not as good as before. Perhaps this job will require more than 11 elements.

ZOOM POSITION 1

Tan.

0.02000 MM

Sag.

TRANSVERSE ABER. 1.00E-06 REL. FIELD 0.75000 1.00000
Merit = 0.428291

SYNOPSYS
21-FEB-19 11:10:56

Another run on AEI seems called for. We increase the weight on the full-field image from 3 to 5 and run AEI once more. The lens is improved.
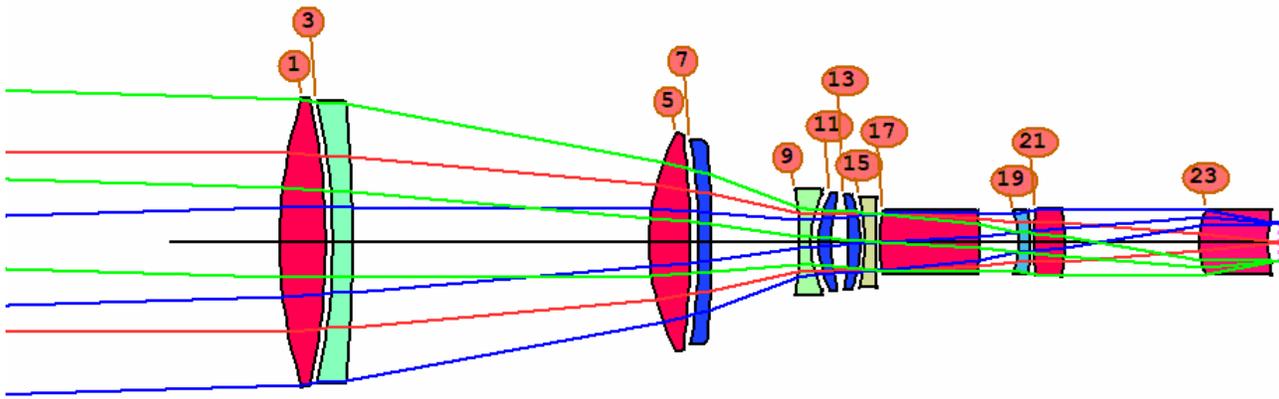

ZOOM POSITION   1

Tan.

0.02000   MM

Sag.

TRANSVERSE ABER.   1.00E-06   REL. FIELD   0.75000   1.00000
Merit = 0.543166   SYNOPSYS
                                                                                           21-FEB-19 11:46:30

Sometimes one gets a smoother slider analysis by requesting a piecewise-cubic expansion instead of the power-series used above. Open WS and click on the **ZFILE** button Z . This loads the zoom definitions into the edit pane. Type `CUBIC` and DFOCUS 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
```
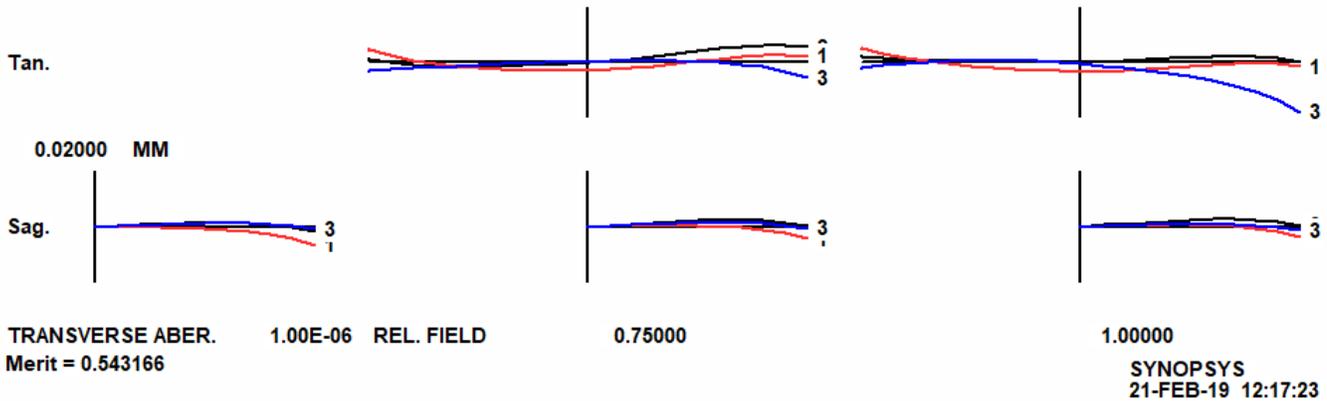
(This is what zoom lens makers do in practice: move one group and refocus with another, then mark the locations and cut the cam curves accordingly.) See the help file under ZFILE for details.
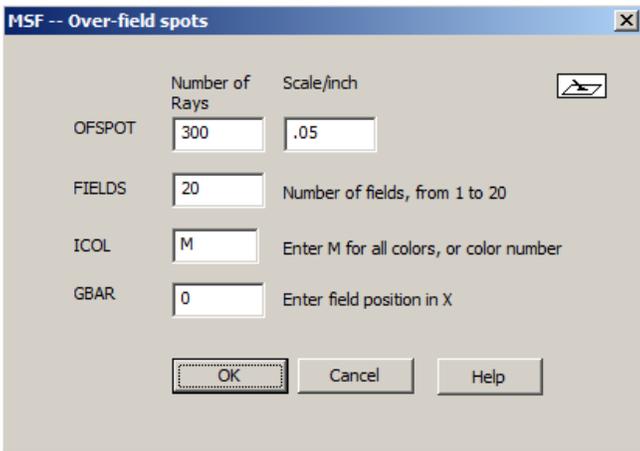
Viola! Performance is very smooth over the zoom range. And here we are, at zoom 10:

11

ZOOM POSITION   10

Tan.

0.02000   MM

Sag.

TRANSVERSE ABER.   1.00E-06   REL. FIELD   0.75000   1.00000
Merit = 0.543166   SYNOPSYS
                                                                                             21-FEB-19 12:17:23

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.

MULTI-FIELD SPOT DIAGRAM
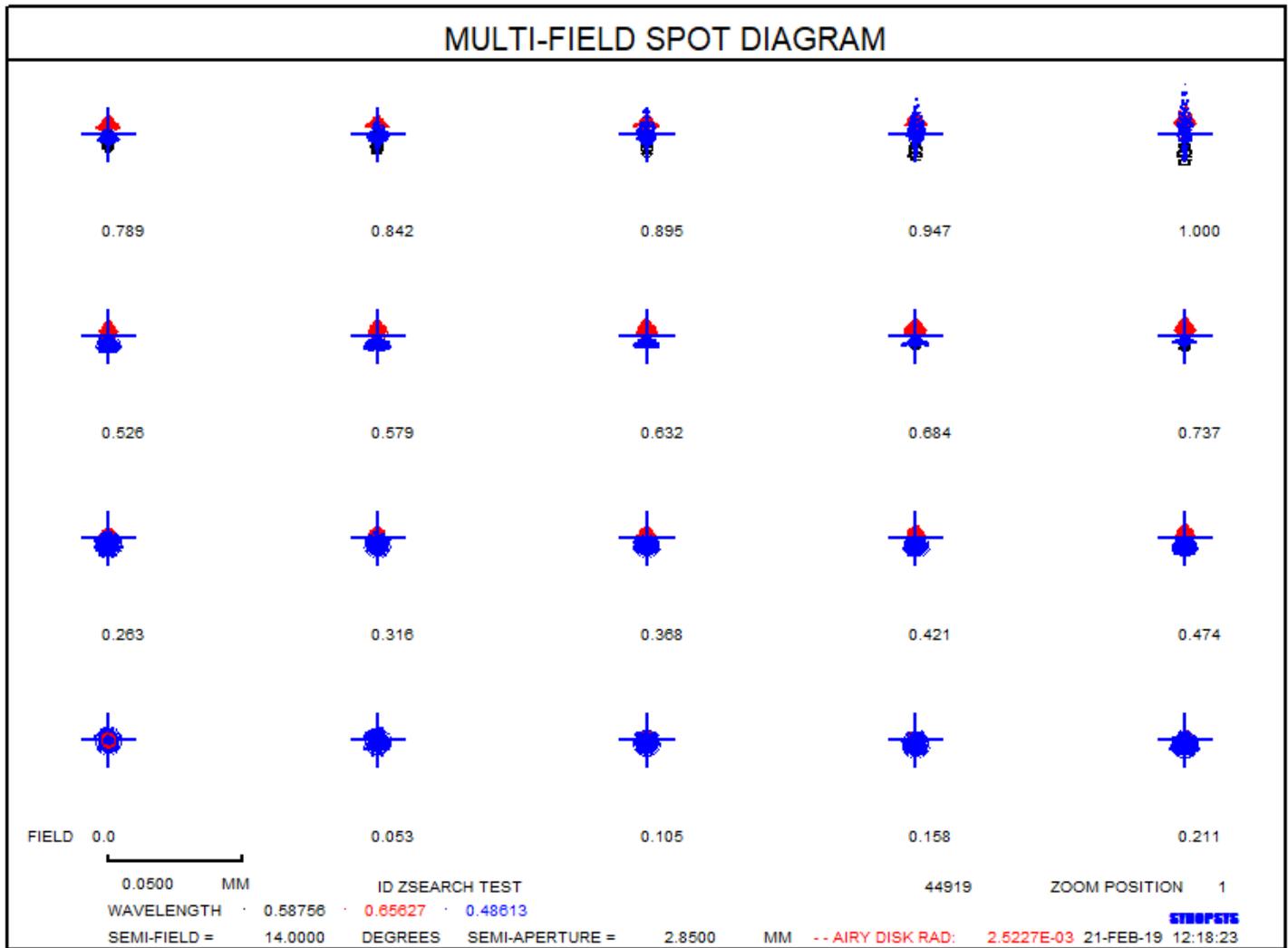
It's time for some finishing touches.

We have to replace the model glasses with real glass. Type **HELP ARGLASS** and read about that feature.
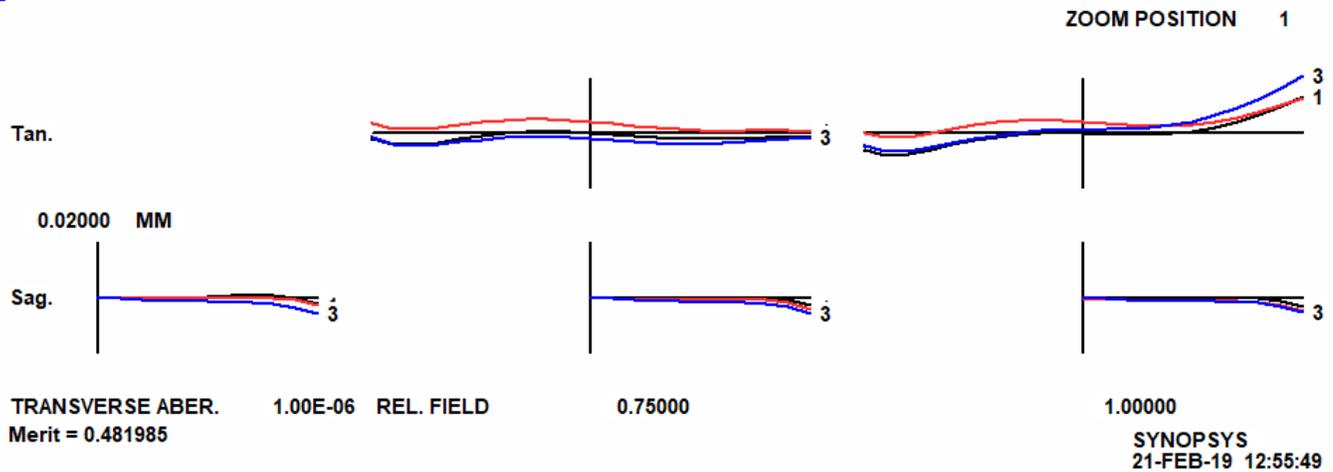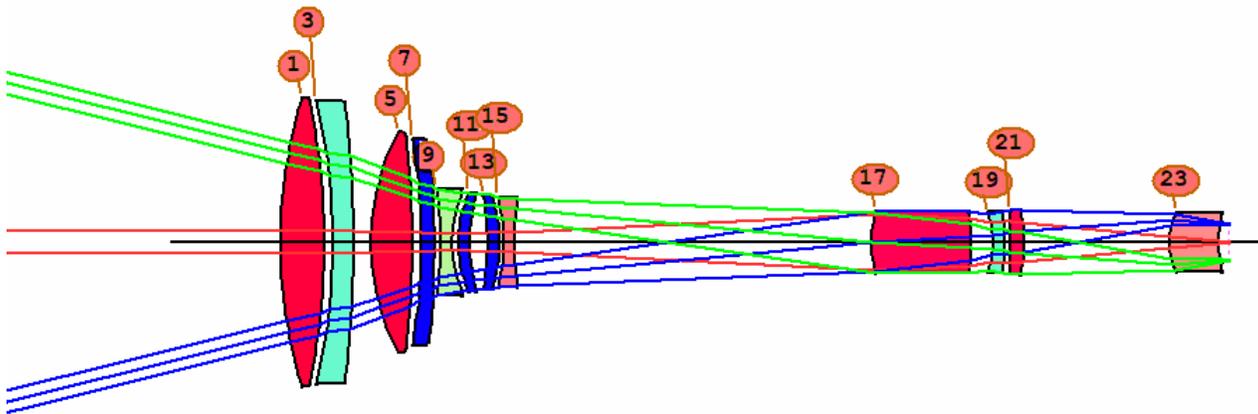Since we have come a long way, it's time to save this lens so we can easily get back to it if necessary. Click the button
in the top toolbar, and the lens is saved with a name taken from the current log number. ZSEARCH has already added a LOG command to your MACro, so each run increases this number. 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:

Automatic real glass insertion (MRG)

ARGLASS — Library — 1 — ☑ QUIET

CATALOG
- ○ Schott
- ⦿ Ohara
- ○ Hoya
- ○ Corning France
- ○ Guangming
- ○ LZOS
- ○ Sumita
- ○ Unusual
- ○ Private
- ○ Nikon

INCLUDE 1 TO 999

EXCLUDE

PRICE 99

BUBBLE 6

STAIN 6

ACID 6

ALKALI 6

HUMIDITY 6

○ SEQUENTIAL ⦿ SORT ○ REVERSE ORDER

☑ PREFERRED
☐ SAFE
☐ ILINE

OK   Cancel   Help

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

Tan.

0.02000   MM

Sag.

TRANSVERSE ABER.   1.00E-06   REL. FIELD   0.75000   1.00000
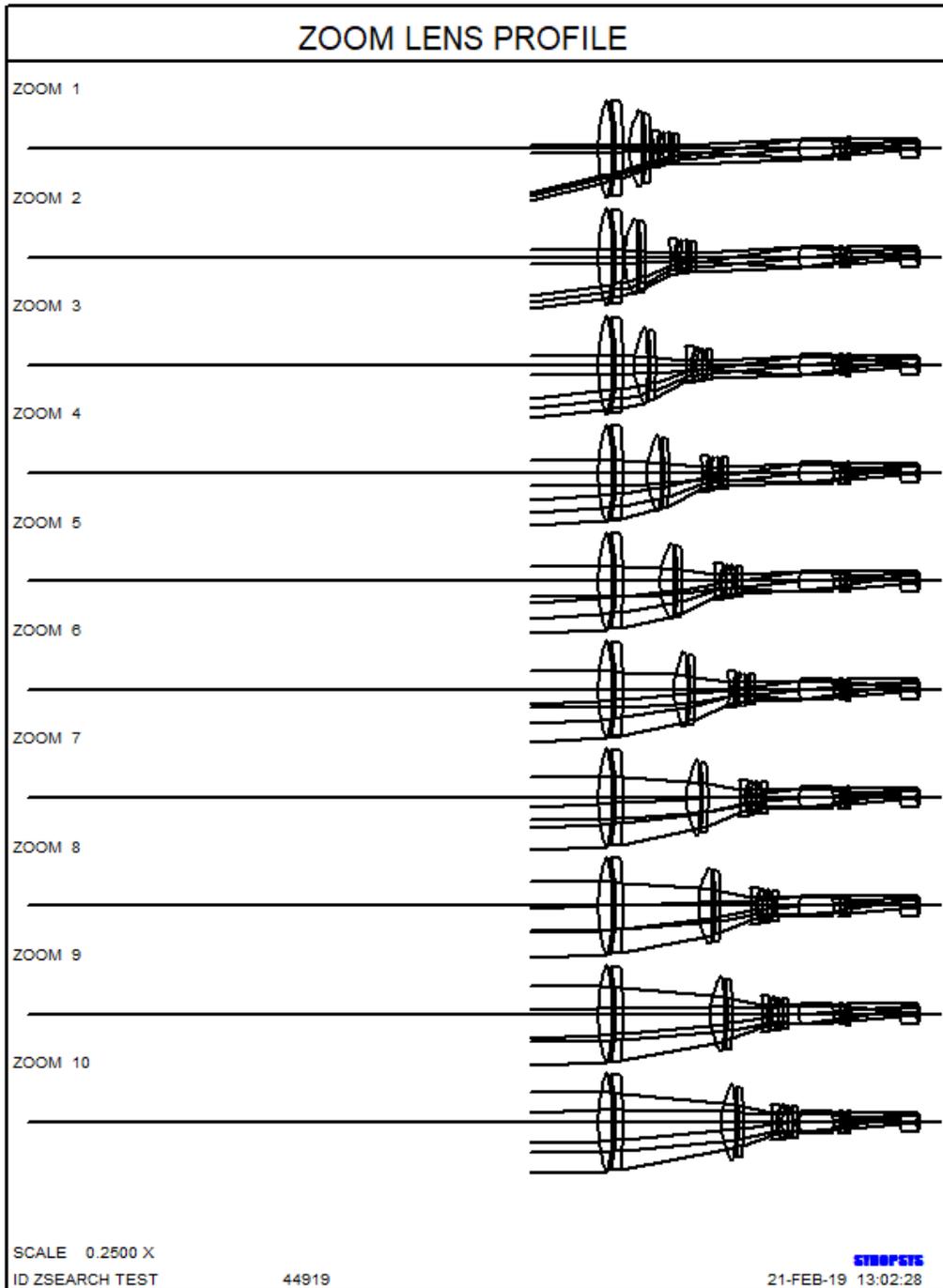Merit = 0.481985   SYNOPSYS
21-FEB-19 12:55:49

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

1. Run **CAM ZMAG 0.125 APERT**. 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.

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

ZOOM 1

ZOOM 2

ZOOM 3

ZOOM 4

ZOOM 5

ZOOM 6

ZOOM 7

ZOOM 8

ZOOM 9

ZOOM 10

SCALE   0.2500 X
ID ZSEARCH TEST   44919   21-FEB-19 13:02:28

That's enough for this lesson. You get the idea. If the lens is still not good enough, another run with AEI should help. Or you can try one of the other configurations returned by ZSEARCH. Use the same MF, and you quickly see how it compares with what we did above. 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 SYNOPSYS™.

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