Lesson 16: A Practical Camera Lens

Global search for a camera lens design

Although the lens we designed in Lesson 15 was pretty good, let us assume it was a little too long. To be practical, we would like it to be shorter, and we also want very high resolution. Here are the goals for this lesson:

1. Focal length 90 mm
2. Semi field angle 20 degrees
3. Semi aperture 25.4 mm
4. Cell length approximately 100 mm
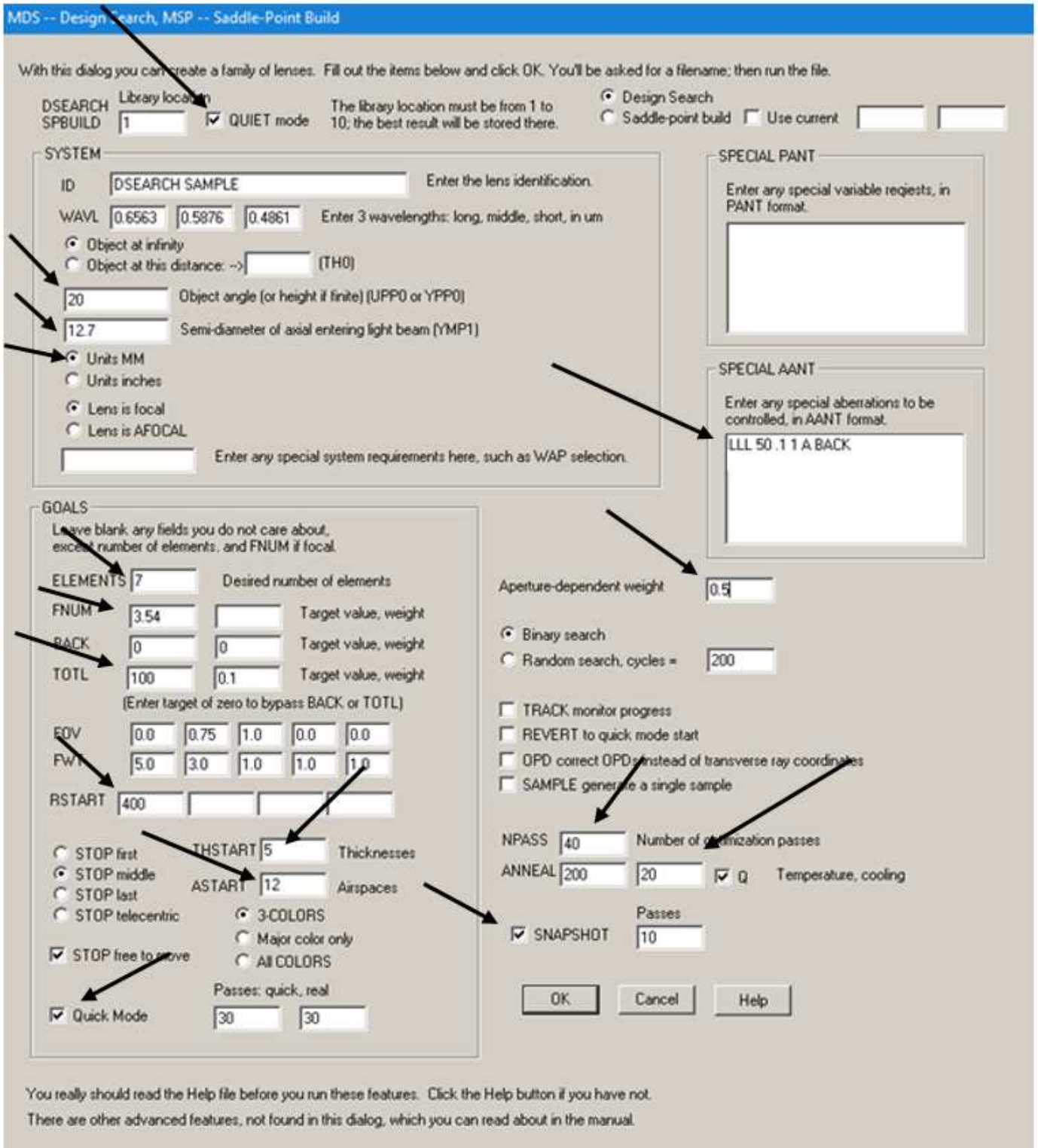5. Back focus distance 50 mm or greater

For this lesson, we will let **DSEARCH** find a starting point. Type **MDS** in the Command Window, to open the design search menu, shown below.

Enter the data shown by the arrows, and click OK. We can modify this input later, when we see the results. We guess the lens will need seven elements. The program asks you for a file name, so type a name such as LENS_7. An editor window opens, containing the input required to run the program.

```
CORE 14
TIME
DSEARCH 1  QUIET
SYSTEM
ID DSEARCH SAMPLE
OBB 0 20 12.7
WAVL 0.6563 0.5876 0.4861

UNITS MM
END
GOALS
ELEMENTS 7
FNUM 3.54
BACK 0 0
TOTL 100 0.1
STOP MIDDLE
STOP FREE
RSTART 400
THSTART 5
ASTART 12
RT 0.5
FOV 0.0 0.75 1.0 0.0 0.0
FWT 5.0 3.0 3.0
NPASS 40         ! this gives the number of passes in the final MACro
ANNEAL 200 20 Q
COLORS 3
SNAPSHOT 10
QUICK 30 30     ! this option runs much faster
END
SPECIAL PANT

END
SPECIAL AANT
LLL 50 .1 1 A BACK
END
GO
TIME
```

MDS -- Design Search, MSP -- Saddle-Point Build

With this dialog you can create a family of lenses. Fill out the items below and click OK. You'll be asked for a filename; then run the file.

DSEARCH   Library location
SPBUILD [1]   ☑ QUIET mode   The library location must be from 1 to 10; the best result will be stored there.

◉ Design Search
◯ Saddle-point build ☐ Use current [   ] [   ]

SYSTEM

ID [DSEARCH SAMPLE]   Enter the lens identification.

WAVL [0.6563] [0.5876] [0.4861]   Enter 3 wavelengths: long, middle, short, in um.

◉ Object at infinity
◯ Object at this distance: -->[   ]   (THO)

[20]   Object angle (or height if finite) (UPPO or YPPO)

[12.7]   Semi-diameter of axial entering light beam (YMP1)

◉ Units MM
◯ Units inches

◉ Lens is focal
◯ Lens is AFOCAL

[   ]   Enter any special system requirements here, such as WAP selection.

SPECIAL PANT

Enter any special variable reqiests, in PANT format.

SPECIAL AANT

Enter any special aberrations to be controlled, in AANT format.

[LLL 50 .1 1 A BACK]

GOALS

Leave blank any fields you do not care about, except number of elements, and FNUM if focal.

ELEMENTS [7]   Desired number of elements
FNUM [3.54] [   ]   Target value, weight
BACK [0] [0]   Target value, weight
TOTL [100] [0.1]   Target value, weight
(Enter target of zero to bypass BACK or TOTL)

EOV [0.0] [0.75] [1.0] [0.0] [0.0]
FWT [5.0] [3.0] [1.0] [1.0] [1.0]

RSTART [400] [   ] [   ]

◯ STOP first
◉ STOP middle   THSTART [5]   Thicknesses
◯ STOP last   ASTART [12]   Airspaces
◯ STOP telecentric   ◉ 3-COLORS
                      ◯ Major color only
☑ STOP free to move   ◯ All COLORS

Passes: quick, real
☑ Quick Mode   [30] [30]

Aperture-dependent weight [0.5]

◉ Binary search
◯ Random search, cycles = [200]

☐ TRACK monitor progress
☐ REVERT to quick mode start
☐ OPD correct OPDs instead of transverse ray coordinates
☐ SAMPLE generate a single sample

NPASS [40]   Number of optimization passes
ANNEAL [200] [20] ☑ Q   Temperature, cooling

Passes
☑ SNAPSHOT [10]

[OK] [Cancel] [Help]

You really should read the Help file before you run these features. Click the Help button if you have not.
There are other advanced features, not found in this dialog, which you can read about in the manual.

The DSEARCH dialog, opened with the command `MDS`

We elected not to assign a weight to the back focus distance in the dialog, preferring to put that requirement in the SPECIAL section, where we gave it a one-sided requirement. **LLL** means limit, lower limit, and this lets the back focus become larger than 50 without any penalty – but not smaller.

Notice the **RT** parameter in this file. That controls how individual rays are weighted in the merit function. A value of zero gives all the rays in a given grid the same weight, while a higher value will weight rays near the center of the pupil more than rays near the edge. That is a useful way to increase the resolution of a lens; the ray fans may fly away strongly right near the edge, but if the central portion is very flat the resolution will be high anyway. This is a parameter you will often want to experiment with.

Run this macro, and you get a collection of potential starting points, as shown below.
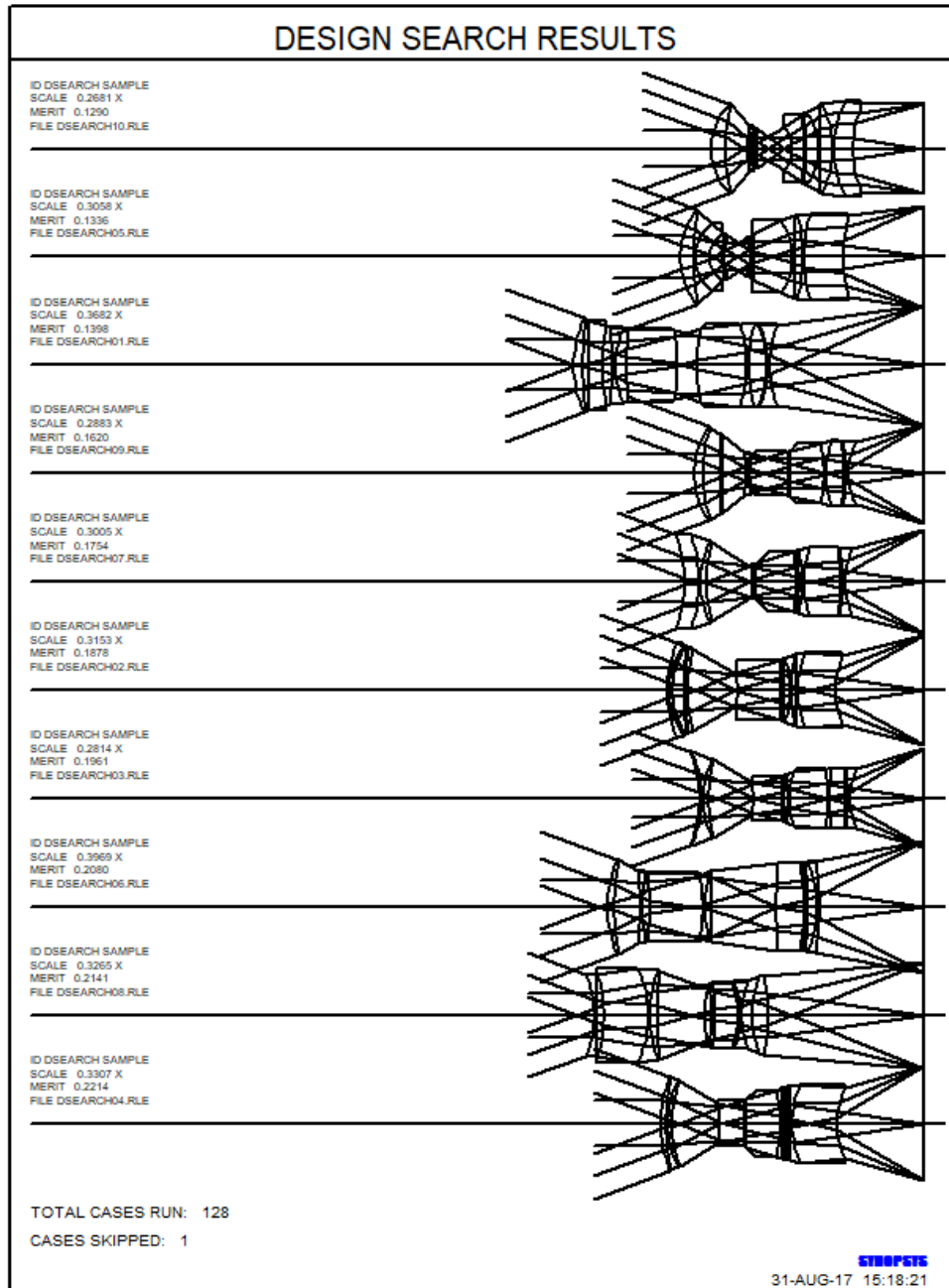
10 lenses returned by DSEARCH

Let's examine these lenses more closely. Type, in the CW,

        EM DSS

This command loads and runs the file DSS.MAC, which DSEARCH has created. That macro will open each of the lenses returned by DSEARCH, show it on the PAD display, and then wait for you to press the <Enter> key before opening the next. You will see that many of them have similar quality. When you see one you like, just press the <Esc> key to stop the macro at that point. We like the one saved by DSEARCH with the name DSEARCH9.RLE, which was also the top one in this example. (The names in your results may be different, since the order depends on which cores finished when.)
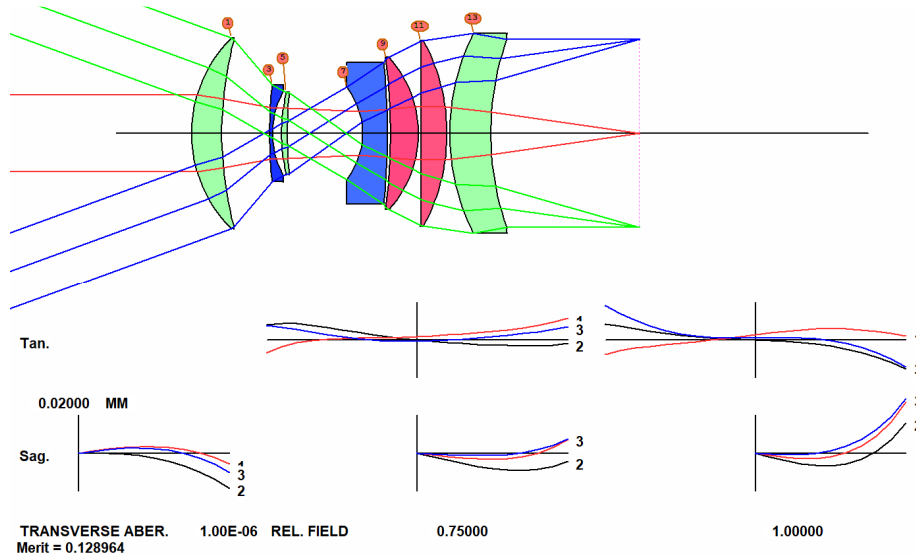
A good candidate from the DSEARCH results

Run the optimization MACro DSEARCH_OPT, which DSEARCH has created in a new window; then anneal (**55, 2, 50**). The lens changes somewhat. How good is this lens? Open the dialog **MOP** and enter the data shown below. Click the MOF button, and you get the MTF curves. Call this lens Version 1.

Not too good – but we learned some things. The MTF can vary rapidly with field, so we need more field points in the DSEARCH input. We also decide that, since this lens is not far from the diffraction limit, we should target OPDs instead of transverse aberrations. Here is our revised input for the GOALS section:

```
GOALS
 ELEMENTS 7
 FNUM 3.54
 BACK 0 0
 TOTL 100 0.1
 STOP MIDDLE
 STOP FREE
 RSTART 400
 THSTART 5
 ASTART 12
 RT 0
 FOV 0.0 .5 .7 .9 1
 FWT 3 2 2 2 2
 OPD
 NPASS 40
 ANNEAL 200 20 Q
 COLORS 3
 SNAPSHOT 10
 QUICK 50 50
 END
```
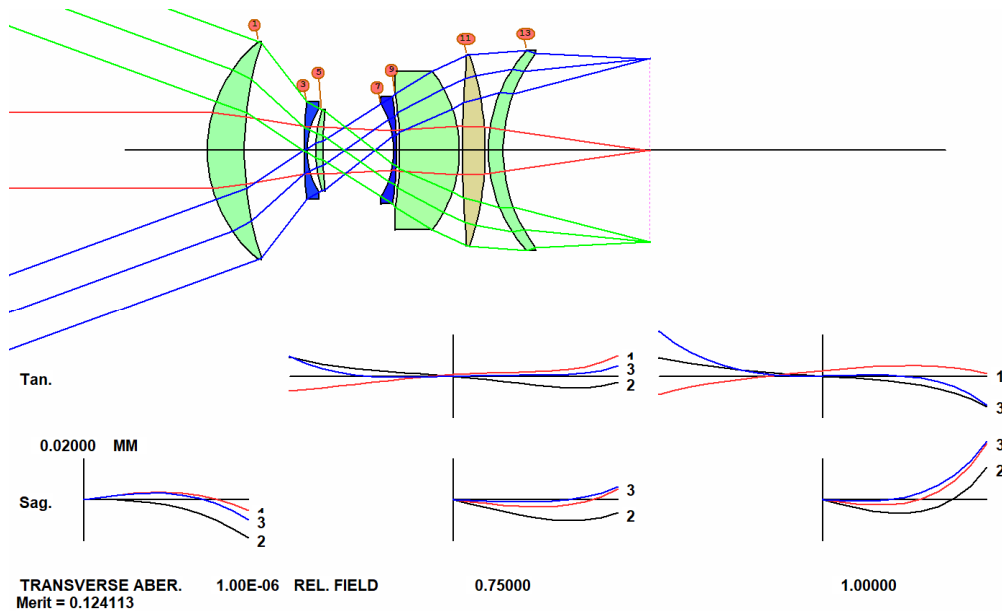
Lens optimized and annealed, Version 1

Dialog to run MOF, with four spatial frequencies requested.
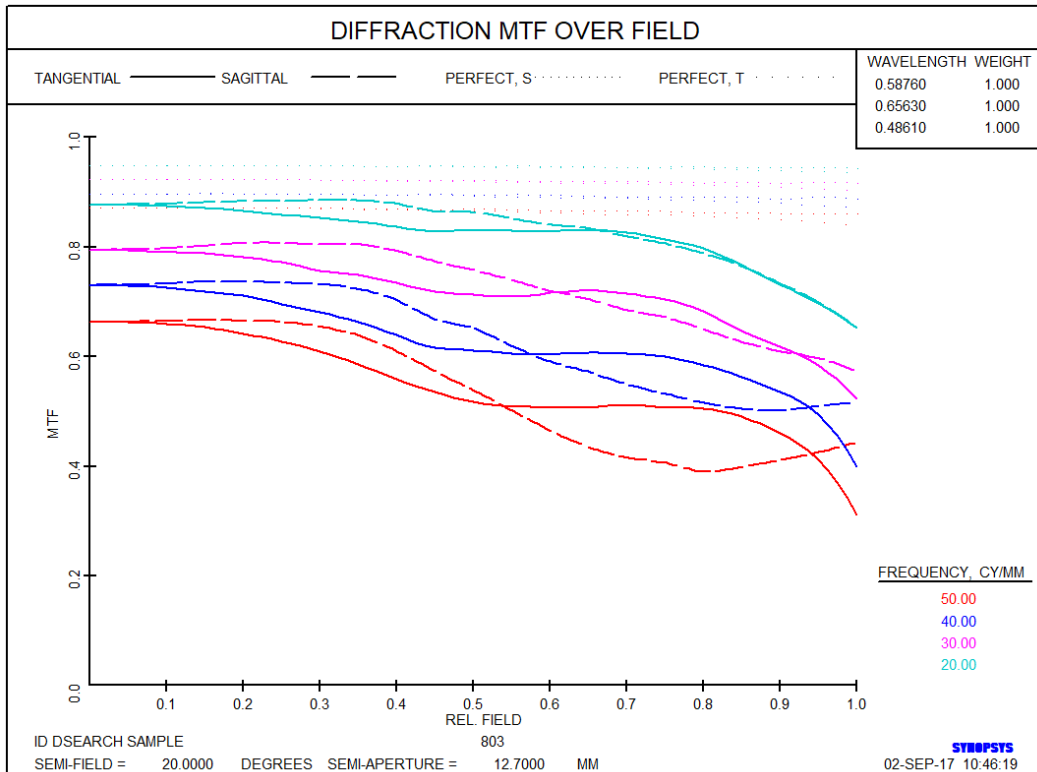
DIFFRACTION MTF OVER FIELD
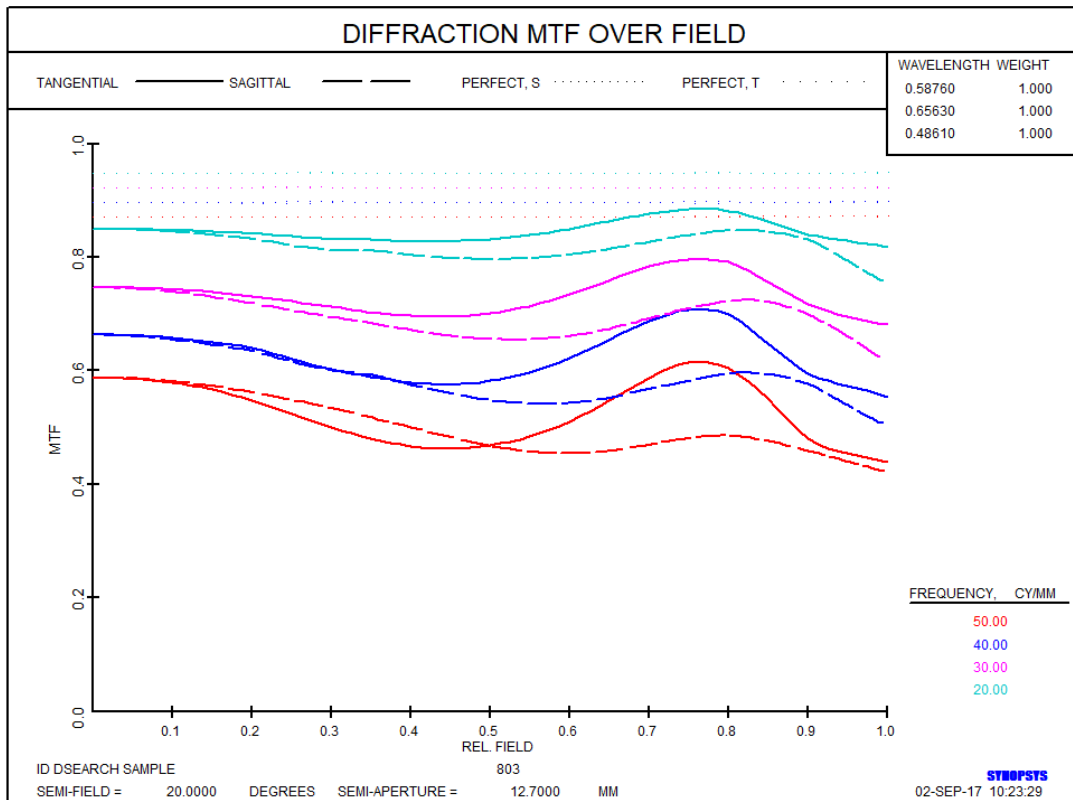
MTF curves for Version 1

Run this DSEARCH file, then optimize and anneal. You get a very different lens and MTF curves. Better on axis, not as good at the edge. What should we do?

TRANSVERSE ABER.   1.00E-06   REL. FIELD   0.75000   1.00000
Merit = 0.372349
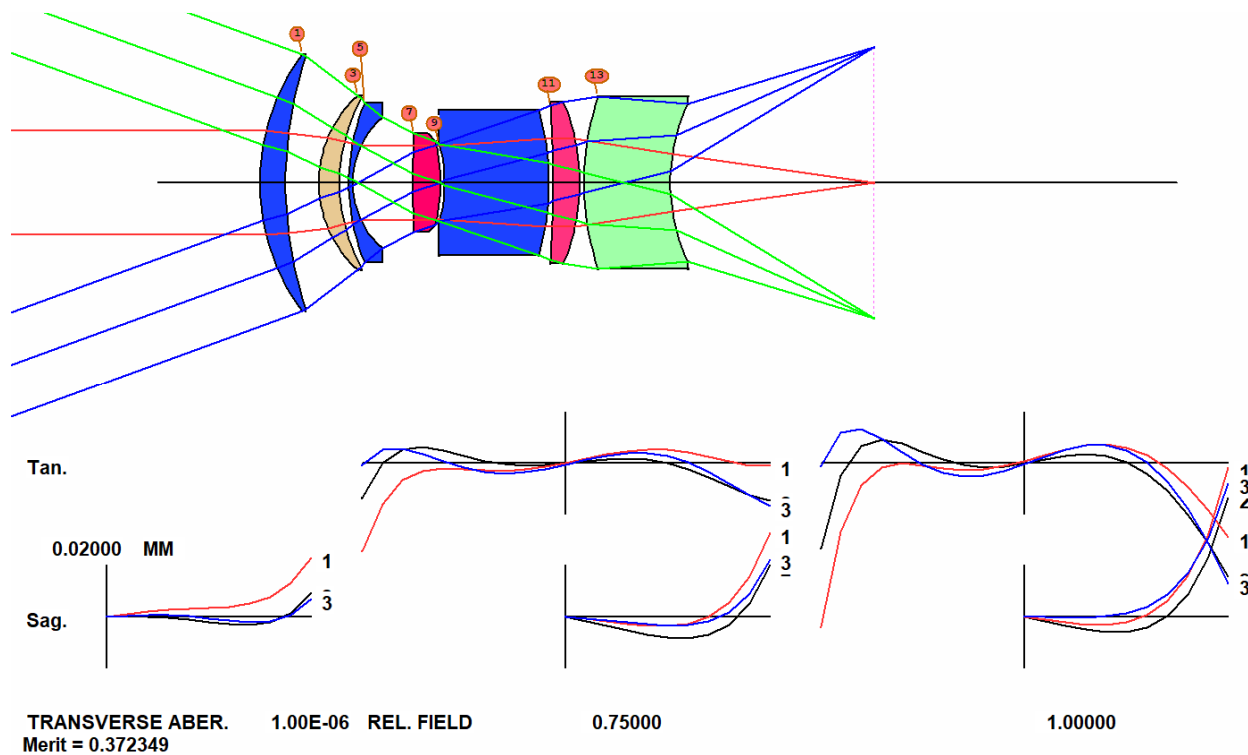
Version 2 lens, optimized and annealed

MTF of Version 2 lens

Let us try a tool we haven't used yet.

In the AANT file, delete all the GSO and GNO requests, and substitute the lines

```
GSHEAR .2 1 6 M 0 0 X
GSHEAR .2 1 6 M 0.5 0 X
GSHEAR .2 1 6 M 0.7 0 X
GSHEAR .2 1 6 M 0.9 0 X
GSHEAR .2 1 6 M 1 0 X

GSHEAR .2 1 6 M 0 0 Y
GSHEAR .2 1 6 M 0.5 0 Y
GSHEAR .2 1 6 M 0.7 0 Y
GSHEAR .2 1 6 M 0.9 0 Y
GSHEAR .2 1 6 M 1 0 Y
```

To understand this input, you have to understand how the MTF is calculated. A common method is to evaluate a *convolution integral*, which is based on combining two copies of the pupil, one sheared in X or Y by an amount that varies with the frequency to be calculated. If the OPD errors at a given point are the same as those at the sheared point, the MTF is perfect, as far as those points go. Calculated over the whole pupil, one gets the MTF of the lens. The above requests tell the program to evaluate the difference in OPD between a grid of points in the pupil and a corresponding point that is sheared according to the first argument, here 0.2. So this will optimize the lens while trying to peak the MTF at a spatial frequency that is 1/5 of cutoff, at each of five field points in three colors.

Run this optimization on the Version 2 lens and anneal. Then open each of the other 10 lenses returned by DSEARCH and do the same with them. (Perhaps the top one is not the best under these conditions.) We got the best results with the lens returned as DSEARCH08.RLE. Call this Version 3.

TRANSVERSE ABER.   1.00E-06   REL. FIELD   0.75000   1.00000
Merit = 92.502
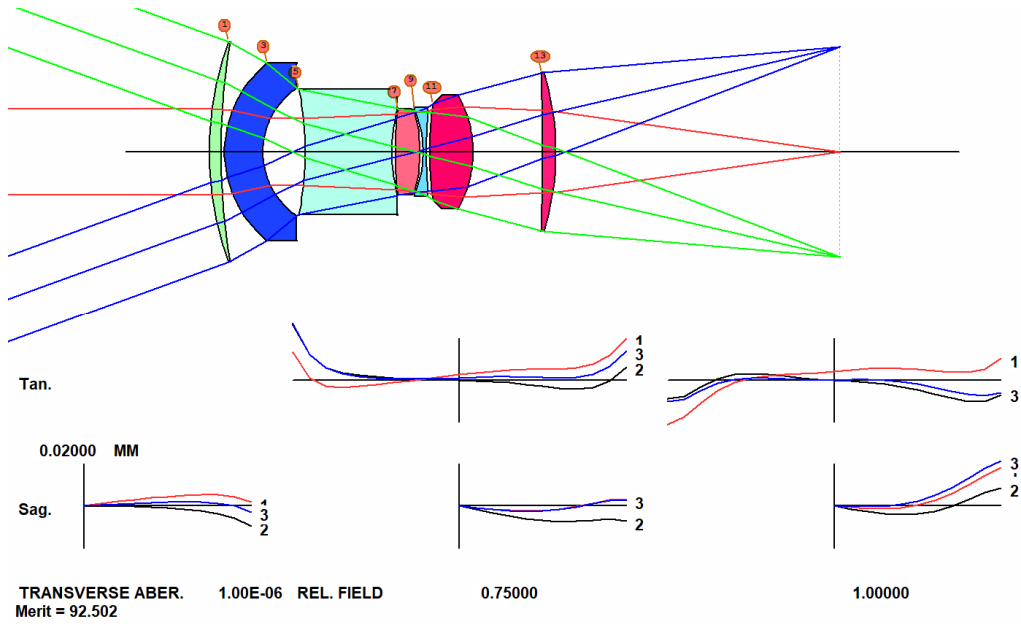
Version 3 lens, optimized with GSHEAR requests.

This is definitely better, but suppose we need even higher resolution. What now?

Perhaps we cannot do better with only seven elements. Add a line before the PANT command,
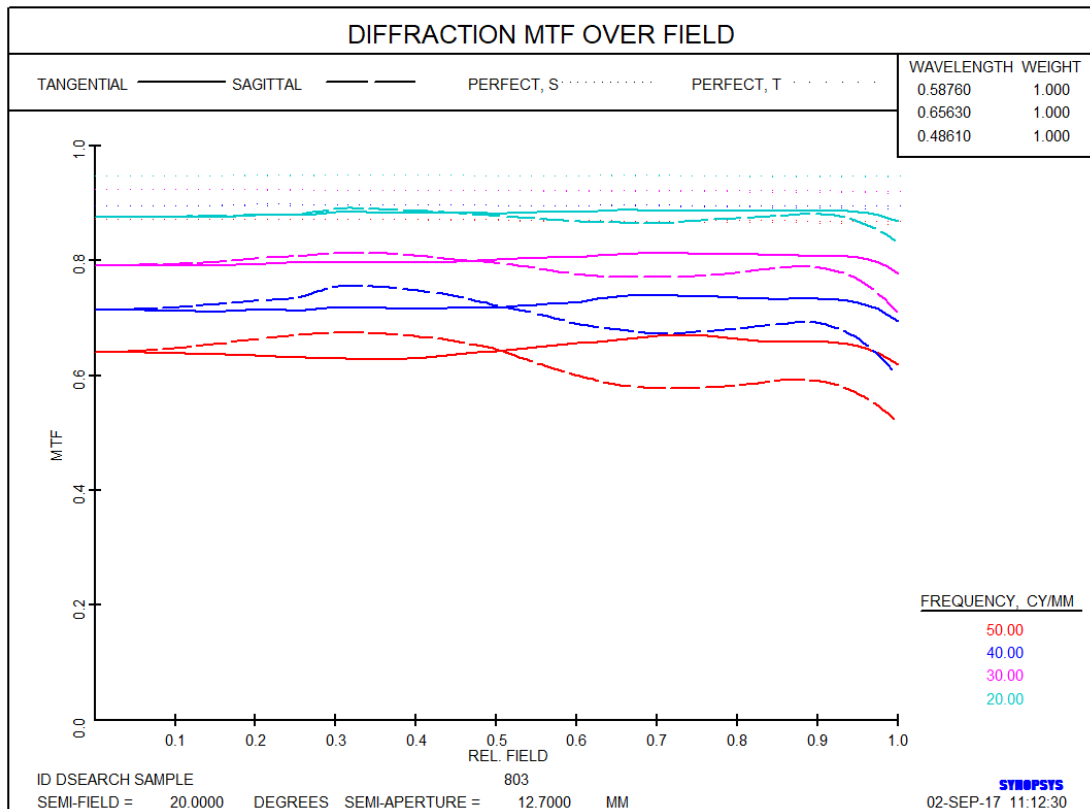
```
AEI 5 1 123 0 0 0 50 10
```

and run it again. Then comment out the AEI line, optimize, and anneal once more. The program has added a new element at surface 11, and the MF comes down from 92.5 to 71.8. Call the lens Version 4. This is an excellent lens.

MTF of Version 3 lens.

TRANSVERSE ABER.   1.00E-06   REL. FIELD   0.75000   1.00000
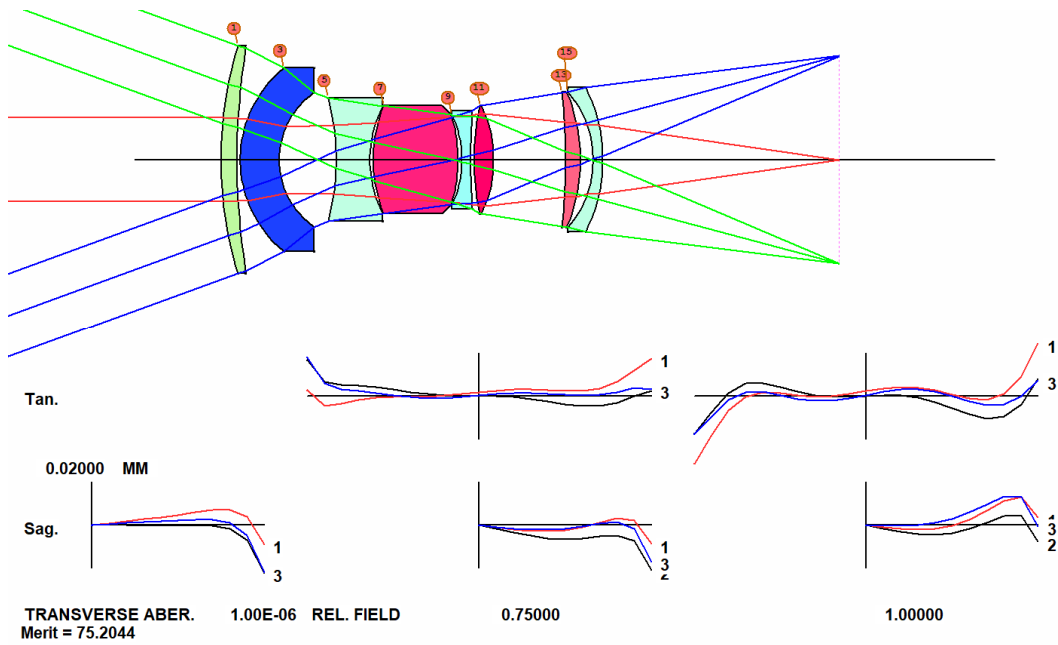
Merit = 71.7776
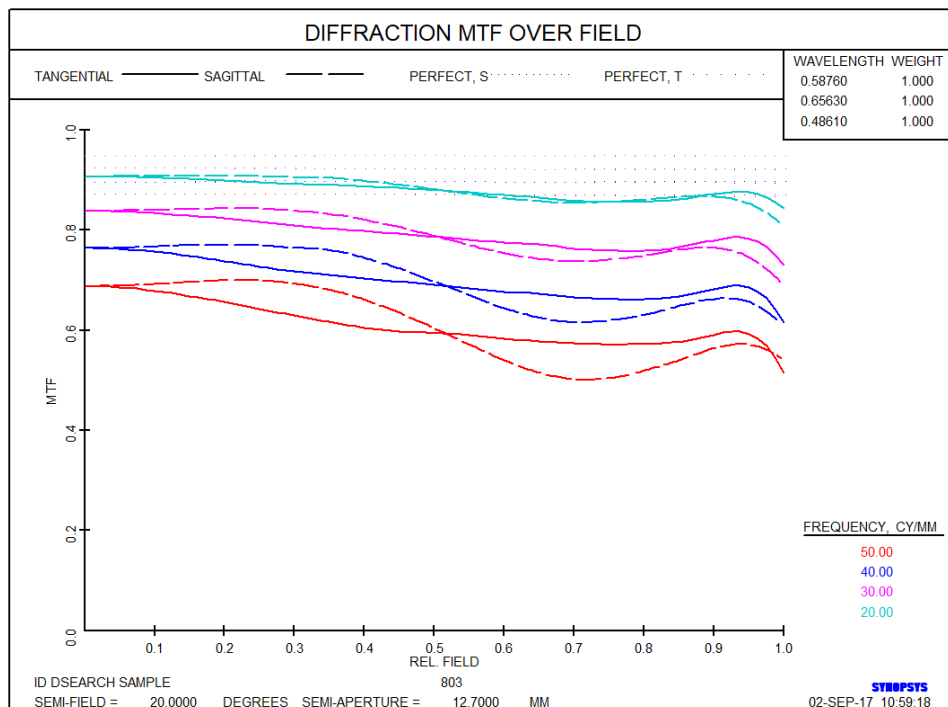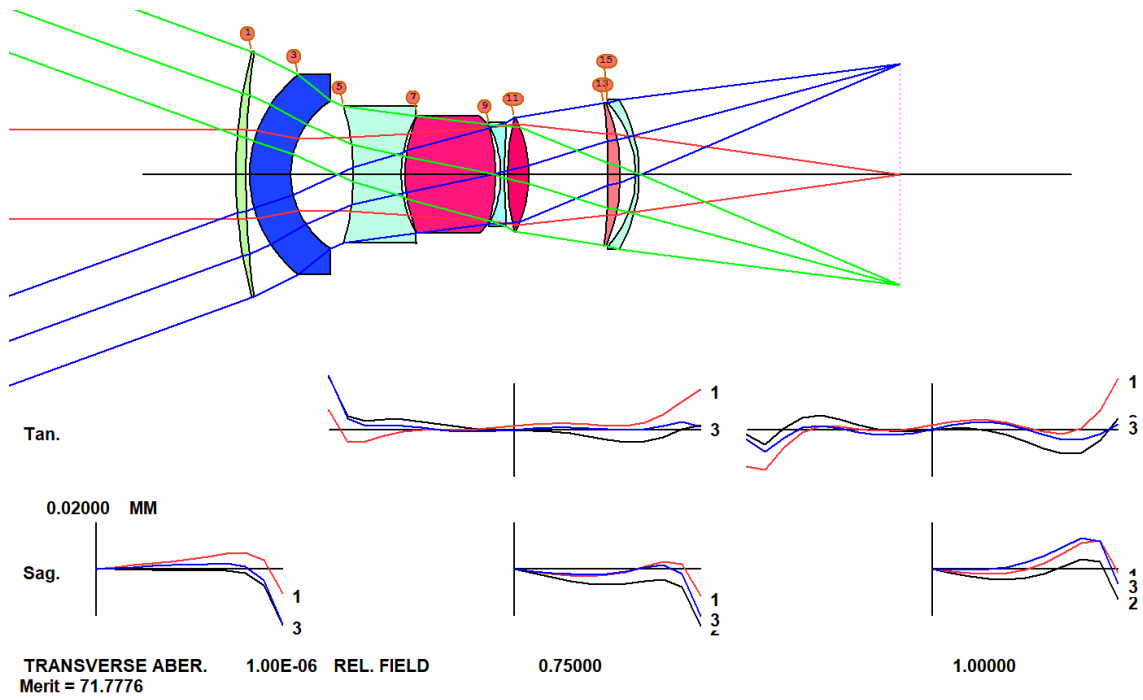
Version 4 lens, with element 7 inserted by AEI

MTF of Versions 4 and 5 lenses.

Make a final run, with an added monitor **ADT 8 .1 1**, and the lens looks great. This is the Version 5 lens, ready for real glasses and finishing touches.

Version 5 lens

With so many tools available, one naturally wants to know which ones to use. If you want an 8-element lens, for example, should you ask DSEARCH for eight, or ask it for, say, six – and then use AEI twice to get to eight elements? Can we predict what Nature will favor? Guidance, please.

Experience alone will tell. We ran this job again, asking DSEARCH for six elements, and then ran AEI twice, using only the GSHEAR aberrations. Testing all 10 of the DSEARCH results in this way, we found that seven of them returned a lower MF than Version 4, above. It seems that is a good strategy. The picture below shows the best of that lot, and MTF curves.

Another experiment: We ran DSEARCH again, with FOV 0 only, and put all the GSHEAR requests in the SPECIAL AANT section, with QUICK mode turned off. That input makes DSEARCH optimize every candidate lens completely, with no quick screening, and specifies the shear aberrations from the very start. How did it do?

Not very well. It seems you really should get close to a solution before using those targets. It is experiments like this that will show the way forward. We have new tools, and no long tradition of how to proceed. We are all learning together.

TRANSVERSE ABER.   1.00E-06 REL. FIELD   0.75000   1.00000
Merit = 60.7181
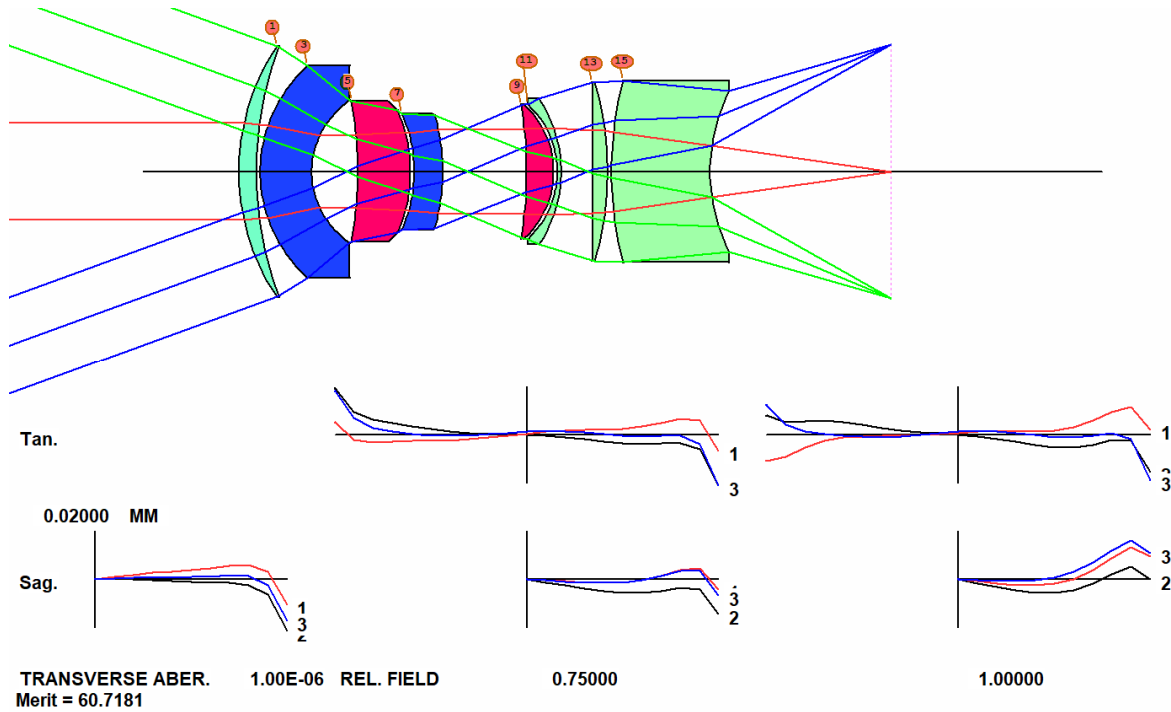
Lens found by asking DSEARCH for six elements, running AEI twice on all cases, and then optimizing the best one.
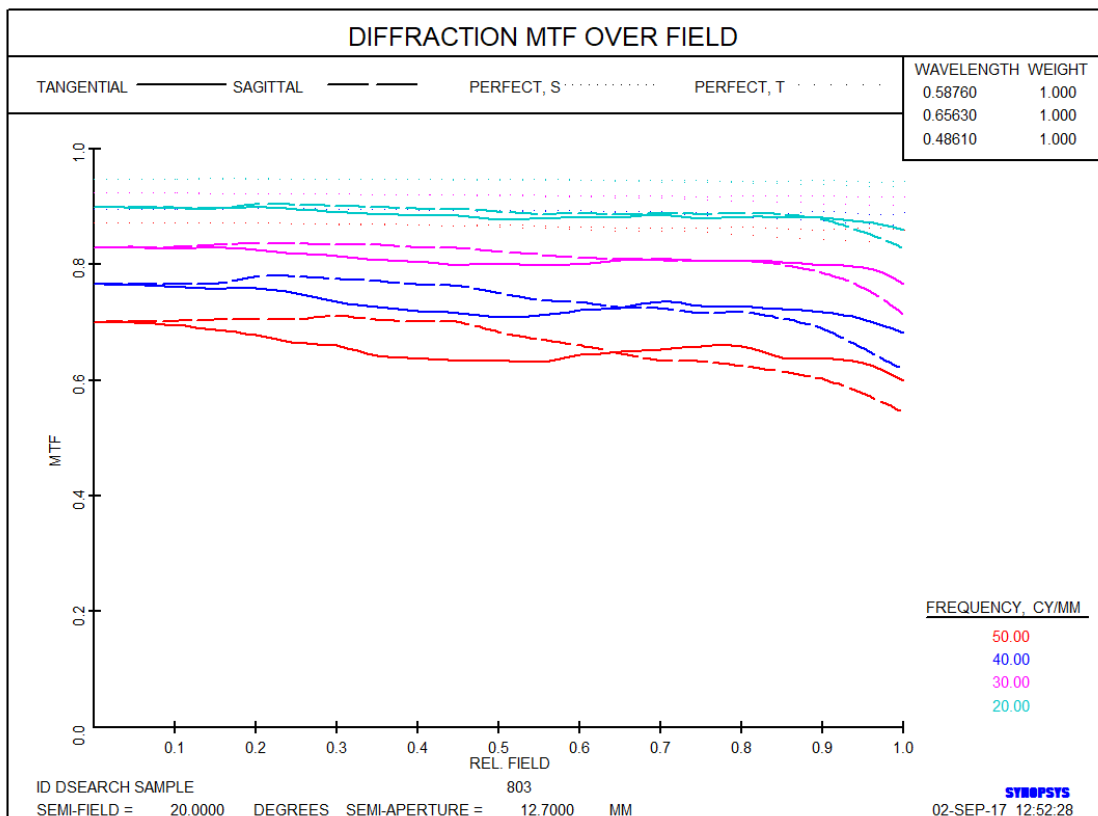
MTF of the lens above

This lesson illustrates quite graphically that, in lens design, you are dealing with a landscape with a great many solutions. Unless you already have a very good starting lens, your chances of finding a great one improve as you experiment with the parameters of DSEARCH.

The art of lens design has changed significantly with the advent of new tools like DSEARCH. Whereas in former ages an expert designer would work for days or weeks on a single design, using sophisticated knowledge to steer the process, today one can produce a great many designs in a matter of minutes and then select the most promising for further work. Some of those designs often turn out to be superior to what an expert was able to come up with in days past.

In a practical situation, I would next add an ADT monitor (the diameter/thickness ratio) to the AANT file, since some of the elements are too thin. (The program often returns better lenses if you *don't* use this monitor right at the start. Thicknesses are easy to modify later, after you have a good design, and we have found that controlling this ratio right at the start strongly affects which branches the program will investigate – and you might well miss a good one. Try it both ways and select the best result.) Then I would finalize the lens, see how the image correction changes with conjugate (if that is a requirement, and reoptimize the lens as shown in Chapter 19 if so), insert real glass types with ARGLASS, assign a real stop to the surface closest to the implied stop, perhaps decrease the thickness of some elements, reoptimize, define edge geometry with the Edge Wizard, match the curves to a vendor's testplate list with TPM, prepare tolerances with BTOL, make element drawings with ELD, system drawings with DWG, and so on. There is much to do when designing a lens, and this has been a practical lesson that shows how to use a few of the many tools that are available. We started with nothing more than a list of requirements and in a fairly brief time came up with some rather good lenses.

Feel free to experiment with this problem, and try various values for the starting radius, thickness, airspaces, and other parameters for DSEARCH. If you find a result different from the one above but just as good, please let me know.