

Lesson 37: Finding and Changing Lens Structure Automatically

If you have read and understood the previous lessons in this series, you are already familiar with the tools we will use in this lesson – but you probably do not know how excellent the results can be when you combine them. Here we will present a challenging problem and then show how those tools can find an excellent design in a fraction of the time needed by those using classical design methods. Time is money, after all, and this is worth knowing about. We will use DSEARCH to derive a starting configuration, and then use other features to modify the lens construction, always improving its performance. No other lens design code has this kind of power.

In lesson 34 we designed a very good 90-degree eyepiece, where the eye point was the last surface. Here we will do an even more challenging task and put the eye point before surface 1. We also have to ensure that the image of a field stop is sharp to the eye.

(In this lesson we will use the simulated annealing feature for the search and optimization, since it usually returns the best results. That feature does not always return the same answer, however, because of the random nature of the process, so if you run this exercise yourself, the result will likely be somewhat different. But the overall quality is usually about the same.)

The problem is to design a wide-angle eyepiece according to the goals summarized below.

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 μ m.

Correction to ½ wave or better in C (0.6563 μ m) and F (0.4876 μ m) light.

Pupil aberration at eye point no greater than 1/2 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.

This is not an easy problem – nor should it be. If the problem could be solved entirely by the computer, the results would appear in a manner of minutes and the lesson would not be very interesting. But these requirements cannot all be input to any lens design code with a single set of commands, so here we will use the computer to do the job that it does best, and the skill of the designer to fill in where needed and to direct the program as necessary.

The most difficult part of the job is the selection of a promising starting point. Many designers resort to lists of patents or lenses on file with their company, rather than working out a design from scratch. Here, we start with absolutely nothing and require the computer to come up with a starting design all by itself. To accomplish this, we use **DSEARCH**, which you have seen in earlier lessons. The input to this program is listed below. Readers are referred to the **SYNOPSIS** User's Manual for a description of the formats involved. Most of this input can be created in the dialog **MDS**, which will create a **MACRO** for you. Then you can edit it as you wish; we show here a useful example.

```
LOG
TIME
CORE 14
DSEARCH 5 QUIET
SYSTEM
```

ID EYEPIECE EXAMPLE

OBD 1.0E9 45 1.27

UNI MM

WAVL CDF

WAP 1

END

GOALS

ELEMENTS 9

TOTL 200 .01

BACK 0 0

FNUM 8.0 10

ASTART 10

THSTART 10

RSTART 400

RT 0.0

NPASS 80

DELAY OFF

ANNEAL 100 25 Q

SNAP 10

TOPD

STOP FIRST ! keep the stop at the eye point

STOP FREE

QUICK 50 100

FOV 0 .3 .6 .75 .9 1. ! correct over five field points

FWT 3 1 1 1 1 1

END

SPECIAL AANT

ACA 50 1 1

ADT 10 .1 1

M 15 1 A P YA 1 0 0 0 1 ! control eye relief

M -.008 4 A P HH 1 ! aim light at objective to right

M -.004 4 A P HH .5 ! and control pupil aberrations

M -.0064 4 A P HH .8

M 0 1 A P YA 1 ! and distortion too

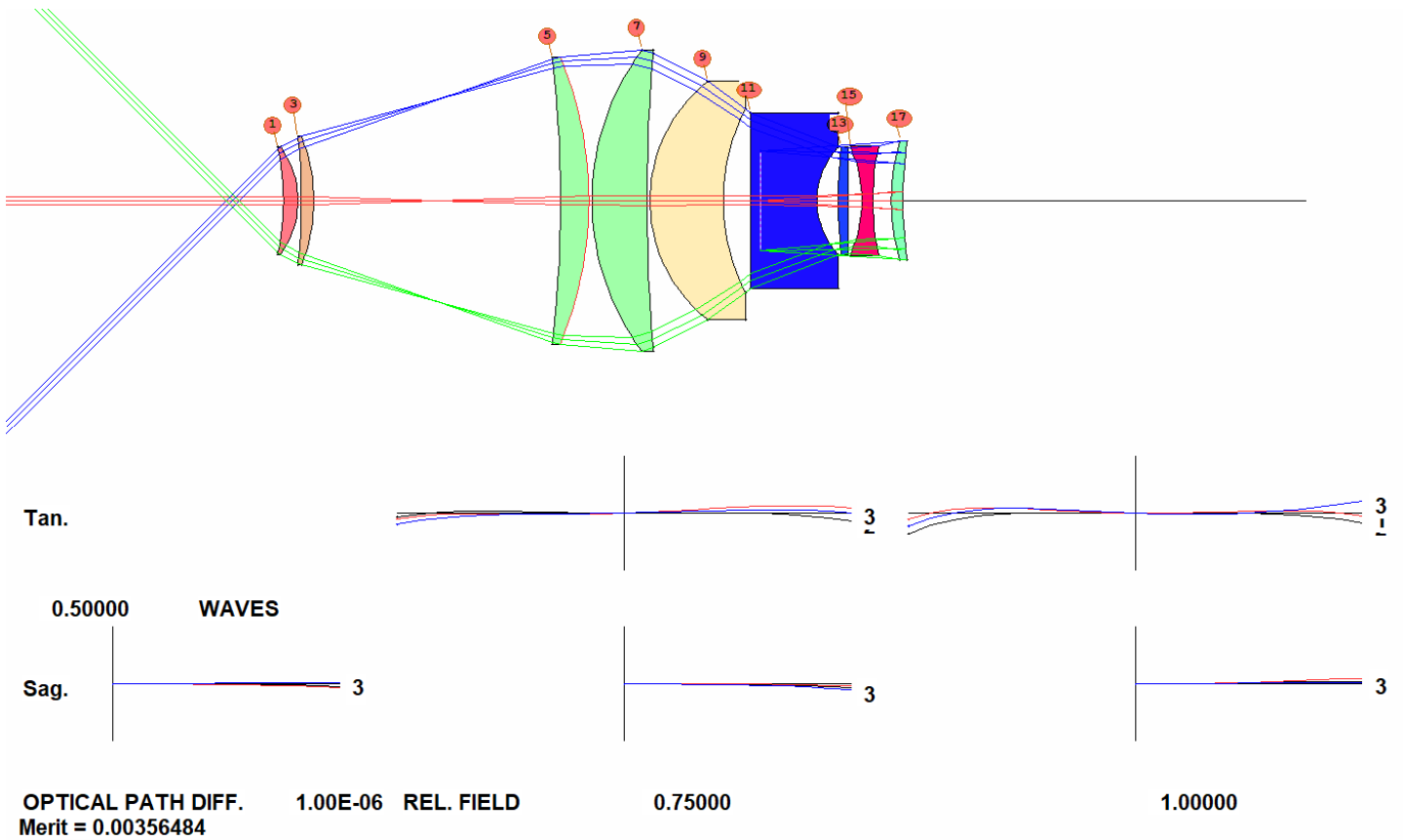
S GIHT

END

GO

TIME

Run this, and when the search finishes, the program displays a picture of the 10 best configurations it found and loads the top one. After running the optimization MACro prepared by DSEARCH on that lens and annealing, the lens is quite good, as shown below.



Best design returned by DSEARCH, optimized and annealed

The figure shows the wavefront errors, which are all less than 1/4 wave. So far, so good. But one must also watch and correct pupil aberrations in these wide-angle eyepieces. If those aberrations are too large, the eyepiece will suffer from the notorious “kidney bean” effect, which causes portions of the field to go black as the user scans their eye over the field. We have to check.

Prepare a new MACro as follows:

```

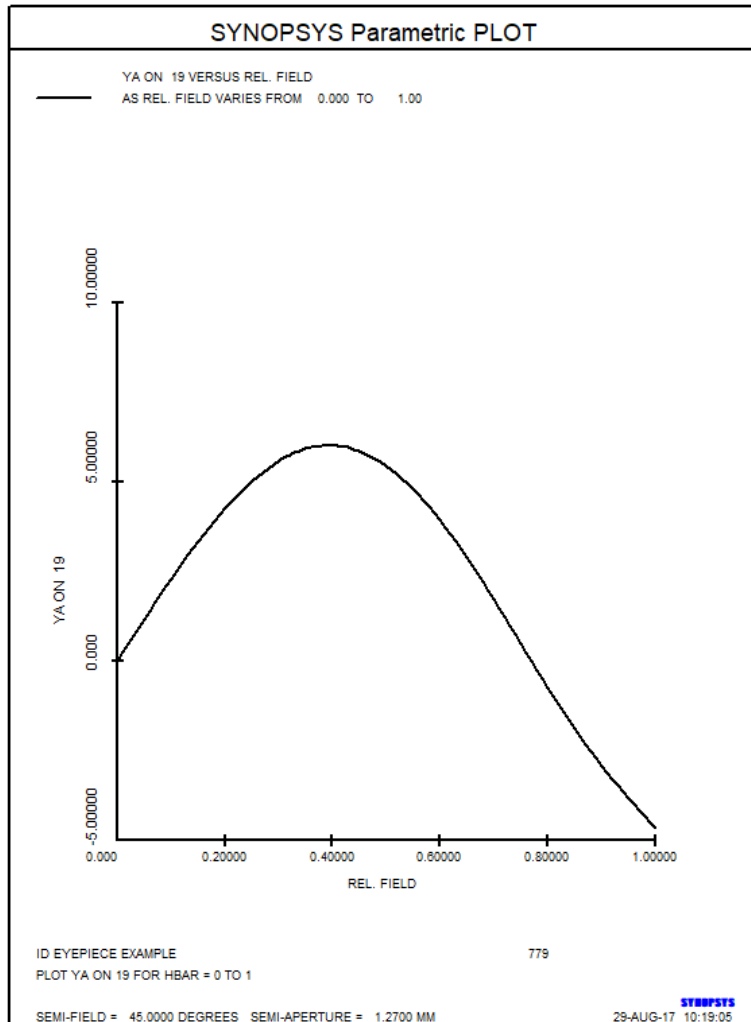
STO 9
CHG
NOP
18 TH 2000
19 YMT
20
END
STEPS = 100
PLOT YA ON 19 FOR HBAR = 0 TO 1
GET 9

```

and run it. This will do the following:

1. Remove the YMT solve on surface 18 (via NOP, which removes all solves).
2. Put surface 19 at a distance of 2000 mm. This will model the telescope objective, assumed at that distance.
3. Assign a YMT solve to surface 19, which then focuses on 20.
4. Declare surface 20, so it exists.
5. Make a plot of the chief-ray intercept on 19 over the field. If the rays all hit near the center of surface 19, the aberrations will be under control.

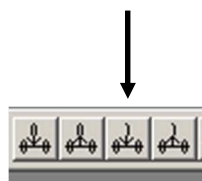
Run this MACro, and you see the pupil aberration at the objective, shown below. At F/8, at a distance of 2000 mm, the diameter of the objective will be 250 mm. A chief-ray error of 6 mm is therefore only about 2.4% of the size of the objective, and we are allowed 1/2 mm on an entrance pupil of 2.54 mm, or about 20%, so we judge this degree of correction satisfactory. That did not come for free, however; the HH targets in the SPECIAL AANT section penalized any solution that showed large pupil aberrations. You should feel free to adjust the weights on those targets to balance all the errors as you prefer.



Pupil aberration at the objective lens, calculated for the eyepiece.

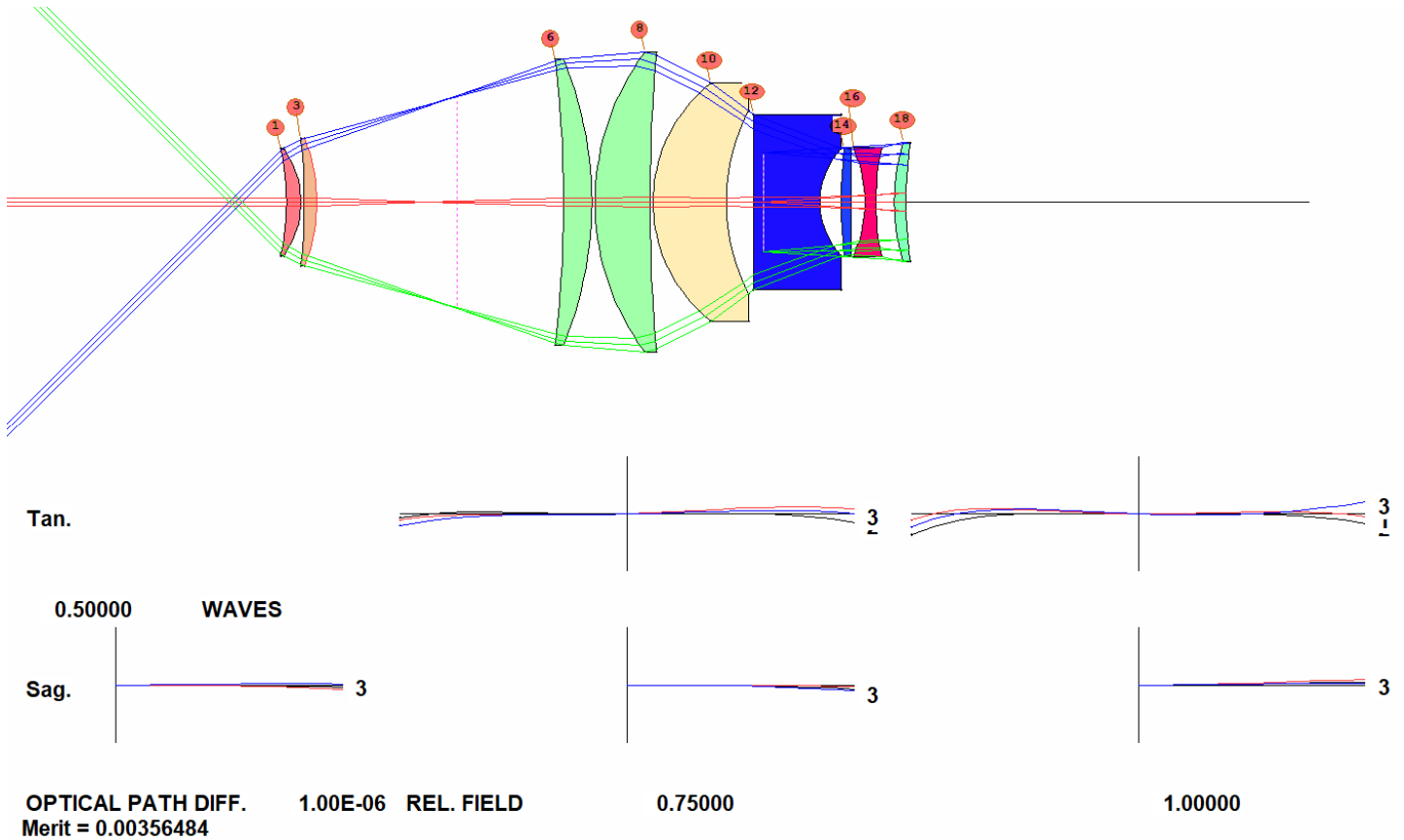
The eyepiece is already at the diffraction limit, but is not yet finished since we have not controlled image quality at the field stop.

We have to control that – but the lens does not even have a field stop yet. In the WorkSheet, click the Add Surface button, shown below



Selecting the Add Surface button

and then click on the axis between surfaces 3 and 4 (or wherever the intermediate image is in your lens). A surface is added, as shown.



Lens with added surface for the field stop

Now type, in the WS edit pane,

5 FLAG

and click Update. Now you can refer to that surface in the AANT file with that name.

Edit the MACro that DSEARCH prepared for you.

```

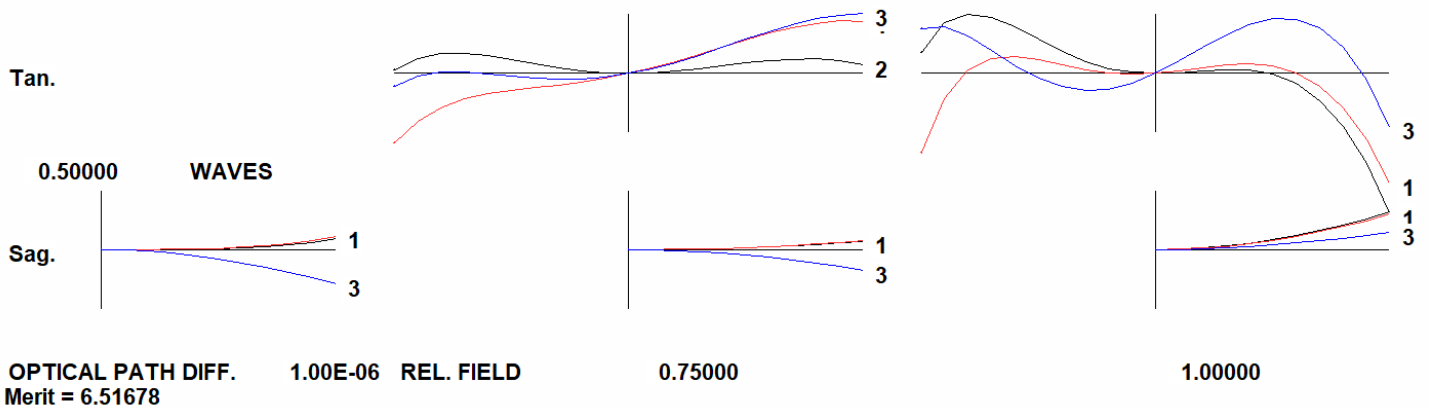
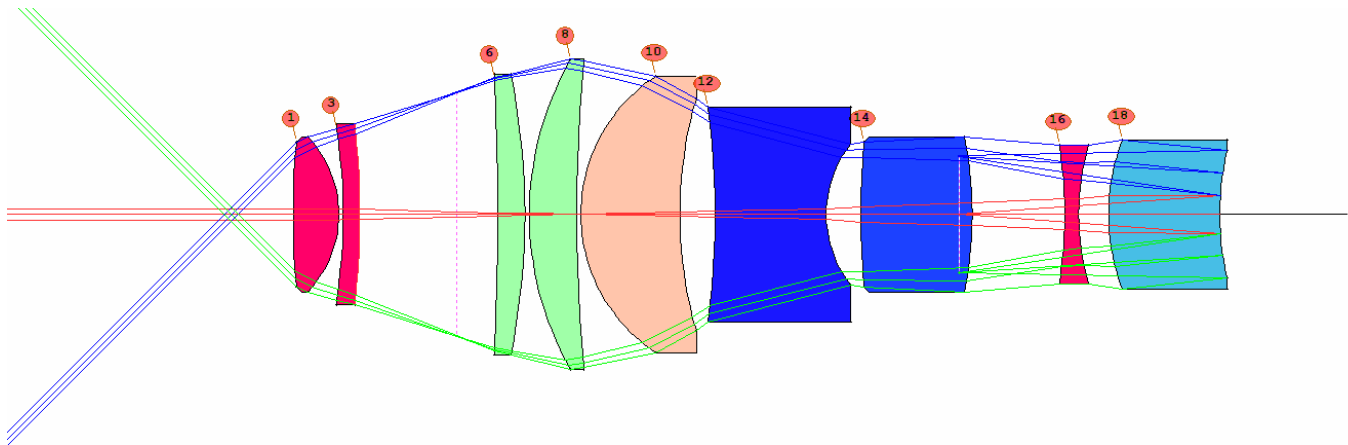
PANT
VY 0 YP1
VLIST RD ALL
VLIST TH ALL
VLIST GLM ALL
END
AANT P
AEC 3 1 1
ACM 3 1 1
ACC
GTR 0 2 4 P 1 0 FLAG
GTR 0 2 4 1 1 0 FLAG
GTR 0 2 4 3 1 0 FLAG
M 0 10 A 1 YA 1 0 0 0 FLAG
S 3 YA 1 0 0 0 FLAG
    
```

```

M 0.125000E+00 0.100000E+02 A CONST 1.0 / DIV FNUM
GSR 0.000000 3.000000 4 M 0.000000
GNR 0.000000 1.000000 4 M 0.300000
GNR 0.000000 1.000000 4 M 0.600000
GNR 0.000000 1.000000 4 M 0.750000
GNR 0.000000 1.000000 4 M 0.900000
GNR 0.000000 1.000000 4 M 1.000000
GSO 0.000000 0.281753 4 M 0.000000
GNO 0.000000 0.093918 4 M 0.300000
GNO 0.000000 0.093918 4 M 0.600000
GNO 0.000000 0.093918 4 M 0.750000
GNO 0.000000 0.093918 4 M 0.900000
GNO 0.000000 0.093918 4 M 1.000000
M 0.200000E+03 0.100000E-01 A TOTL
ACA 50 1 1
M 15 1 A P YA 1 0 0 0 1 ! CONTROL EYE RELIEF
M -.01 5 A P HH 1 ! AIM LIGHT AT OBJECTIVE TO RIGHT
M -.005 5 A P HH .5 ! AND CONTROL PUPIL ABERRATIONS
M -.008 5 A P HH .8
M 0 1 A P YA 1 ! AND DISTORTION TOO
S GIHT
END
SNAP/DAMP 1
SYNOPSIS 80

```

When you run this MACro, the image gets worse! Correcting the blur at the field stop is not so easy, and the program had to make tradeoffs. An expert would note that you cannot correct lateral color at the field stop with just two crown elements to the left. You need a flint element in there – but we will let the program figure that out.

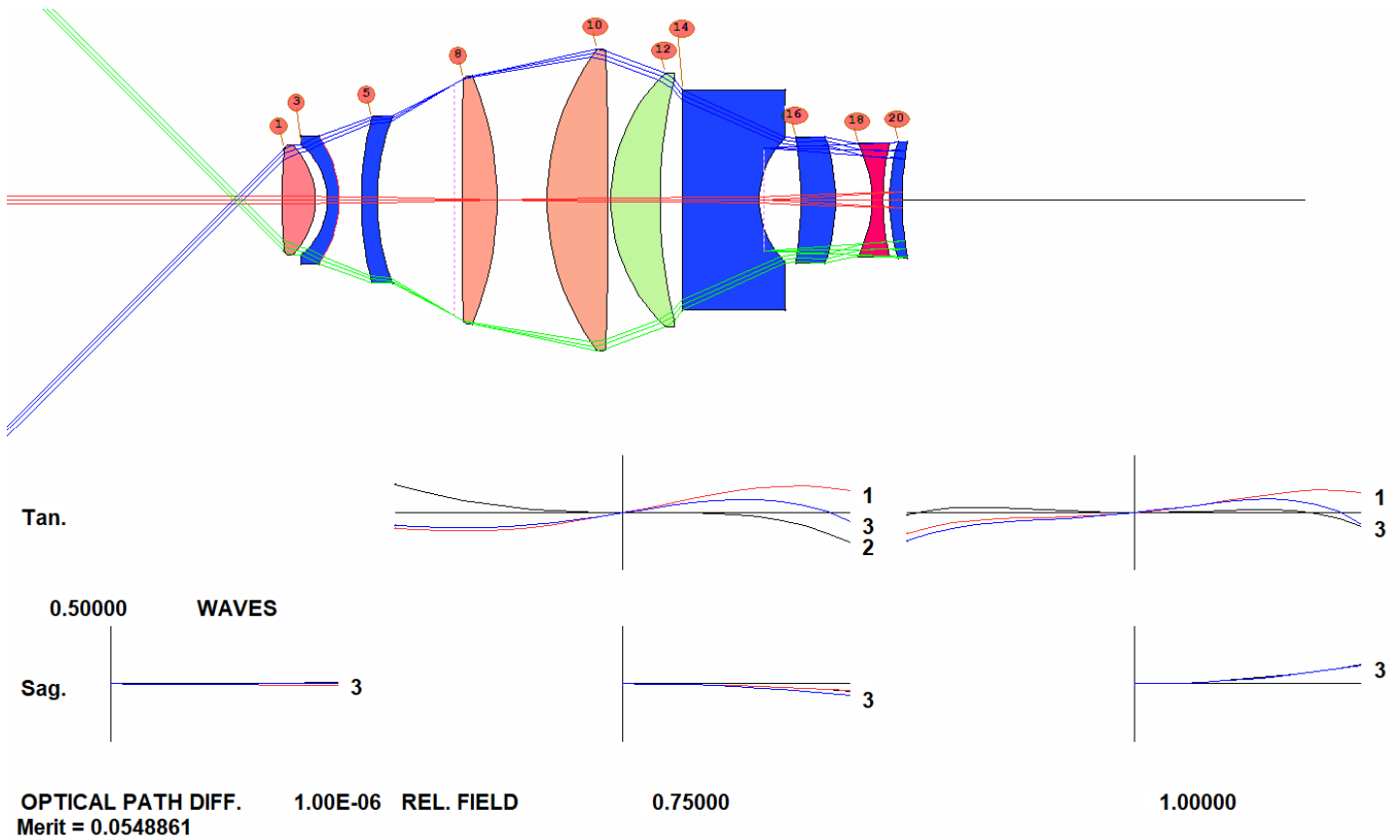


Lens optimized with field stop, before adding a new element

It's time to run the **Automatic Element Insertion** feature. Add the line

AEI 6 1 123 0 0 1 0 0

before the PANT command, and run the MACro again. The program adds a flint element near the front end, and the image is better. Comment out the AEI line, optimize again, and then anneal. The merit function comes down.



Lens reoptimized with added element

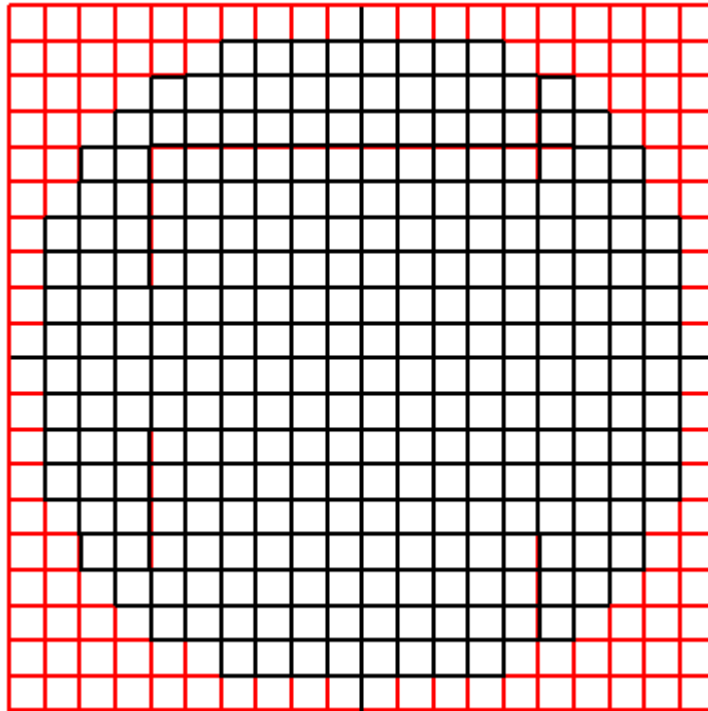
You also have to watch out for intermediate field points in wide-angle designs like this. Run the PAD scan, and you see the correction remains below ¼ wave everywhere.

Make a checkpoint and type **MRG** to open the Real Glass Menu. Select the Ohara catalog, Library 6, QUIET, SORT, and then OK.

```

--- ARGLASS 6 QUIET
Lens number      6 ID EYEPIECE EXAMPLE
GLASS S-FSL5Y    HAS BEEN ASSIGNED TO SURFACE 18; MERIT = 0.567006E-01
GLASS S-LAL14    HAS BEEN ASSIGNED TO SURFACE 1; MERIT = 0.559695E-01
GLASS S-LAL8     HAS BEEN ASSIGNED TO SURFACE 10; MERIT = 0.606200E-01
GLASS S-LAL8     HAS BEEN ASSIGNED TO SURFACE 8; MERIT = 0.586577E-01
GLASS S-NPH4     HAS BEEN ASSIGNED TO SURFACE 3; MERIT = 0.463717E-01
GLASS S-NPH4     HAS BEEN ASSIGNED TO SURFACE 14; MERIT = 0.561651E-01
GLASS S-NPH4     HAS BEEN ASSIGNED TO SURFACE 5; MERIT = 0.511101E-01
GLASS S-NPH4     HAS BEEN ASSIGNED TO SURFACE 16; MERIT = 0.551983E-01
GLASS S-LAH92    HAS BEEN ASSIGNED TO SURFACE 20; MERIT = 0.485848E-01
GLASS S-LAH89    HAS BEEN ASSIGNED TO SURFACE 12; MERIT = 0.507509E-01
    
```

The lens is now almost perfect. Let's look at the distortion. Type `GDIS 21 G`. The eye will not notice any distortion at all.



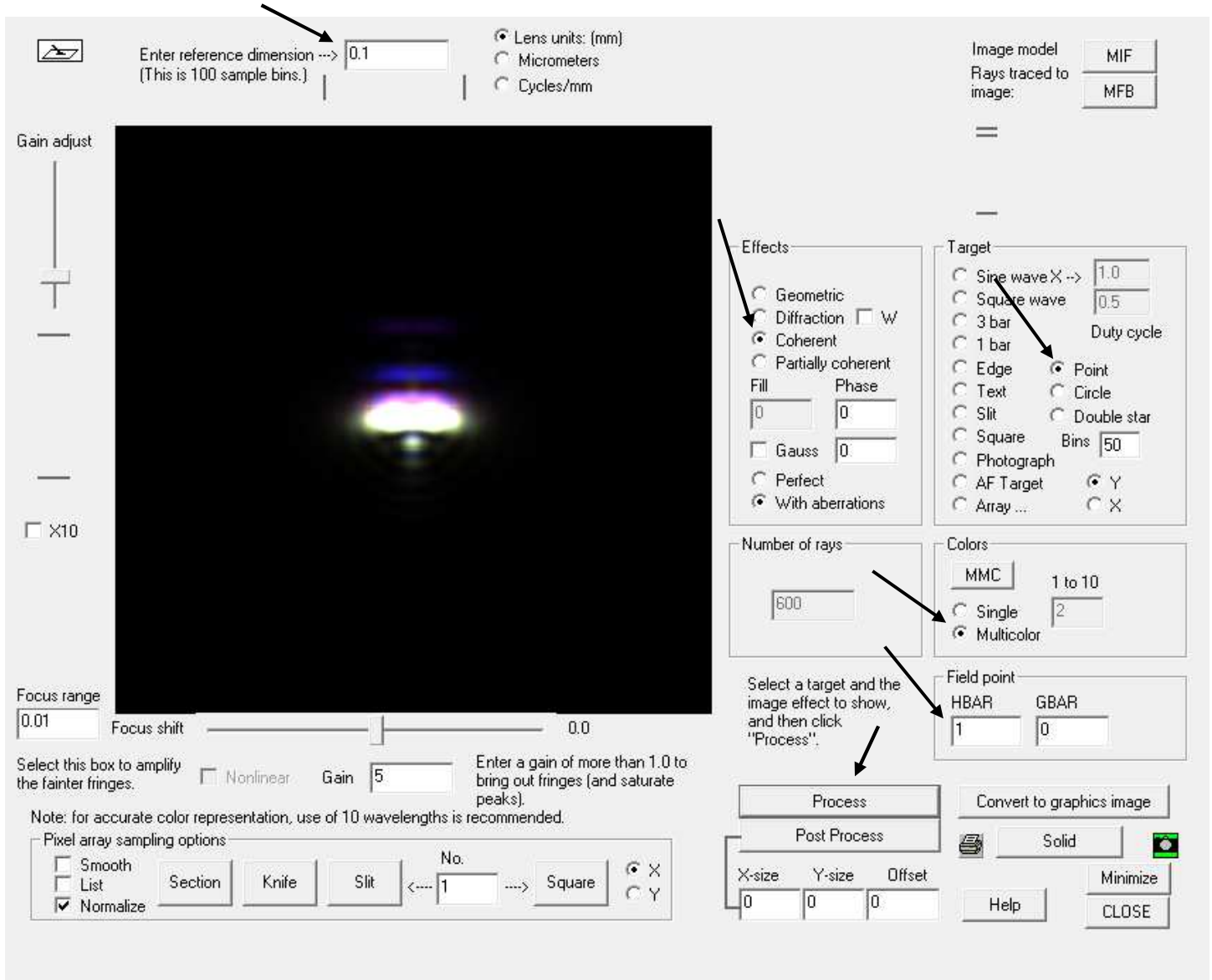
Distortion plot for the final design

Now we have to check how well the image is corrected at the field stop. Make a checkpoint and type

```
CHG
7 MXSF
END
```

This truncates the lens at surface 11 (temporarily, so we can evaluate the image at the field stop). Only the TFAN affects the sharpness of the field stop as seen by the eye.

Use the Spectrum Wizard to model 10 wavelengths, visible spectrum, bright light. Then open the Image Tools Menu (**MIT**), select a reference dimension of 0.1 mm, Coherent effect, Point source at HBAR = 1, Multicolor, and click Process.



MIT dialog with image of a point on the edge of the field stop. This will look sharp to the eye.

Indeed, the blur at the field stop is close to the diffraction limit in the Y-direction. Restore your checkpoint so you can evaluate the final image.

This lens seems to meet every one of our goals. To verify, run the **Spectrum Wizard (MSW)** to define 10 wavelengths spaced across the visible spectrum, and then run the **OPSPRD** feature to show the diffraction pattern over the field. (This is best done with the **MFB** dialog; select Show visual appearance, Magnify 4.) One could not ask for a better eyepiece than this. The result is shown below.

To the eye, this eyepiece will produce an image that is essentially perfect and undistorted. A check of the pupil aberrations shows that pupil wander is less than the allowed 1/2 mm over the field.

Since this is a paper exercise, I will stop here. A design for a real market would need more attention, perhaps reducing the thickness of some of the elements. But the point has been made.

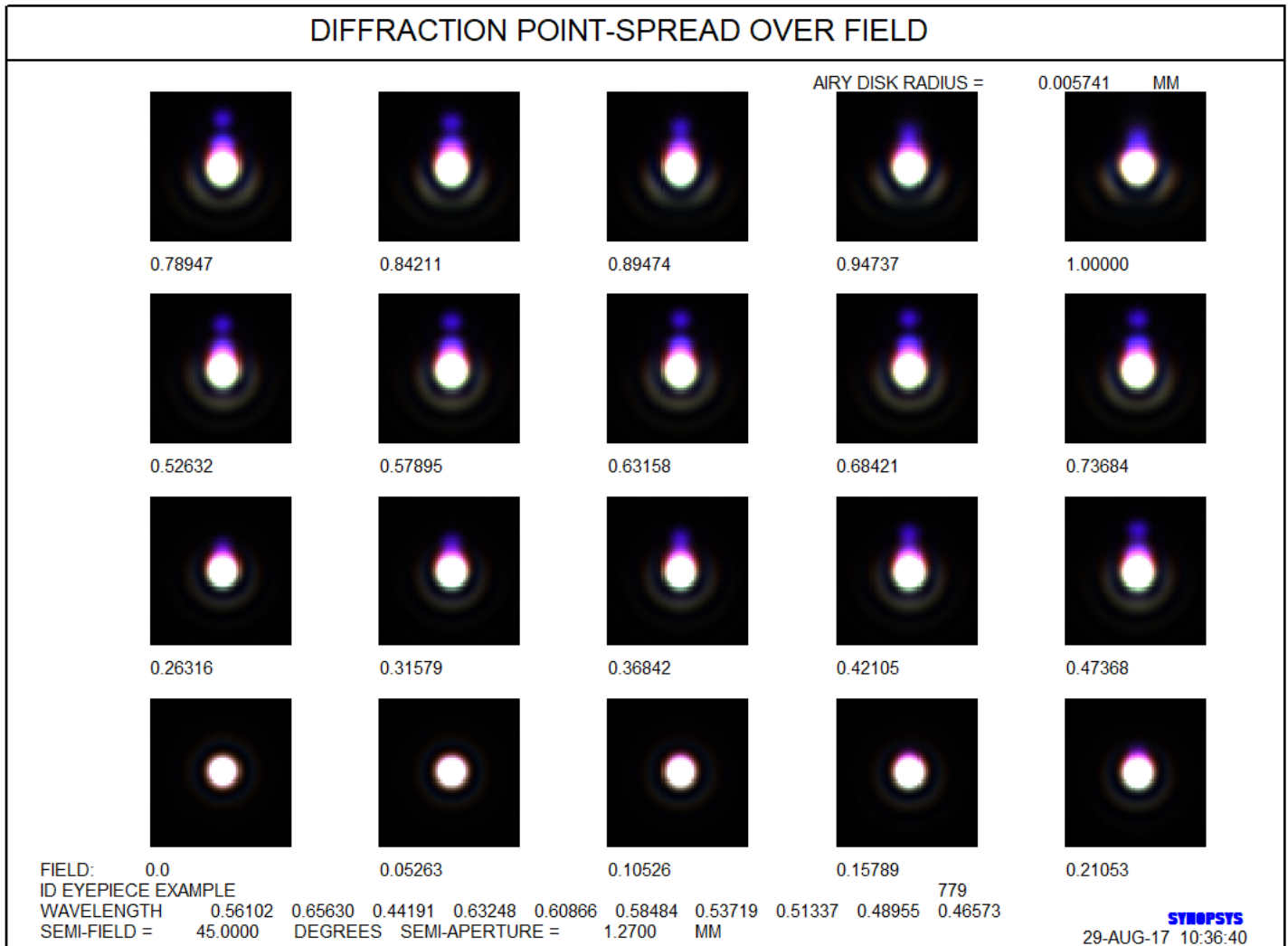


Fig. 41.8. Diffraction pattern across the field of the eyepiece

We ran this lesson several times; sometimes the results were not quite as good as this, and in one case we got a lens of only *nine* elements that was very nearly as good as this 10-element lens. DSEARCH can explore hundreds of the branches of the design tree in a matter of seconds, and with slightly different input will explore yet others. For investigating the design space, this is the tool to use.

New users may wonder why this lesson called for object type OBD and activated the WAP 1 option. There is some optics here, and it's a good idea to understand it. When designing an eyepiece like this, you are after what's called an "F-theta" lens. In a normal camera lens, one wants the image height to be proportional to the object height; then there is no distortion. But that would not work in an eyepiece, for which one wants the *angles* of the object and image to be proportional, not the heights. Object OBD specifies an object angle (here 45 degrees, tracing from the eye point) and then the field parameter HBAR refers to a fractional angle, instead of height, as well. When distortion is corrected, the angles are proportional, and the apparent angular separation between a pair of a double stars is constant, no matter where they appear in the field of view, as one would expect. Since the angular magnification is constant over the field, by Lagrange's law the diameter of the entering beam (at the eye) is constant as well. The WAP 1 option takes care of that.

What did we learn from this lesson? It is clear that the numerical approach works. Designers of the classic school will work for many days on a design like this and will rightly be proud of the result if they succeed. They will have developed some insight into which elements are correcting which aberrations and the like. The numerical tools used in this lesson,

on the other hand, will produce an excellent design in a fraction of the time. If your goal is to get a product out the door at minimal cost, never mind how it works, then the numerical approach is clearly superior. And if you do want to know how it works, check out the **THIRD CPLOT** feature. It's all there, in living color.