

Lesson 19: Using DOEs in modern Lens Design

In this lesson we will start from scratch, design a 5-element lens, and then see if adding a diffractive optical element (DOE) somewhere can improve its performance.

Here is the problem, as defined by our entries in the MDS dialog. This will create a MACro that will run the DSEARCH command, with all of the data filled in.

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: [] The library location must be from 1 to 10; the best result will be stored there. Design Search Saddle-point build Use current [] []

SPBUILD QUIET mode

SYSTEM

ID: 5-ELEMENT LENS FOR DOE STUDY 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: --> [] (TH0)

Object angle (or height if finite) (UPPO or YPP0)

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 requests, in PANT format.

[]

SPECIAL AANT

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

ACA 60.1 1
 ADT 6.1 1
 M 0.01 A P HH 1
 LLL 22 1 1 A BACK
 LUL 250 1 1 A TOTL

GOALS

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

ELEMENTS: 5 Desired number of elements

FNUM: 3.5 Target value, weight

BACK: 0 0 Target value, weight

TOTL: 0 0 Target value, weight
 (Enter target of zero to bypass BACK or TOTL)

FOV: 0.0 .4 .6 .85 1

FWT: 5.0 3.0 3 3 3

RSTART: 50 100 200 400

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

Passes: quick, real Quick Mode

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: 100 Number of optimization passes

ANNEAL: 200 20 Q Temperature, cooling

Passes: SNAPSHOT

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.

This input will design a lens at F/3.5 with a semi-field angle of 25 degrees and an aperture radius of 12 mm. We elect to control the back focus with the SPECIAL AANT entry, which lets the distance grow but will not let it become less than about 22 mm. We also ask for the chief-ray angle tangent to be small, with a low weight, with the ACA request, so we don't get solutions with wild angles at the image, and avoid steep ray refraction.

When we click the OK button, the program loads our MACRO. We add the **CORE 16** directive at the top, to speed things up on our 8-core hyper-threaded PC, and specify a long delay (so it won't ask to abort the other cores, which may take longer) and a grid number of 6 (because aspherics and DOEs can cause high-order aperture aberrations).

```
CORE 16
DSEARCH 1 QUIET
SYSTEM
ID 5-ELEMENT LENS FOR DOE STUDY
OBB 0 25 12
WAVL 0.6563 0.5876 0.4861

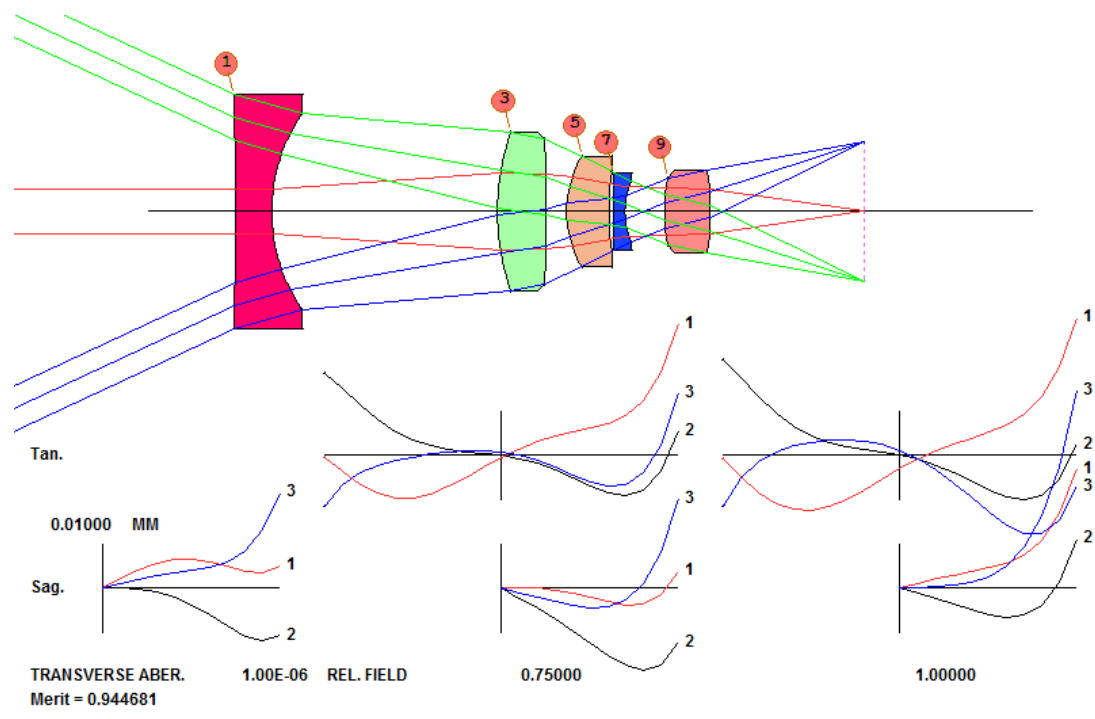
UNITS MM
END
GOALS
ELEMENTS 5
FNUM 3.5
BACK 0 0
TOTL 0 0
STOP MIDDLE
STOP FREE
RSTART 50 100 200 400
RT 0.5
FOV 0.0 .4 .6 .85 1
FWT 5.0 3.0 3 3 3
NPASS 100
DELAY 9999
NGRID 6
ANNEAL 200 20 Q
COLORS 3
SNAPSHOT 10
QUICK 40 100
END
SPECIAL PANT

END
SPECIAL AANT
ACA 60 .1 1
ADT 6 .1 1
M 0 .01 A P HH 1
LLL 22 1 1 A BACK
LUL 250 1 1 A TOTL
END
GO
```

Since we are going to implement DOE surfaces, we elect to specify five field points for correction. This is a good idea when using any kind of aspheric surfaces, since otherwise one might get great correction where specified and poor correction at intermediate fields.

We also specify four different starting values for the radius of curvature of each case, to be investigated in turn. Remember, even a small change to the initial conditions can send DSEARCH to a different branch of the lens design tree, and this will increase the number of cases searched by a factor of four.

We run this MACro and see that the best lens that comes back from DSEARCH is not too good – but what can you expect with only five elements at this field and speed?



We can probably get better results by requesting a greater number of elements – but here we want instead to see how much improvement we can get by changing one of the lenses to a DOE. The program has created an optimization MACro for us, making it very easy to continue optimizing and annealing. Let’s try a DOE. We add to the MACro another line at the top. (“ADA” means Automatic DOE Assignment.)

ADA 5 QUIET

```

PANT
VY 0 YP1
VLIST RD ALL
VLIST TH ALL
VY 1 GLM
VY 3 GLM
VY 5 GLM
VY 7 GLM
VY 9 GLM
END
AANT P
AEC
ACC
GSR 0.700000 5.000000 4 2 0.000000
GSR 0.700000 5.000000 4 1 0.000000
GSR 0.700000 5.000000 4 3 0.000000
GNR 0.700000 3.000000 4 2 0.400000
GNR 0.700000 3.000000 4 1 0.400000
GNR 0.700000 3.000000 4 3 0.400000
GNR 0.700000 3.000000 4 2 0.600000
GNR 0.700000 3.000000 4 1 0.600000
GNR 0.700000 3.000000 4 3 0.600000
GNR 0.700000 3.000000 4 2 0.850000
GNR 0.700000 3.000000 4 1 0.850000

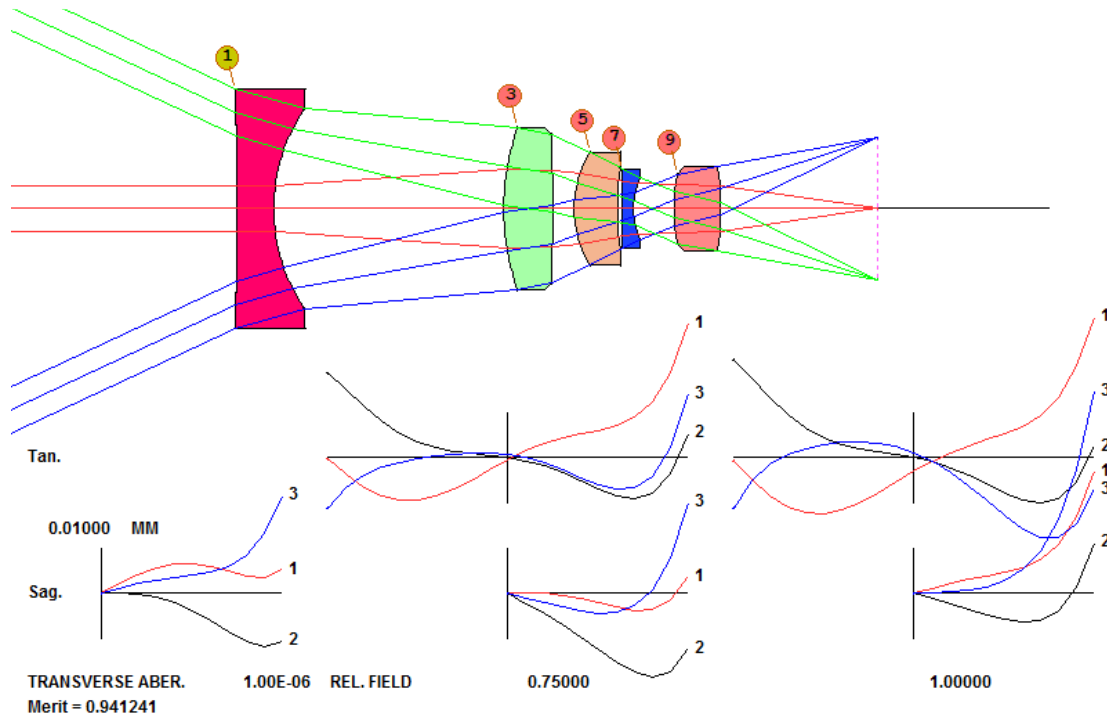
```

```

GNR      0.700000      3.000000      4 3      0.850000
GNR      0.700000      3.000000      4 2      1.000000
GNR      0.700000      3.000000      4 1      1.000000
GNR      0.700000      3.000000      4 3      1.000000
  ACA 60 .1 1
  M 0 .01 A P HH 1
  LLL 22 1 1 A BACK
  LUL 250 1 1 A TOTL
END
SNAP/DAMP 1
SYNOPSIS 40

```

The program finds that a DOE at surface 1 works best.



The command **ASY** shows the data of this DOE.

SPECIAL SURFACE DATA

```

SURFACE NO. 1 -- UNUSUAL SURF TYPE 16 (SIMPLE DOE)
WAVELENGTH OF OPD DEFINITION: 0.587600
Nd, Vd OF DOE MATERIAL: 1.517000 55.000000
NORMALIZING RADIUS: 61.613800
DIFFRACTION ORDER: -1
XD 1 -0.000671 (CV) XD 11 1.852479E-06 (R**2) XD 12 2.816262E-06 (R**4)
XD 13 5.395981E-06 (R**6) XD 14 6.889557E-06 (R**8)

```

This is only a very small improvement. We are curious what would happen if we added a *second* DOE. That's simple to test. Add variables to the PANT file for the DOE terms we just added,

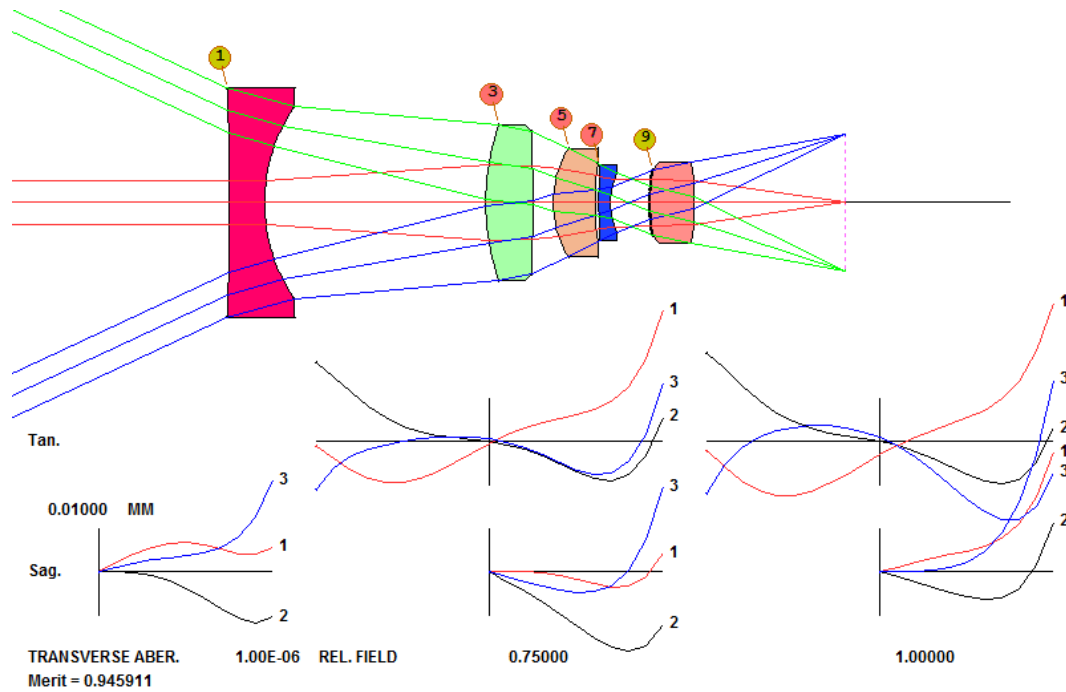
```

VY 1 G 16
VY 1 G 26
VY 1 G 27

```

VY 1 G 28
 VY 1 G 29

then run the MACro again. This time it wants a DOE at surface 9.



There is a big improvement in the merit function. We modify our PANT file so it will vary the coefficients on both DOEs, and include some higher-order terms as well. Term G 32 is the 12th-power coefficient, while the default from ADA only goes to the 8th power. (And we are careful to comment out the ADA command, so we don't get a third DOE!)

!ADA 5 QUIET

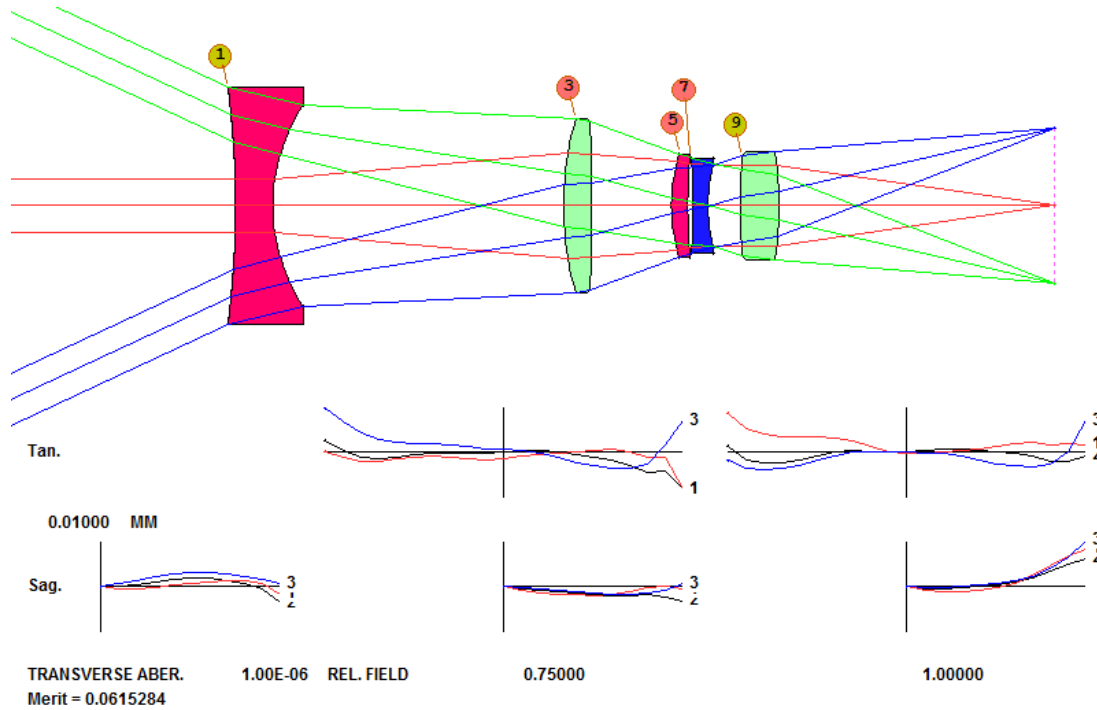
```
PANT
VY 0 YP1
VLIST RD ALL
VLIST TH ALL
VY 1 GLM
VY 3 GLM
VY 5 GLM
VY 7 GLM
VY 9 GLM
```

```
VY 1 G 16
VY 1 G 26
VY 1 G 27
VY 1 G 28
VY 1 G 29
VY 1 G 30
VY 1 G 31
VY 1 G 32
```

```
VY 9 G 16
VY 9 G 26
VY 9 G 27
VY 9 G 28
VY 9 G 29
```

VY 9 G 30
 VY 9 G 31
 VY 9 G 32
 END
 ...

Now we run this again, and then anneal.



Wow! The merit function came down from 0.944 for the lens returned by DSEARCH to a value of 0.061 when optimized with two DOEs. (L19L1) It would be interesting to see how many spherical elements we would need to get this kind of quality, but we'll leave that exercise for the student. For sure it will be more than five.

```

RLE
ID 5-ELEMENT LENS FOR DOE STUDY 189
ID1 DSEARCH CASE WAS 000000000000000000001100 12
WAVL .6563000 .5876000 .4861000
APS 1
UNITS MM
OBB 0.000000 25.00000 12.00000 -40.75533 0.00000 0.00000 12.00000
0 AIR
1 CV 0.000000000000000 TH 17.18886085
1 GLM 1.50000000 73.64948718
1 USS 16
CWAV 0.587600
HIN 1.517000 55.000000
RNORM 61.6138
1 XDD 1 -2.3573567E-03 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
1 XDD 2 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
1 XDD 3 1.6576954E+01 -1.5772577E+02 5.5355850E+02 -1.2824350E+03 2.0288263E+03
1 XDD 4 -1.6583719E+03 5.4539892E+02 0.0000000E+00 0.0000000E+00
2 RAD 83.7333797612760 TH 133.80801226 AIR
3 RAD 145.6651342237978 TH 12.84766300
3 GLM 1.90000000 37.62897436
4 RAD -936.8282816530643 TH 36.68042679 AIR
5 RAD 77.0117799868350 TH 7.56136252
5 GLM 1.60190936 64.47241855
6 RAD 300.9357930535547 TH 2.49443964 AIR
  
```

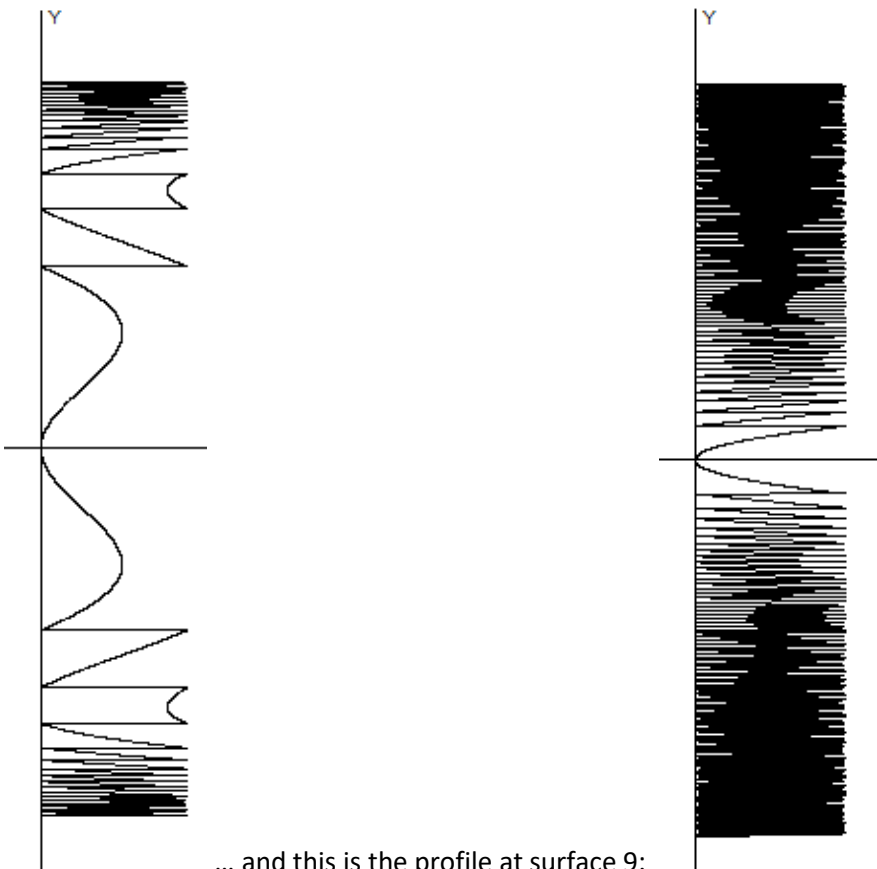
```

7 RAD -321.5452747117334 TH 6.92345376
7 GLM 1.81849484 24.49789036
8 RAD 80.4305830784560 TH 14.77333385 AIR
9 CV 0.000000000000 TH 17.77216658
9 GLM 1.89731741 37.87054525
9 USS 16
CWA 0.587600
HIN 1.517000 55.000000
RNORM 17.8887
9 XDD 1 3.7006321E-03 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
9 XDD 2 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
9 XDD 3 7.5557923E+01 -1.1770634E+01 1.0593009E+01 -1.4354614E+01 1.1908357E+01
9 XDD 4 -4.9678199E+00 8.1921021E-01 0.0000000E+00 0.0000000E+00
10 RAD -155.4022209171318 TH 127.09309610 AIR
10 CV -0.00643491
10 UMC -0.14285714
10 TH 127.09309610
10 YMT 0.00000000
11 CV 0.000000000000 TH 0.00000000 AIR
END

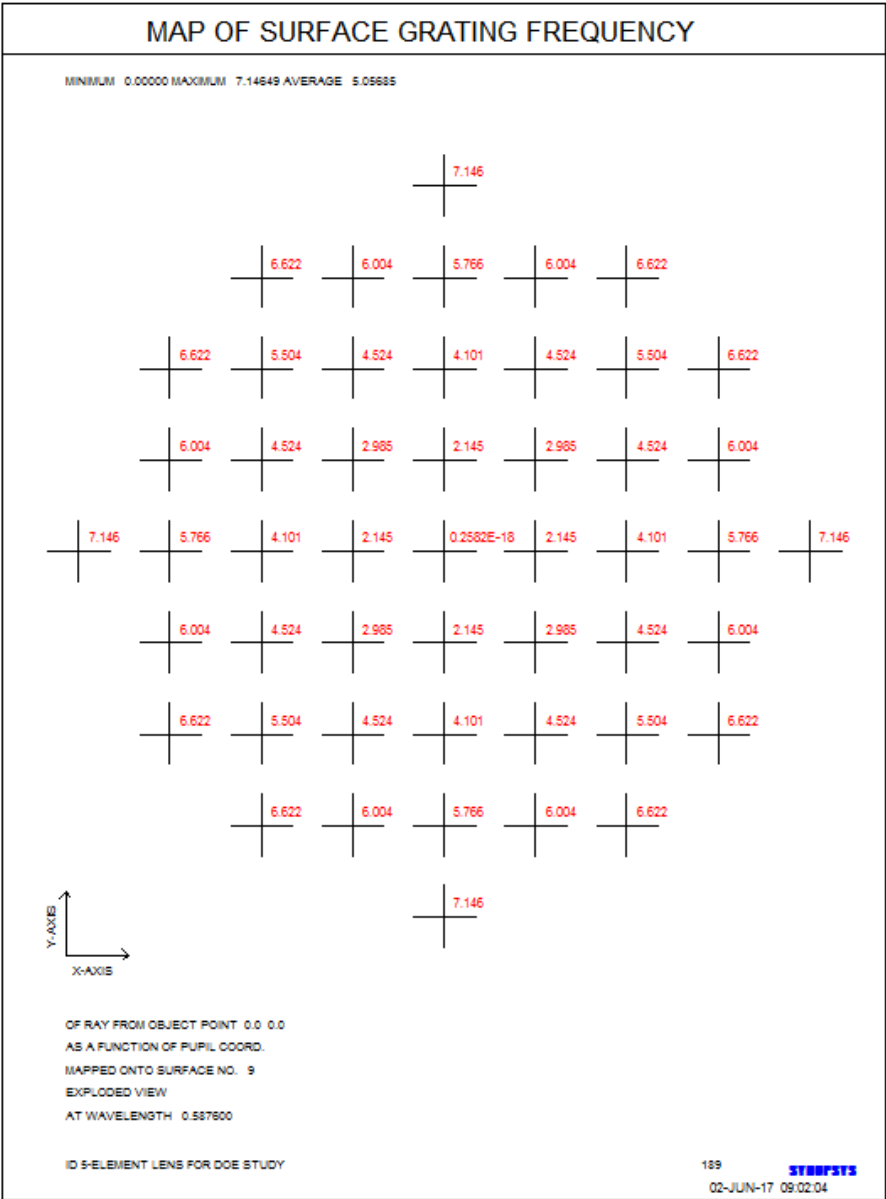
```

This lesson has shown how converting a lens surface to a DOE can significantly improve image quality – or let you get the quality you need with fewer elements. Of course it all depends now on whether the lens vendor can *make* the DOEs. These may not be too easy. Here is the DMASK profile at surface 2:

DMASK 1 PROFILE



The second might be a challenge for the shop. Let's examine the spatial frequency. Open the MAP dialog with MMA, select a map of HSFREQ over PUPIL, object point 0, Ray Pattern CREC 9, DIGITAL, and Execute. The highest frequency is just over 7 c/mm at the edge. This is looking pretty good, but that of course depends on the capability and technology of the shop that will make them.



We expect that, as this technology improves, the designs presented here will become more and more practical. In any event, it is better to be ahead of the technology rocket than running behind, trying to keep up. The ADA feature of SYNOPSIS™ is in the lead, as you can see, and well ahead. We invite lens vendors with DOE capability to comment on this lesson and perhaps offer insights and design tradeoffs as they understand them today.