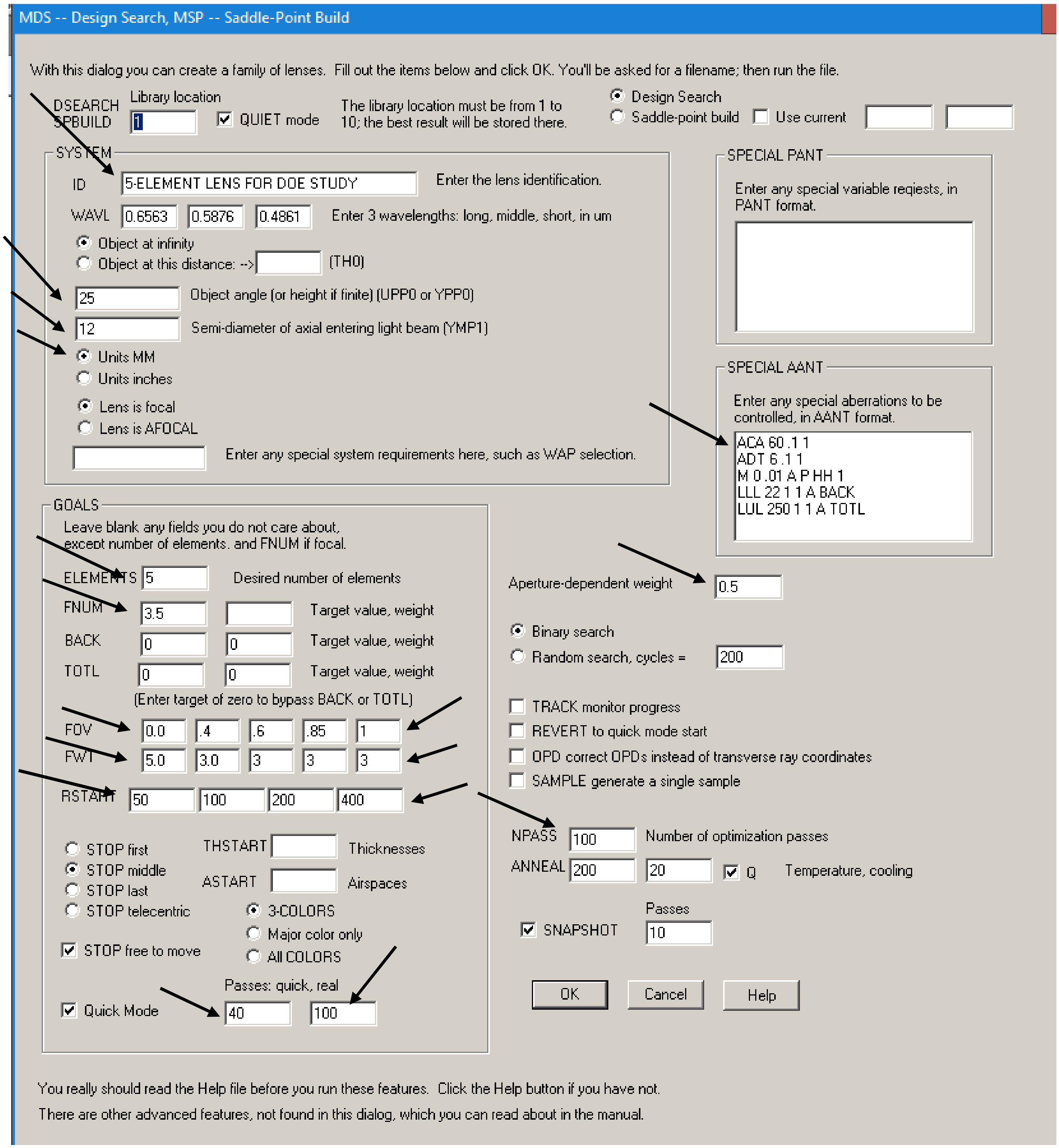
Lesson 19: Using DOEs in modern Lens Design

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.



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.

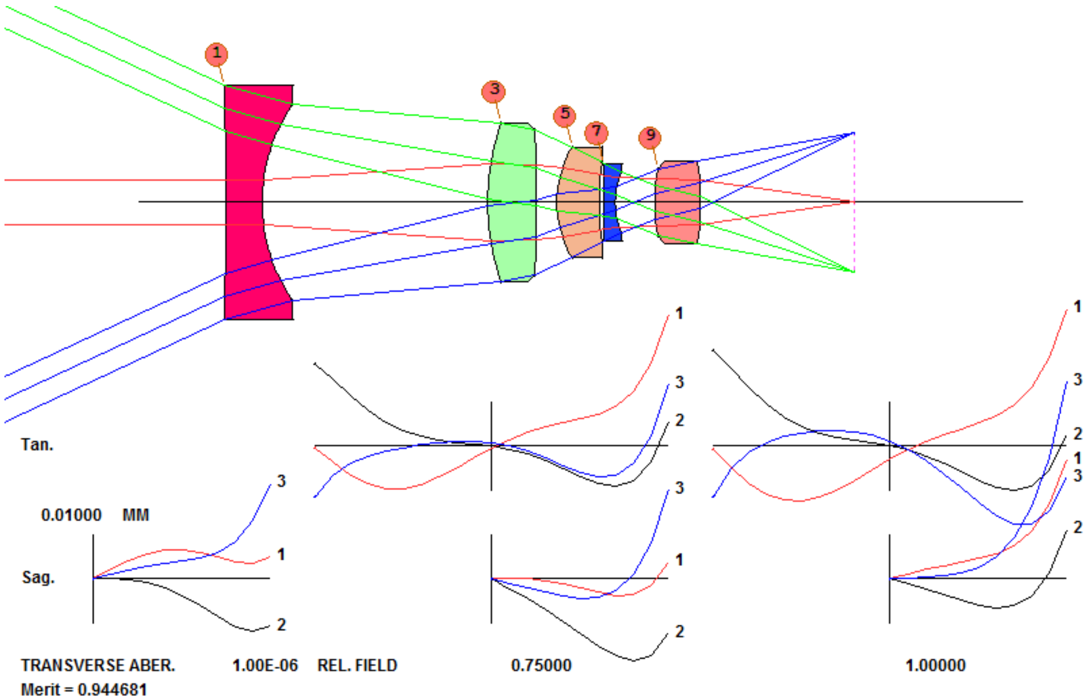
When we click the OK button, the program loads our MACRO. We add the **CORE 16** directive at the top, to speed things up on our 8-core hyper-threaded PC, and specify a long delay (so it won't ask to abort the other cores, which may take longer) and a grid number of 6 (because aspherics and DOEs can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

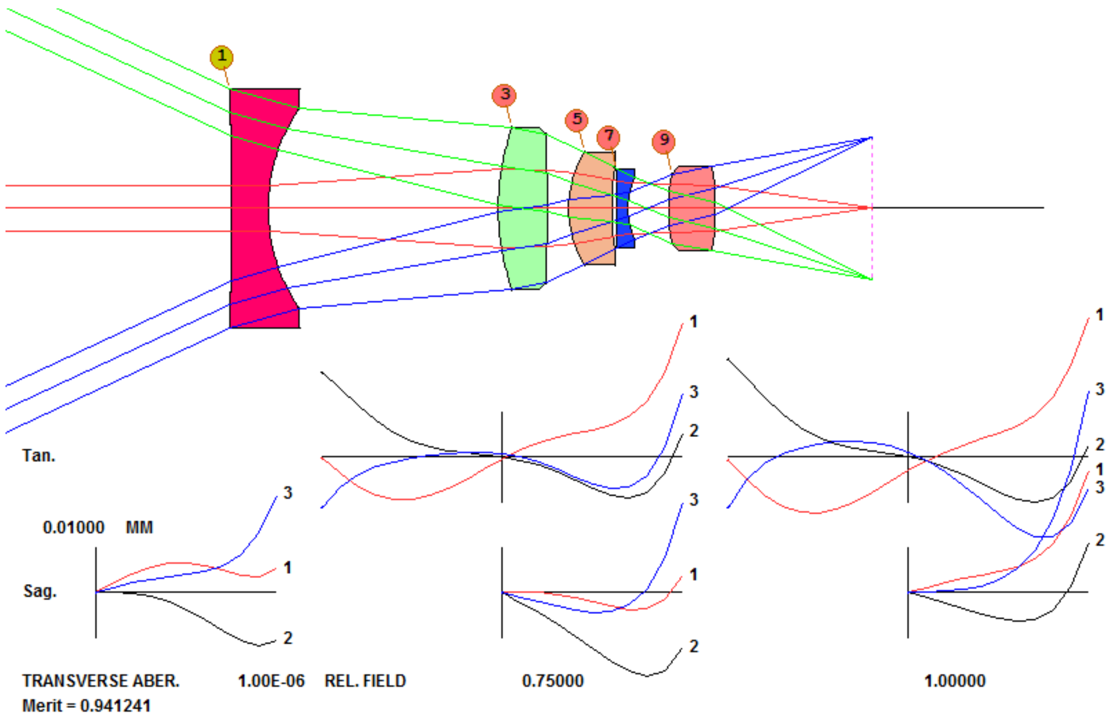


We can probably get better results by requesting a greater number of elements – but here we want instead to see how much improvement we can get by changing one of the lenses to a DOE. The program has created an optimization MACro for us, making it very easy to continue optimizing and annealing. Let's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

```
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
SYNOPSYS   40
```

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



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

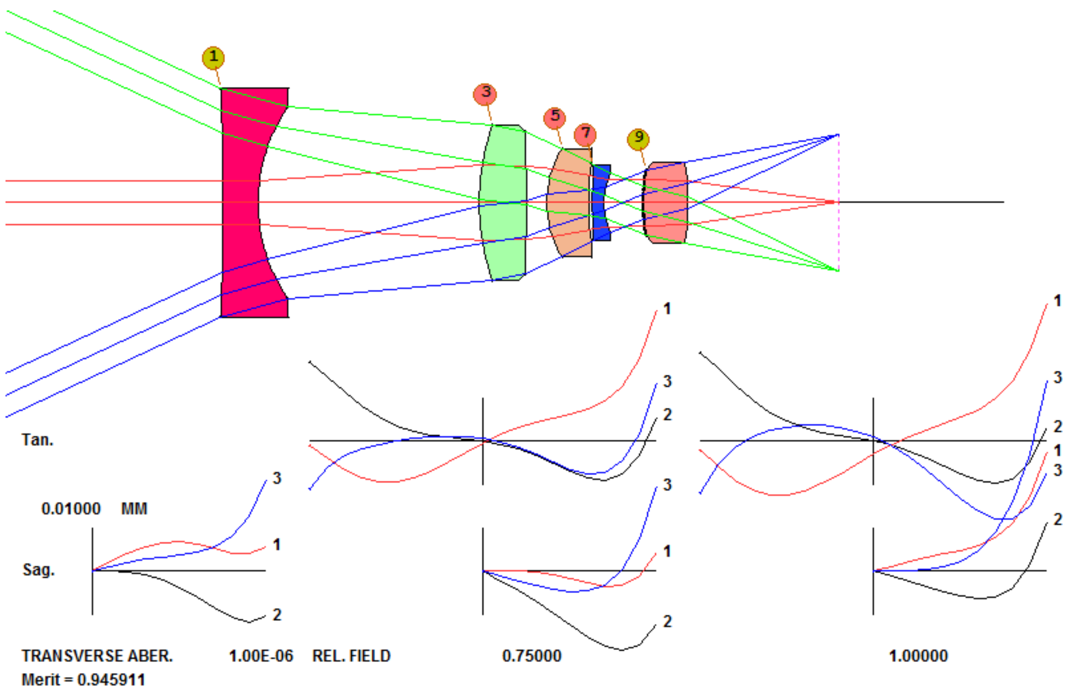
```
SPECIAL SURFACE DATA
_____________________________________________________________________________

 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.

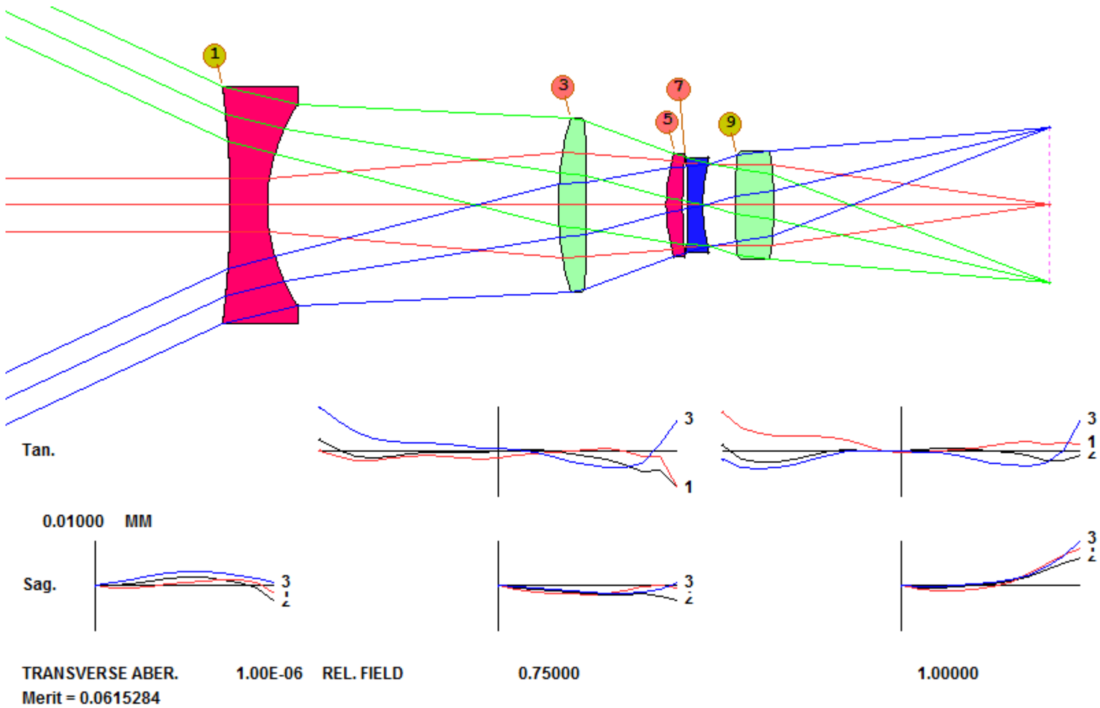


There is a big improvement in the merit function. We modify our PANT file so it will vary the coefficients on both DOEs, and include some higher-order terms as well. Term G 32 is the 12th-power coefficient, while the default from ADA only goes to the 8th power. (And we are careful to comment out the 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.



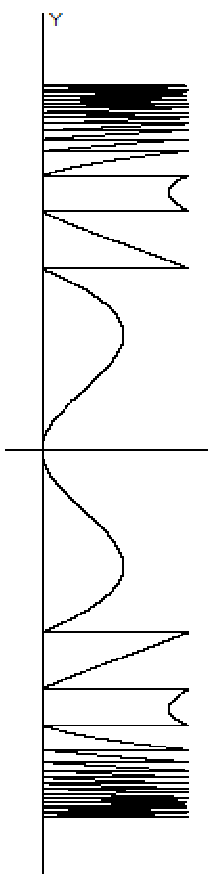
Wow! The merit function came down from 0.944 for the lens returned by DSEARCH to a value of 0.061 when optimized with two DOEs. (**L19L1**) It would be interesting to see how many spherical elements we would need to get this kind of quality, but we'll leave that exercise for the student. For sure it 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      0.0000000000000   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
```

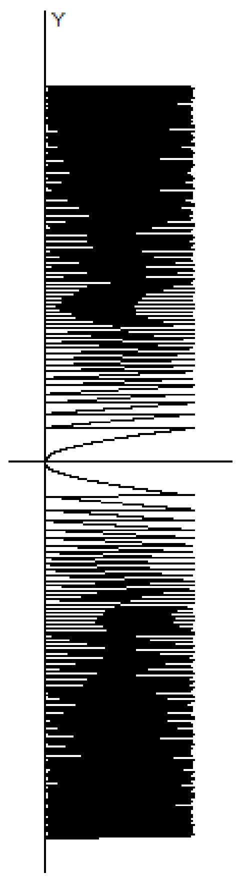
```
   7 RAD   -321.5452747117334   TH      6.92345376
   7 GLM      1.81849484              24.49789036
   8 RAD     80.4305830784560   TH     14.77333385 AIR
   9 CV      0.0000000000000   TH     17.77216658
   9 GLM      1.89731741              37.87054525
   9 USS  16
 CWAV        0.587600
 HIN        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      0.0000000000000   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:

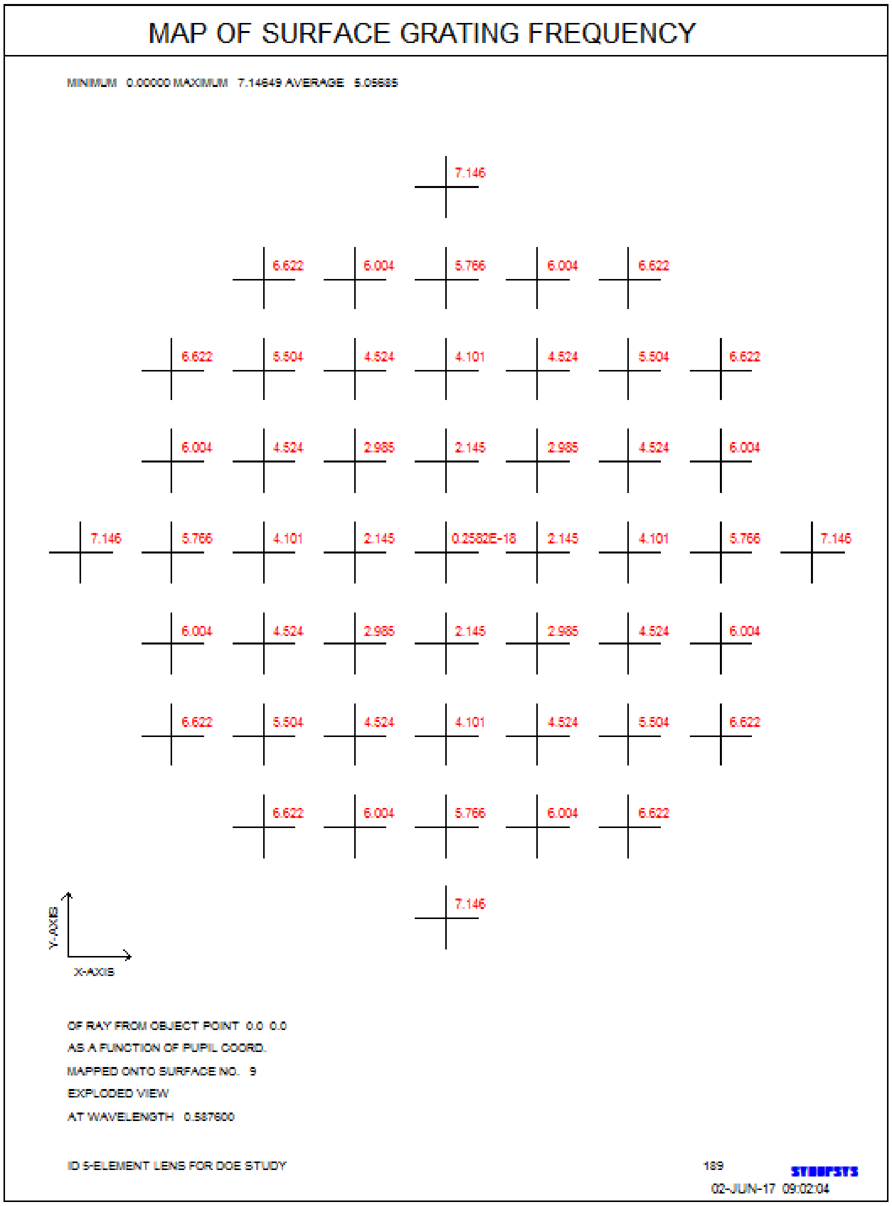
DMASK 1 PROFILE



… and this is the profile at surface 9:



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 SYNOPSYS™ 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.