Lesson 6. The importance of Third-order Aberrations

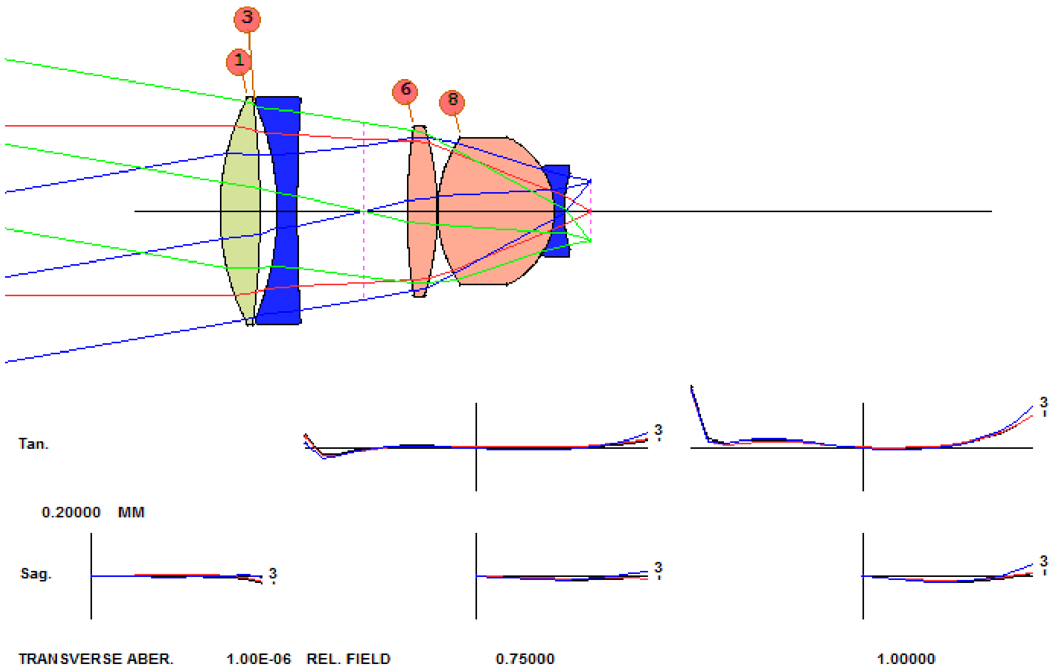
Many students of lens design, and many managers who hire lens designers, are adamant that aberrations have to be very well controlled. They are partly right -- but those requests invariably refer to 3rd-order aberrations, which should all be zero in the opinion of the manager. This is unwise. The point of this lesson is that third-order aberrations are in fact *not* very important – although they do still have some uses.

The reason they are not important is because most lenses also have higher-order aberrations, and all orders must be properly balanced. I sometimes get the feeling that the reason some folks put very tight limits on "spherical aberration" and the others is because they learned those words in a textbook years ago and want to demonstrate their knowledge. Perhaps saying this is unkind – but you have not seen the requests that I have.

Let me illustrate. Copy the following lens file and paste it into the EE editor and run it. This is a five-element lens with rather good correction.

```
RLE
ID FIVE-ELEMENT LENS                            124
 WAVL .6562700 .5875600 .4861300
 APS                5
 UNITS MM
 OBB  0.000000     10.00000     25.40000     -8.63996      0.00000      0.00000
25.40000
 MARGIN       1.270000
 BEVEL       0.254001
   0 AIR
   1 RAD     73.9295960000000   TH     12.00000000
   1 N1 1.79798347 N2 1.80318130 N3 1.81530119
   1 GTB S    'LASFN30          '
   1 EFILE EX1    34.000000    34.000000    34.000000     0.000000
   1 EFILE EX2    34.000000    34.000000     0.000000
   2 RAD   -263.9335099999995   TH      5.22356650 AIR
   2 EFILE EX1    34.000000    34.000000    34.000000
   3 RAD    -81.3505230000000   TH      6.00000000
   3 N1 1.83648474 N2 1.84664080 N3 1.87201161
   3 CTE   0.830000E-05
   3 GTB S    'SF57             '
   3 EFILE EX1    31.841015    33.619003    34.000000     0.000000
   3 EFILE EX2    33.365005    33.365005     0.000000
   4 RAD    553.8617899999995   TH     19.92504900 AIR
   4 EFILE EX1    33.365005    33.365005    34.000000
   5 CV      0.0000000000000   TH     13.18557900 AIR
   6 RAD    169.2089400000000   TH      9.00000000
   6 N1 1.67418625 N2 1.67790015 N3 1.68646733
   6 GTB S    'LAKN12           '
   6 EFILE EX1    25.241916    25.241916    25.495917     0.000000
   6 EFILE EX2    25.241916    25.241916     0.000000
   7 RAD    -83.9867310000000   TH      0.10051658 AIR
   7 EFILE EX1    25.241916    25.241916    25.495917
   8 RAD     39.2493850000000   TH     34.99484900
   8 N1 1.67418625 N2 1.67790015 N3 1.68646733
   8 GTB S    'LAKN12           '
   8 EFILE EX1    22.063038    22.063038    22.063038     0.000000
   8 EFILE EX2    22.063038    22.063038     0.000000
   9 RAD    -24.3037950000000   TH      3.00000000
   9 N1 1.79607463 N2 1.80516268 N3 1.82772732
   9 CTE   0.810000E-05
   9 GTB S    'SF6              '
   9 EFILE EX1    12.935701    12.935701    13.697701     0.000000
   9 EFILE EX2    11.336482    13.443700     0.000000
```

```
 10 RAD     38.6888290000000   TH      7.79631890 AIR
 10 EFILE EX1     11.336482    13.443700    13.697701
 11 CV       0.0000000000000   TH       0.00000000 AIR
END
```



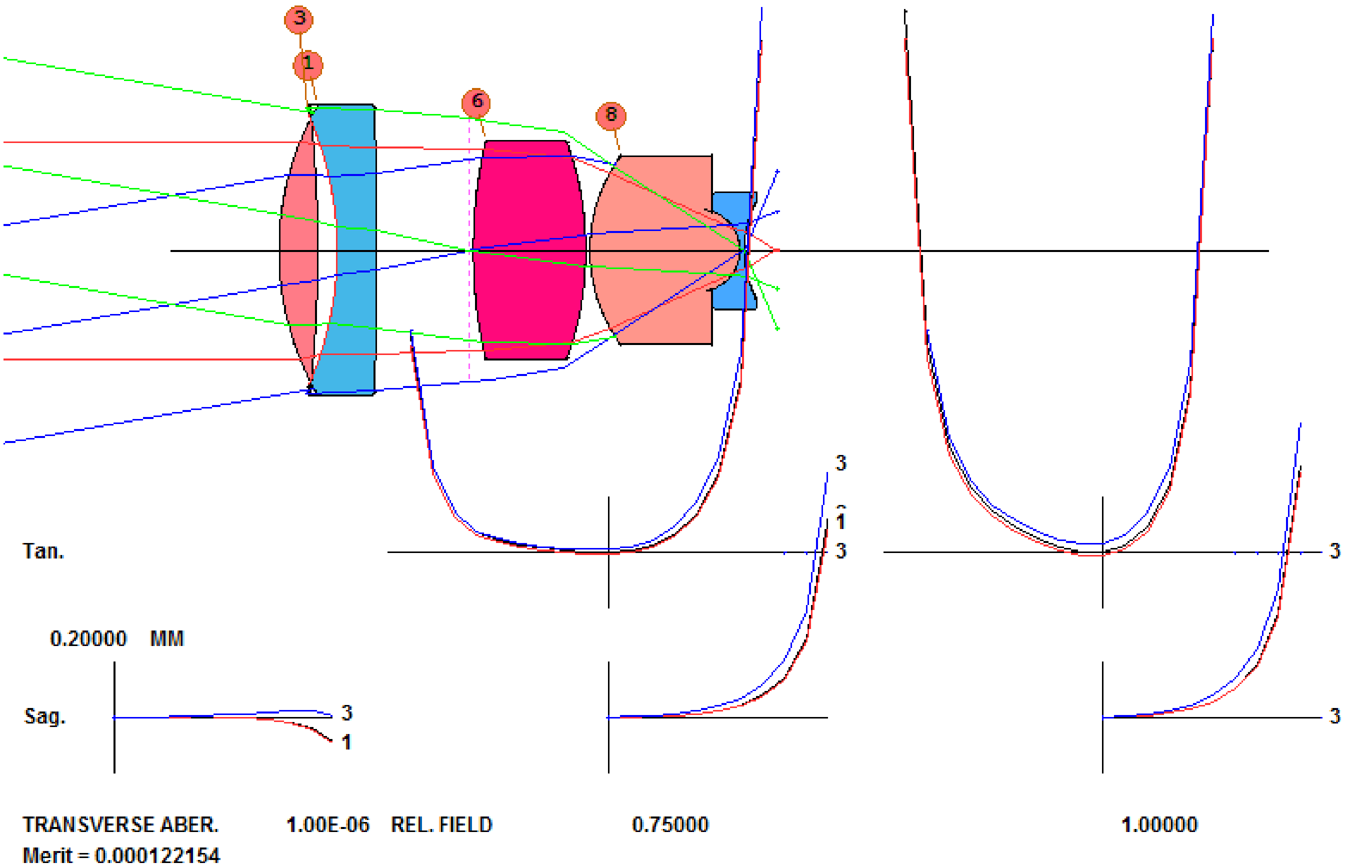
Let us make an optimization MACro that will strongly control the 3rd-order aberrations.

In the EE editor, type (L6M1.MAC)

```
PANT
VLIST RAD ALL
VLIST TH ALL
VLIST GLM 1 3 6 8 9
END

AANT
M 1 1 A FNUM
M 7.8 1 A BACK
M 0 1 A DELF
M 0 1 A SA3
M 0 1 A CO3
M 0 1 A TI3
M 0 1 A SI3
M 0 1 A PETZ
M 0 1 A DI3
M 0 1 A PAC
M 0 1 A SAC
M 0 1 A PLC
M 0 1 A SLC
END

SNAP
SYNO 30
```

This MACro will vary all the design variables and control the F/number, defocus, and back focus distance, all the while correcting the 3rd-order aberrations to a target of zero. The input VLIST RAD ALL will vary all radii, and VLIST TH ALL will vary all thicknesses and airspaces, but we could not use the form VLIST GLM ALL in this case since that form will only vary those materials that *already* have a glass model, and in this example lens none of them have. So we have to declare the surfaces individually in this case.

We run this MACro and … the lens is horrible!



What happened? Did the optimization fail? We ask for the third-order aberrations with the command

```
       THIRD

 SYNOPSYS AI>THIRD

 ID FIVE-ELEMENT LENS                        179            01-JUN-17   13:49:05

 THIRD-ORDER ABERRATION ANALYSIS

 FOCAL LENGTH  ENT PUP SEMI-APER  GAUSS IMAGE HT
       50.804              25.400           8.958

 THIRD-ORDER ABERRATION SUMS
                SPH ABERR        COMA  TAN ASTIG  SAG ASTIG    PETZVAL DISTORTION
                    (SA3)       (CO3)      (TI3)      (SI3)     (PETZ)   (DI3(FR))
               -9.657E-06    -0.00027 -3.991E-05 -6.235E-06  1.060E-05    -0.00056

 PARAXIAL CHROMATIC ABERRATION SUMS
                 AX COLOR   LAT COLOR  SECDRY AX SECDRY LAT
                    (PAC)       (PLC)      (SAC)      (SLC)
                 -0.00276    -0.00027    0.01062    0.00112
 SYNOPSYS AI>
```

Indeed. Those aberrations are very small. How about the starting lens?

```
 ID FIVE-ELEMENT LENS
```

```
THIRD-ORDER ABERRATION ANALYSIS

FOCAL LENGTH  ENT PUP SEMI-APER  GAUSS IMAGE HT
      50.800            25.400           8.957

THIRD-ORDER ABERRATION SUMS
             SPH ABERR       COMA  TAN ASTIG  SAG ASTIG    PETZVAL DISTORTION
                 (SA3)      (CO3)      (TI3)      (SI3)     (PETZ)  (DI3(FR))
              -0.01806   -0.03730   -0.04236   -0.08744   -0.10998   -0.01754

PARAXIAL CHROMATIC ABERRATION SUMS
              AX COLOR  LAT COLOR  SECDRY AX SECDRY LAT
                 (PAC)      (PLC)      (SAC)      (SLC)
              -0.01215    0.01518    0.00724    0.00478
```

Wow! Those aberrations are much larger – but the original lens was much better! Lesson learned. Do not try to out-guess the program when it comes to aberration balancing. I don't care what words you learned in college.

Let me repeat: When you design a lens, you are usually only concerned with two things: **Is the image sharp, and is it in the right place**. If people start talking about aberrations, be polite and smile.

We mentioned earlier, however, that those aberrations still have a use. The most important of these deals with *tolerance desensitization*. This is because, when lenses are improperly manufactured, it is the 3rd-order aberrations that change the fastest. So we have defined a set of eight quantities that can be put into the AANT file:

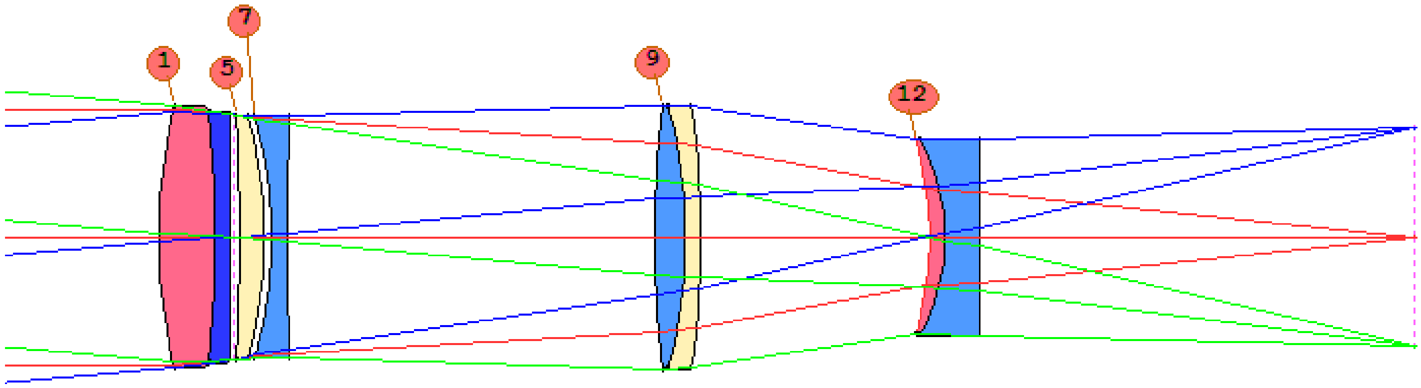
SAT COT ACD ACT ECD ECT ESA ECO

SAT	The sum of the squares of the surface contributions to spherical aberration, SA3.
COT	The sum of the squares of the surface contributions to coma, CO3.
ACD	The sum of the squares of the amount by which CO3 varies as each surface is decentered.
ACT	The sum of the squares of the amount by which CO3 varies as each surface is tilted.
ECD	The sum of the squares of the amount by which CO3 varies as each element is decentered.
ECT	The sum of the squares of the amount by which CO3 varies as each element is tilted.
ESA	The sum of the squares of the element contributions to spherical aberration, SA3.
ECO	The sum of the squares of the element contributions to coma, CO3.

Here is an example of how you might use these aberrations to loosen the lens tolerances. We optimized the lens shown below and ran BTOL with a target wavefront quality of 0.05.

```
RLE
ID 8-ELEMENT TELEPHOTO                          236
 FNAME 'L6L2.RLE                                    '
 MERIT   0.145212E-01
 LOG      236
 WAVL .6562700 .5875600 .4861300
 APS               4
 GLOBAL
```

```
 UNITS MM
 OBB  0.000000      5.00000     25.40000     -0.88448      0.00000      0.00000
25.40000
   0 AIR
   1 RAD    107.5431718565176   TH     11.00000000
   1 N1 1.61726800 N2 1.62040602 N3 1.62755182
   1 CTE   0.630000E-05
   1 GTB S    'SK16            '
   2 RAD   -349.2713337442812   TH      3.00000000
   2 N1 1.69220502 N2 1.69894060 N3 1.71544645
   2 CTE   0.790000E-05
   2 GTB S    'SF15            '
   3 RAD -2.9912862137173E+05   TH      1.00000001 AIR
   4 CV      0.0000000000000   TH      1.00000001 AIR
   5 RAD   -581.7494610200599   TH      5.00000000
   5 N1 1.51981155 N2 1.52248493 N3 1.52859442
   5 CTE   0.820000E-05
   5 GTB S    'K5              '
   6 RAD    -90.4865897926554   TH      1.35282284 AIR
   7 RAD    -87.2286998720792   TH      3.00000000
   7 N1 1.61502503 N2 1.62003267 N3 1.63207204
   7 CTE   0.820000E-05
   7 GTB S    'F2              '
   8 RAD    491.7930148457936   TH     73.15839431 AIR
   9 RAD    218.6390525466715   TH      6.00000000
   9 N1 1.61502503 N2 1.62003267 N3 1.63207204
   9 CTE   0.820000E-05
   9 GTB S    'F2              '
  10 RAD    -99.1627747164714   TH      3.00000000
  10 N1 1.51981155 N2 1.52248493 N3 1.52859442
  10 CTE   0.820000E-05
  10 GTB S    'K5              '
  11 RAD   -182.3746109793576   TH     45.48880137 AIR
  12 RAD    -67.5075897018110   TH      3.00000000
  12 N1 1.61726800 N2 1.62040602 N3 1.62755182
  12 CTE   0.630000E-05
  12 GTB S    'SK16            '
  13 RAD    -40.7083005956173   TH      7.00000000
  13 N1 1.61502503 N2 1.62003267 N3 1.63207204
  13 CTE   0.820000E-05
  13 GTB S    'F2              '
  14 RAD   -832.2479524920537   TH     86.31660394 AIR
  14 CV      -0.00120156
  14 UMC     -0.10260000
  14 TH      86.31660394
  14 YMT      0.00000000
  15 CV      0.0000000000000   TH      0.00000000 AIR
 END
```



Some of the tolerances came back very tight, as shown in the table below, where the nominal data are for this lens.

	3 TH	6 wedge	7 tilt	5 YDC	7 YDC	9 YDC	12 YDC
Nominal	0.034	0.23 min	0.24 min.	0.0042	0.0034	0.0053	0.0086
Case A	0.091	0.67	0.42	0.011	0.009	0.011	0.011
Case B	0.112	0.87	0.89	0.015	0.018	0.025	0.014

It would be expensive indeed to hold lens positions to these tight values. (Look at the centration tolerance on surface 7.) so we proceed as follows:

1. Run the command **THIRD SENS**, to see the current values of these parameters.

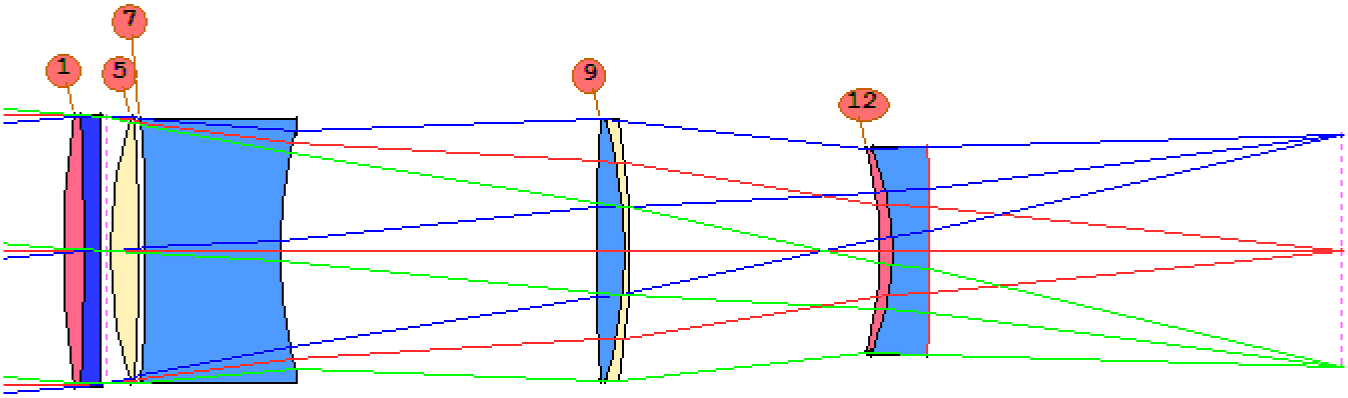
```
THIRD SENS
ID 8-ELEMENT TELEPHOTO

NORMALIZED 3RD-ORDER ANALYSIS OF TOLERANCE SENSITIVITY

SS OF SA3 BY SURFACE (SAT) =           85.107903
SS OF CO3 BY SURFACE (COT) =           21.404938
SS OF CO3/YDC BY SURFACE (ACD) =        0.007657
SS OF CO3/TILT BY SURFACE (ACT) =      73.889722
SS OF CO3/YDC BY ELEMENT (ECD)  =       0.003941
SS OF CO3/TILT BY ELEMENT (ECT) =      31.259708
SS OF SA3 BY ELEMENT (ESA) =            1.944190
SS OF CO3 BY ELEMENT (ECO) =            0.492351
```

2. Since we are mainly concerned about centration errors, we might try to reduce the value of ECD, the change in CO3 when an element is decentered. Let us add to the AANT file (in L6M2.MAC) the line

```
M .001 100 A ECD
```

Since ECD is already a small number (compared to the others in the list) we give it a high weight so it makes a difference to the merit function. Keep in mind that we cannot simply target all of these values to zero, since lens elements in general cannot be designed without any aberrations and still have any optical power. Also, these quantities are coupled in obscure ways. If, for example, you reduce the value of SAT, you will probably find that COT also got much smaller.

You could not give an independent value to both of them and expect that the program could find such a combination. So it is wise to proceed with one at a time, until you find the parameter that works best with your lens. In this example, controlling the value of ECD, the lens came back like this.

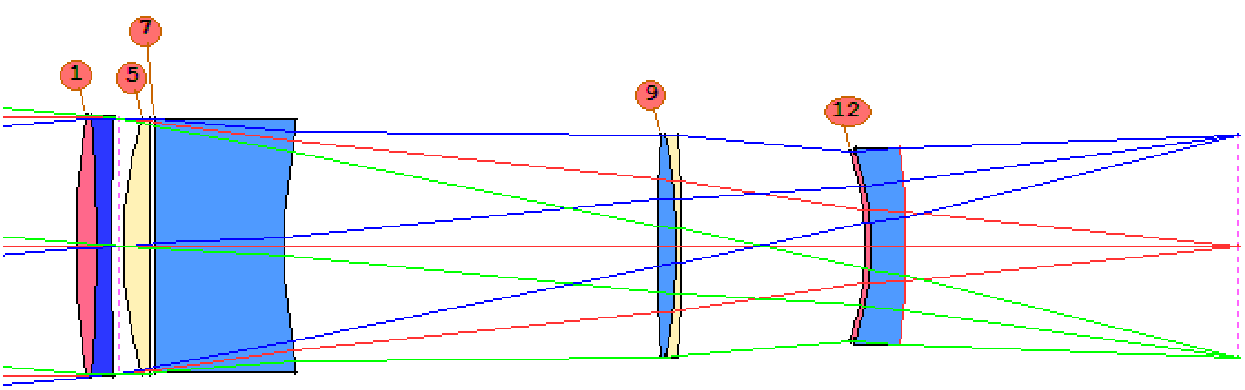



```
THIRD SENS
 ID 8-ELEMENT TELEPHOTO

 NORMALIZED 3RD-ORDER ANALYSIS OF TOLERANCE SENSITIVITY

 SS OF SA3 BY SURFACE (SAT) =             7.027782
 SS OF CO3 BY SURFACE (COT) =             4.876613
 SS OF CO3/YDC BY SURFACE (ACD) =         0.001649
 SS OF CO3/TILT BY SURFACE (ACT) =       19.621736
 SS OF CO3/YDC BY ELEMENT (ECD)  =        0.001064
 SS OF CO3/TILT BY ELEMENT (ECT) =        8.602740
 SS OF SA3 BY ELEMENT (ESA) =             0.185606
 SS OF CO3 BY ELEMENT (ECO) =             0.127624
```

Notice how all of the values have changed, even though we only targeted one of them (ECD). Tolerances of this lens are listed as Case A in the above table. Clearly, the tolerances are much looser now, although still a challenge for the shop. Let us experiment some more. This time we will target the value of ACT to the value 7.0, which is 1/10 of the nominal value.

M 7 1 A ACT

The lens now looks like this:



The tolerances are listed as Case B, above. For some shops this may be the better budget. (We ignore for this lesson the issue of manufacturability: some elements are much too thin and should be controlled with the ACM monitor.)

The quantity that you elect to control depends on which tolerances you want to affect. Airspace tolerances, for example, may respond to control over the quantity ESA. Lens thickness tolerances, on the other hand, may respond better to SAT. You will have to understand your lens, and experiment with these tools, to find the best targets and the best BTOL budget.

Sometimes the effect of these quantities is to *increase* the merit function. Normally this would not be a good idea, since if the image gets worse, tolerances generally get tighter. But the relaxing effect of the tools in this lesson can sometimes outweigh that effect, giving tolerances that are looser anyway. This only works up to a point, of course, and if the merit function gets too large, you should require a less-demanding value in your merit function.

We cannot guarantee that any of these aberration targets will work in any given case, but experience has shown that they are certainly worth a try. Your tolerances may be relaxed by a factor of from two to 10.

We close by mentioning that another very effective way to control the sensitivity of an individual element is to use the SECTION aberrations. Whereas the quantities discussed in this lesson apply to all surfaces or elements and are therefore very easy to use, the SECTION aberrations apply only to the surface range you specify. If an element still gets assigned a very tight centration tolerance, even after you try the targets given in this section – which can happen if some elements get much looser but the problem element gets tighter – you might control only the coma or spherical aberration of *that* element. This gives you precise control over the aberrations where you need it, and is often worth the extra step. For example, if the element at surfaces 13 and 14 were very sensitive, you might try

```
M 0 .1 A SECTION SA3 13 14
```

and experiment with the target and weights until you get the best results.