NIRSPEC

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NIRSPEC Optics Design Note 23.01

Calibration Unit Tolerances

I.   Introduction

This document gives the mechanical tolerances for the calibration unit. The optical tolerances on the irregularity, radii, index, and such, were determined by Sam Larson and can be found in his notes. We assume that the optics are perfect for the purposes of generating the mechanical tolerances.

II.   Procedure

I used Zemax to generate the tolerances by specifying a merit function and then allowing the prescription to vary until the value of the merit function exceeded some critical number. This method was applied, separately, on the front end (before the integrating sphere), and the back end (after the integrating sphere). The prescriptions, tolerance listings, tolerance output, and the merit functions are given in the appendix.

III.   Front-end

Criteria

For the front end, we care mostly about the angle between rays which travel into the etalon. This cone angle will determine which wavelengths will be passed out of the etalon. Ideally, we want to limit the transmitted wavelengths so that sharp lines are formed on the spectrometer detector. In practice, some bandwidth of wavelengths will be transmitted, thus blurring the emission lines on the detector. This would not reduce our ability to centroid on those lines, but we do have to worry about the lines getting so broad that they start to blend with lines in adjacent orders.

We can estimate the distance between lines in adjacent orders divided by the size of the lines as a function of the cone angle incident on the etalon. When this ratio becomes 1, the emission line spectrum will end up looking like just one big broad band of light. It would then be impossible to extract the centroids of the lines. I have calculated this ratio assuming the following: finesse=29, etalon spacing=1 mm, lambda=1 micron. The results are shown in Figure 1. From the figure, we can see that we reach a constant band of light at about 0.015 radians. Clearly, we need to do much better than this.

The pinhole limits the cone of field angles. The original design had a pinhole with about 350 micron radius. This produced a nominal cone angle of about 0.010 radians. We can do even better by making a smaller pinhole, say one with a radius of 250 microns. This gives a field angle of about 0.060 radians. In the end, we decided to use the smaller pinhole. Technically, this means that the tolerances in

this document will be much looser because we are starting out with a smaller cone angle. Instead of redoing all the tolerances, we simply should note that the tolerances are probably tighter than necessary for the front end.
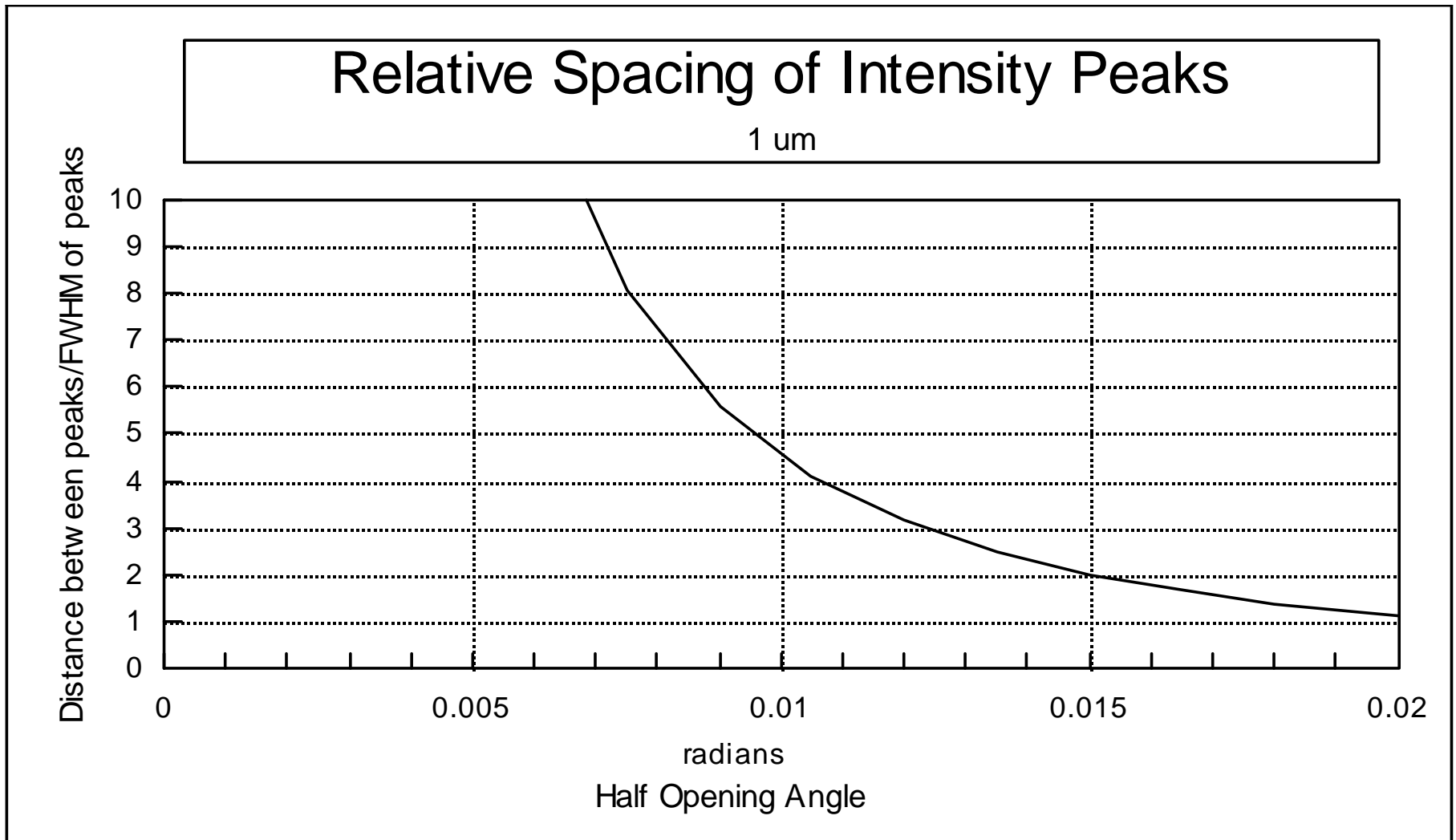
Figure 1. Relative spacing of emission lines at the spectrometer detector as a function of half opening angle at the etalon. A ratio of 1 means that the spectrum will be one continuous band at the detector. The nominal design in Zemax gives a half opening angle of 0.010 radians for a ratio of around 4. We allow the half angle to be as much as 0.015 radians in the tolerance analysis.

3

The Merit Function

The merit function is constructed to calculate the cone angle of rays coming out of the last lens of the front-end. I use RANG operands evaluated for marginal pupil rays at 1 microns; the situation should be better at longer wavelengths. The SUMM/MAXX/DIVI operands serve to select the maximum half angle for the value of the merit function. The fact that we are using maximum values means that the results will be overly pessimistic. Very little light is traveling through the most extreme angles. In any case, it will give us an idea of just how sensitive the system is.

The Tolerance Analysis

I limited the merit function (the half-angle) to less than 0.015 radians in the inverse sensitivity of the tolerance analysis. I allowed the parameters in the tolerance listing to vary within some narrow range. For instance, I generally allow +/- 0.5 degrees for element tilts. The inverse sensitivity adjusts these parameters within the specified boundaries until the merit function equals 0.015. The values at which the tolerance operands satisfy this condition are given in the "Tolerance listing - after running inverse sensitivity."

Because we are not considering a symmetric array of field points, we need to do some interpretation of this tolerance listing. We should regard the true tolerances on tilts and decenters as being symmetric. So, for instance, the true tolerance on decenter for element 8/9 (the final lens) should be +/- 0.000224594 m, or about +/- 225 microns. Notice that I took the minimum of the absolute value of the min/max on TEDX and TEDY. In the end, then, element 8/9 should have a single decenter tolerance, regardless of the axis (X or Y). The same is true for tilts. The distance between the pinhole and the following lens is used as a compensator.

IV.   Back-end

Criteria

For the back-end, we are interested in two things: that a good pupil image is formed at the Lyot stop, and that a good focal plane image is formed at the slit plane. We adopt the performance criteria used to design the NIRSPEC front-end, i.e. the spot size at the Lyot stop be no more than 267 microns, and that the image performance at the slit plane give less than 0.12 HeNe waves (RMS) at 2.2 microns. It is more difficult to construct the merit function in this case, as opposed to the CU front-end, because we are trying to include two totally different kinds of criteria. We handle this by demanding that the merit function blow up if it fails to meet either spec.

The Merit Function

The first 29 operands calculate the "spot size" as a percentage of the pupil image size at the Lyot Stop. Notice that we are considering 1 and 2.2 micron light. We demand a spot size which is less than 1% (267 microns) of the pupil size. You can see that the nominal size is 0.35%. The EQUA does the following: This operand constrains all operands within the specified range of operands to have the same value within the tolerance specified by the target. The value of this operand is computed by finding the average of the range of values, and then summing the absolute value of the errors between each operand and the average

if the error exceeds the target value. So, the nominal average deviation is 92 microns. To get the percentage error, we have to divide by 2 because the REA operands are really calculating radius. Our criterion is 1% of the diameter.

The second part of the merit function examines the image performance at the slit plane. The performance is limited to 0.12 HeNe waves (RMS) for 5 extreme field points at 2.2 microns.

The Tolerance Analysis

Notice that the nominal value for the merit function is zero. It only exceeds this value if either or both of the pupil plane/image plane criteria are violated. In the tolerance analysis, I demand that the merit function be no more than 0.001. There is nothing special about this number, just that it is small, but non-zero. The tolerancing routine would have a problem if we told it to relax the system until the merit function gets to zero value if it already starts at zero. The distance between the pupil stop and the following lens was used as a compensator.

What does all this mean?

The tolerance analyses can be reduced to two simple tolerance tables, one for the front-end and one for the back-end. These tables list the true element/spacing tolerances for the lenses. The values should be taken as plus and minus. They differ somewhat from tolerances generated for the front-end of NIRSPEC. In that case, the tolerances were on output rays with respect to the input beam. For the CU case, the tolerances are on the parts themselves, not on the output beams.

Table 1. Front-end Tolerance Table

Element	Distance	Decenter	Tilt
	mm	mm	degrees
QTH	5.000	NA	NA
L1	1.500	0.107	0.383
L2	3.000	0.073	0.493
L3	3.000	0.122	0.500
L4	3.000	0.225	0.500

Table 2. Back-end Tolerance Table

Element	Distance	Decenter	Tilt
	mm	mm	degrees
Integrating Sphere	3.000	NA	NA
L1	3.000	3.000	0.500
L2	0.377	0.188	0.250
L3	3.000	0.188	0.500
L4	3.000	0.375	0.500
L5	0.781	0.188	0.250
L6	0.150	0.188	0.500

Appendix

Front-end

Prescription

```
System/Prescription Data

File : G:\CALUNIT\ZEMAX\cufrntl2.ZMX
Title: Cal Unit: Section #1, tolrance analysis
Date : THU OCT 30 1997

GENERAL LENS DATA:

Surfaces            :               11
Stop                :                1
System Aperture : Entrance Pupil Diameter = 0.019
Ray aiming      : Real Reference, cache on
 X Pupil shift  :    0.0000000E+000
 Y Pupil shift  :    0.0000000E+000
 Z Pupil shift  :    0.0000000E+000
Apodization     :Uniform, factor =    0.00000E+000
Eff. Focal Len. : -3.90647E-002 (in air)
Eff. Focal Len. : -3.90647E-002 (in image space)
Total Track     :   2.27870E-001
Image Space F/# :   2.05604E+000
Para. Wrkng F/# :   2.70259E+000
Working F/#     :   2.69844E+000
Obj. Space N.A. :   4.99376E-002
Stop Radius     :   9.50000E-003
Parax. Ima. Hgt.:   5.65661E-004
Parax. Mag.     :   2.70259E-001
Entr. Pup. Dia. :   1.90000E-002
Entr. Pup. Pos. :   0.00000E+000
Exit Pupil Dia. :   1.63292E-002
Exit Pupil Pos. :  -4.29392E-002
Field Type      : Object height in Meters
Maximum Field   :   2.09304E-003
Primary Wave    :   2.20000E+000
Lens Units      :          Meters
Angular Mag.    :  -1.16356E+000


Fields          : 2
Field Type: Object height in Meters
#        X-Value         Y-Value         Weight
 1       0.000000        0.000000        1.000000
 2       0.001480        0.001480        1.000000


Vignetting Factors
#      VDX       VDY       VCX       VCY
1  0.000000  0.000000  0.000000  0.000000
2  0.000000  0.000000  0.000000  0.000000


Wavelengths     : 5
Units: Microns
#         Value          Weight
 1       1.000000        1.000000
 2       1.250000        1.000000
 3       1.650000        1.000000
 4       2.200000        1.000000
 5       2.500000        1.000000

SURFACE DATA SUMMARY:

Surf   Type          Comment          Radius       Thickness      Glass       Diameter      Conic
 OBJ STANDARD                        Infinity  1.9000000E-001                4.1860721E-003      0
 STO STANDARD                    2.8380000E-002  4.0000000E-003   LIF  1.9166701E-002      0
   2 STANDARD                    1.3870000E-002  3.9396968E-003        1.8537924E-002      0
   3 STANDARD                    1.8323000E-002  1.0000000E-002   BAF2 2.0923942E-002      0
   4 STANDARD                   -3.2660000E-002  4.4273899E-002        2.0594263E-002      0
   5 STANDARD                        Infinity  3.8753374E-002        9.8937405E-004      0
   6 STANDARD                    8.3950000E-002  9.1000000E-003   BAF2 1.8788574E-002      0
   7 STANDARD                   -1.7000000E-002  3.9319776E-003        2.0006774E-002      0
   8 STANDARD                   -1.4060000E-002  4.6000000E-003   LIF  1.8687295E-002      0
```

7

```
         9 STANDARD                              -2.3120000E-002 5.9532260E-002           2.0145186E-002           0
        10 PARAXIAL                                    -  4.9739155E-002                  1.9014032E-002           -
        IMA STANDARD                             Infinity                                 1.2103530E-003           0
```

SURFACE DATA DETAIL:

```
Surface OBJ     : STANDARD
Surface STO     : STANDARD
Surface   2     : STANDARD
Surface   3     : STANDARD
Surface   4     : STANDARD
Surface   5     : STANDARD
Surface   6     : STANDARD
Surface   7     : STANDARD
Surface   8     : STANDARD
Surface   9     : STANDARD
Surface  10     : PARAXIAL
 Focal length   :   5.00000000E-002
Surface IMA     : STANDARD
```

EDGE THICKNESS DATA:

```
Surf        X-Edge         Y-Edge
 OBJ        0.190077       0.190077
 STO        0.006176       0.006176
   2        0.002905       0.002905
   3        0.004999       0.004999
   4        0.045940       0.045940
   5        0.038755       0.038755
   6        0.005741       0.005741
   7        0.003007       0.003007
   8        0.006182       0.006182
   9        0.061842       0.061842
  10        0.049739       0.049739
 IMA        0.000000       0.000000
```

SOLVE AND VARIABLE DATA:

INDEX OF REFRACTION DATA:

```
Surf     Glass      1.000000    1.250000    1.650000    2.200000    2.500000
   0                1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
   1       LIF      1.38876646  1.38685568  1.38345741  1.37766731  1.37390429
   2                1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
   3       BAF2     1.46858622  1.46721981  1.46563303  1.46328725  1.46144752
   4                1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
   5                1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
   6       BAF2     1.46858622  1.46721981  1.46563303  1.46328725  1.46144752
   7                1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
   8       LIF      1.38876646  1.38685568  1.38345741  1.37766731  1.37390429
   9                1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
  10                1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
  11                1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
```

THERMAL COEFFICIENT OF EXPANSION DATA:

```
Surf     Glass           TCE
   0                0.00000000
   1       LIF      0.00000000
   2                0.00000000
   3       BAF2     0.00000000
   4                0.00000000
   5                0.00000000
   6       BAF2     0.00000000
   7                0.00000000
   8       LIF      0.00000000
   9                0.00000000
  10                0.00000000
  11                0.00000000
```

F/# DATA:

F/# calculations consider vignetting factors and ignore surface apertures.

```
          Wavelength:     1.000000          1.250000          1.650000
    #          Field     Tan     Sag       Tan     Sag       Tan     Sag
```

```
1      0.0000, 0.0000 M:    2.6763    2.6763    2.6865    2.6865    2.6930    2.6930
2      0.0015, 0.0015 M:    2.6756    2.6756    2.6858    2.6858    2.6922    2.6922

              Wavelength:       2.200000            2.500000
     #             Field    Tan       Sag       Tan       Sag
     1      0.0000, 0.0000 M:    2.6984    2.6984    2.7063    2.7063
     2      0.0015, 0.0015 M:    2.6977    2.6977    2.7056    2.7056
```

GLOBAL VERTEX COORDINATES AND DIRECTIONS:

Surf	X coord	Y coord	Z coord	X direc	Y direc	Z direc
1	0.000000	0.000000	0.190000	0.000000	0.000000	1.000000
2	0.000000	0.000000	0.194000	0.000000	0.000000	1.000000
3	0.000000	0.000000	0.197940	0.000000	0.000000	1.000000
4	0.000000	0.000000	0.207940	0.000000	0.000000	1.000000
5	0.000000	0.000000	0.252214	0.000000	0.000000	1.000000
6	0.000000	0.000000	0.290967	0.000000	0.000000	1.000000
7	0.000000	0.000000	0.300067	0.000000	0.000000	1.000000
8	0.000000	0.000000	0.303999	0.000000	0.000000	1.000000
9	0.000000	0.000000	0.308599	0.000000	0.000000	1.000000
10	0.000000	0.000000	0.368131	0.000000	0.000000	1.000000
11	0.000000	0.000000	0.417870	0.000000	0.000000	1.000000

ELEMENT VOLUME DATA:

Values are only accurate for plane and spherical surfaces.
Element volumes are computed by assuming edges are squared up
to the larger of the front and back radial aperture.

			Volume cc	Density g/cc	Mass g
Element surf	1 to	2	1.438053	0.000000	0.000000
Element surf	3 to	4	2.600131	0.000000	0.000000
Element surf	6 to	7	2.274649	0.000000	0.000000
Element surf	8 to	9	1.726454	0.000000	0.000000
Total Mass:					0.000000

CARDINAL POINTS:

Object space positions are measured with respect to surface 1.
Image space positions are measured with respect to the image surface.
The index in both the object space and image space is considered.

```
                              Object Space        Image Space
W = 1.000000
Principal Planes  :          -0.083993            0.029118
Nodal Planes      :          -0.083993            0.029118
Focal Planes      :          -0.045069           -0.009806
Anti-Nodal Planes :          -0.006144           -0.048730

W = 1.250000
Principal Planes  :          -0.084257            0.029416
Nodal Planes      :          -0.084257            0.029416
Focal Planes      :          -0.045252           -0.009589
Anti-Nodal Planes :          -0.006247           -0.048593

W = 1.650000
Principal Planes  :          -0.084405            0.029579
Nodal Planes      :          -0.084405            0.029579
Focal Planes      :          -0.045361           -0.009465
Anti-Nodal Planes :          -0.006318           -0.048508

W = 2.200000 (Primary)
Principal Planes  :          -0.084519            0.029699
Nodal Planes      :          -0.084519            0.029699
Focal Planes      :          -0.045454           -0.009366
Anti-Nodal Planes :          -0.006389           -0.048431

W = 2.500000
Principal Planes  :          -0.084714            0.029913
Nodal Planes      :          -0.084714            0.029913
Focal Planes      :          -0.045596           -0.009205
Anti-Nodal Planes :          -0.006478           -0.048323
```

Front-end

Merit Function

Merit Function Listing

File : G:\CALUNIT\ZEMAX\cufrntl2.ZMX
Title: Cal Unit: Section #1, tolrance analysis
Date : FRI OCT 31 1997

Merit Function Value: 9.47102444E-003

Num	Type	Int1	Int2	Hx	Hy	Px	Py	Target	Weight	Value	% Cont
1	RANG	9	1	1.0000	0.0000	1.0000	0.0000	0.00000E+000	0	1.11458E-002	0.000
2	RANG	9	1	1.0000	0.0000	-1.0000	0.0000	0.00000E+000	0	7.79626E-003	0.000
3	RANG	9	1	0.0000	1.0000	0.0000	1.0000	0.00000E+000	0	1.11458E-002	0.000
4	RANG	9	1	0.0000	1.0000	0.0000	-1.0000	0.00000E+000	0	7.79626E-003	0.000
5	SUMM	1	2					0.00000E+000	0	1.89420E-002	0.000
6	SUMM	3	4					0.00000E+000	0	1.89420E-002	0.000
7	MAXX	5	6					0.00000E+000	0	1.89420E-002	0.000
8	CONS							2.00000E+000	0	2.00000E+000	0.000
9	DIVI	7	8					0.00000E+000	1	9.47102E-003	100.000

Front-end

Tolerance Listing

Tolerance Data Listing - before running inverse sensitivity

File : G:\CALUNIT\ZEMAX\cufrntl2.ZMX
Title: Cal Unit: Section #1, tolrance analysis
Date : FRI OCT 31 1997

Num	Type	Int1	Int2	Min	Max
1	(COMP)	5	0	-5.00000E-003	5.00000E-003
2	(TTHI)	0	0	-3.00000E-003	3.00000E-003
3	(TTHI)	2	2	-3.00000E-003	3.00000E-003
4	(TTHI)	4	4	-3.00000E-003	3.00000E-003
5	(TTHI)	5	5	-3.00000E-003	3.00000E-003
6	(TTHI)	7	7	-3.00000E-003	3.00000E-003
7	(TTHI)	9	9	-3.00000E-003	3.00000E-003
8	(TEDX)	1	2	-3.00000E-003	3.00000E-003
9	(TEDY)	1	2	-3.00000E-003	3.00000E-003
10	(TETX)	1	2	-5.00000E-001	5.00000E-001
11	(TETY)	1	2	-5.00000E-001	5.00000E-001
12	(TEDX)	3	4	-3.00000E-003	3.00000E-003
13	(TEDY)	3	4	-3.00000E-003	3.00000E-003
14	(TETX)	3	4	-5.00000E-001	5.00000E-001
15	(TETY)	3	4	-5.00000E-001	5.00000E-001
16	(TEDX)	6	7	-3.00000E-003	3.00000E-003
17	(TEDY)	6	7	-3.00000E-003	3.00000E-003
18	(TETX)	6	7	-5.00000E-001	5.00000E-001
19	(TETY)	6	7	-5.00000E-001	5.00000E-001
20	(TEDX)	8	9	-3.00000E-003	3.00000E-003
21	(TEDY)	8	9	-3.00000E-003	3.00000E-003
22	(TETX)	8	9	-5.00000E-001	5.00000E-001
23	(TETY)	8	9	-5.00000E-001	5.00000E-001

Tolerance Data Listing - after running inverse sensitivity

File : G:\CALUNIT\ZEMAX\cufrntl2.ZMX
Title: Cal Unit: Section #1, tolrance analysis
Date : FRI OCT 31 1997

Num	Type	Int1	Int2	Min	Max
1	(COMP)	5	0	-5.00000E-003	5.00000E-003
2	(TTHI)	0	0	-3.00000E-003	3.00000E-003
3	(TTHI)	2	2	-1.68470E-003	1.50000E-003
4	(TTHI)	4	4	-3.00000E-003	3.00000E-003
5	(TTHI)	5	5	-3.00000E-003	3.00000E-003
6	(TTHI)	7	7	-3.00000E-003	3.00000E-003
7	(TTHI)	9	9	-3.00000E-003	3.00000E-003
8	(TEDX)	1	2	-3.75000E-004	1.07023E-004
9	(TEDY)	1	2	-3.26245E-004	1.07582E-004
10	(TETX)	1	2	-3.83852E-001	5.00000E-001
11	(TETY)	1	2	-5.00000E-001	3.82967E-001
12	(TEDX)	3	4	-7.30978E-005	2.19555E-004
13	(TEDY)	3	4	-7.30978E-005	2.19555E-004
14	(TETX)	3	4	-5.00000E-001	4.93081E-001
15	(TETY)	3	4	-4.93361E-001	5.00000E-001
16	(TEDX)	6	7	-3.09669E-004	1.21740E-004
17	(TEDY)	6	7	-3.09669E-004	1.21740E-004
18	(TETX)	6	7	-5.00000E-001	5.00000E-001
19	(TETY)	6	7	-5.00000E-001	5.00000E-001
20	(TEDX)	8	9	-2.24594E-004	7.38335E-004
21	(TEDY)	8	9	-2.24594E-004	7.38335E-004
22	(TETX)	8	9	-5.00000E-001	5.00000E-001
23	(TETY)	8	9	-5.00000E-001	5.00000E-001

Tolerance Output

Analysis of Tolerances

File : G:\CALUNIT\ZEMAX\cufrntl2.ZMX
Title: Cal Unit: Section #1, tolrance analysis
Date : FRI OCT 31 1997

Units are Meters.
Element tilts are in degrees; surface tilts are in fringes.

Mnemonics:
TRAD: Tolerance on radius of curvature.
TCUR: Tolerance on curvature (inverse length).
TFRN: Tolerance on curvature in fringes.
TTHI: Tolerance on thickness.
TCON: Tolerance on conic.
TSDX: Tolerance on surface decentering in x.
TSDY: Tolerance on surface decentering in y.
TSTX: Tolerance on surface tilt in x (fringes).
TSTY: Tolerance on surface tilt in y (fringes).
TIRX: Tolerance on surface total indicator runout in x.
TIRY: Tolerance on surface total indicator runout in y.
TIRR: Tolerance on irregularity (fringes).
TIND: Tolerance on index of refraction.
TPAR: Tolerance on parameter.
TEDV: Tolerance on extra data value.
TEDX: Tolerance on element decentering in x.
TEDY: Tolerance on element decentering in y.
TETX: Tolerance on element tilt in x (degrees).
TETY: Tolerance on element tilt in y (degrees).
TUDX: Tolerance on user surface decentering in x.
TUDY: Tolerance on user surface decentering in y.
TUTX: Tolerance on user surface tilt (degrees) around the x-axis.
TUTY: Tolerance on user surface tilt (degrees) around the y-axis.
TUTZ: Tolerance on user surface tilt (degrees) around the z-axis.

Compensator: Thickness 5, Min = -0.0050, Max = 0.0050
Mode: Inverse Sensitivities
Maximum Merit Value is 0.01500000
Merit: User defined merit function

Nominal Merit Function (MF) is 0.00904945

Fields: User Defined Object height in Meters
```
 #     X-Field       Y-Field        Weight    VDX     VDY     VCX     VCY
 1   0.000E+000   0.000E+000   1.000E+000   0.000   0.000   0.000   0.000
 2   1.480E-003   1.480E-003   1.000E+000   0.000   0.000   0.000   0.000
```

Sensitivity Analysis:

```
             |------------ Minimum ------------|  |------------ Maximum ------------|
Type Sf1 Sf2      Value        MF       Change       Value        MF       Change
Thickness tolerance on surface 0
TTHI   0   0   -0.003000   0.009164    0.000115    0.003000   0.008931   -0.000118
 Thickness   5:              3.67144E-002                     3.64984E-002
Thickness tolerance on surface 2
TTHI   2   2   -0.001685   0.014998    0.005948    0.001500   0.005914   -0.003135
 Thickness   5:              4.31206E-002                     3.37035E-002
Thickness tolerance on surface 4
TTHI   4   4   -0.003000   0.009057    0.000007    0.003000   0.009069    0.000020
 Thickness   5:              3.96661E-002                     3.37418E-002
Thickness tolerance on surface 5
TTHI   5   5   -0.003000   0.009047   -0.000003    0.003000   0.009051    0.000001
 Thickness   5:              3.66048E-002                     3.66275E-002
Thickness tolerance on surface 7
TTHI   7   7   -0.003000   0.013378    0.004329    0.003000   0.011825    0.002776
 Thickness   5:              4.12848E-002                     3.44879E-002
Thickness tolerance on surface 9
TTHI   9   9   -0.003000   0.009047   -0.000003    0.003000   0.009047   -0.000003
 Thickness   5:              3.66028E-002                     3.66028E-002
```

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```
Decenter X tolerance on surfaces 1 through 2
TEDX    1    2   -0.000375    0.013865    0.004815    0.000107    0.015000    0.005951
 Thickness    5:                     3.69008E-002                            3.55355E-002
Decenter Y tolerance on surfaces 1 through 2
TEDY    1    2   -0.000326    0.015000    0.005950    0.000108    0.015000    0.005951
 Thickness    5:                     3.60331E-002                            3.55355E-002
Tilt X tolerance on surfaces 1 through 2 (degrees)
TETX    1    2   -0.383852    0.015000    0.005950    0.500000    0.009604    0.000555
 Thickness    5:                     3.55005E-002                            3.76220E-002
Tilt Y tolerance on surfaces 1 through 2 (degrees)
TETY    1    2   -0.500000    0.009644    0.000595    0.382967    0.015000    0.005951
 Thickness    5:                     3.76081E-002                            3.55355E-002
Decenter X tolerance on surfaces 3 through 4
TEDX    3    4   -0.000073    0.015000    0.005950    0.000220    0.015000    0.005950
 Thickness    5:                     3.55314E-002                            3.80456E-002
Decenter Y tolerance on surfaces 3 through 4
TEDY    3    4   -0.000073    0.015000    0.005950    0.000220    0.015000    0.005950
 Thickness    5:                     3.55314E-002                            3.80456E-002
Tilt X tolerance on surfaces 3 through 4 (degrees)
TETX    3    4   -0.500000    0.009612    0.000562    0.493081    0.015000    0.005951
 Thickness    5:                     3.75833E-002                            3.55355E-002
Tilt Y tolerance on surfaces 3 through 4 (degrees)
TETY    3    4   -0.493361    0.014999    0.005950    0.500000    0.009612    0.000562
 Thickness    5:                     3.55228E-002                            3.75833E-002
Decenter X tolerance on surfaces 6 through 7
TEDX    6    7   -0.000310    0.015000    0.005950    0.000122    0.015000    0.005951
 Thickness    5:                     3.82098E-002                            3.56595E-002
Decenter Y tolerance on surfaces 6 through 7
TEDY    6    7   -0.000310    0.015000    0.005950    0.000122    0.015000    0.005951
 Thickness    5:                     3.82098E-002                            3.56595E-002
Tilt X tolerance on surfaces 6 through 7 (degrees)
TETX    6    7   -0.500000    0.010380    0.001330    0.500000    0.009383    0.000333
 Thickness    5:                     3.64435E-002                            3.73615E-002
Tilt Y tolerance on surfaces 6 through 7 (degrees)
TETY    6    7   -0.500000    0.009383    0.000333    0.500000    0.010381    0.001332
 Thickness    5:                     3.73614E-002                            3.64655E-002
Decenter X tolerance on surfaces 8 through 9
TEDX    8    9   -0.000225    0.015000    0.005950    0.000738    0.015000    0.005951
 Thickness    5:                     3.55102E-002                            3.73209E-002
Decenter Y tolerance on surfaces 8 through 9
TEDY    8    9   -0.000225    0.015000    0.005950    0.000738    0.015000    0.005951
 Thickness    5:                     3.55102E-002                            3.73209E-002
Tilt X tolerance on surfaces 8 through 9 (degrees)
TETX    8    9   -0.500000    0.012054    0.003005    0.500000    0.014633    0.005584
 Thickness    5:                     3.82251E-002                            4.03617E-002
Tilt Y tolerance on surfaces 8 through 9 (degrees)
TETY    8    9   -0.500000    0.014633    0.005583    0.500000    0.012054    0.003005
 Thickness    5:                     4.04401E-002                            3.82251E-002


Worst offenders:
Type Sf1 Sf2      Value        MF        Change
TEDY    1    2    0.000108    0.015000    0.005951
TETY    1    2    0.382967    0.015000    0.005951
TEDX    1    2    0.000107    0.015000    0.005951
TEDX    6    7    0.000122    0.015000    0.005951
TEDY    6    7    0.000122    0.015000    0.005951
TETX    3    4    0.493081    0.015000    0.005951
TEDY    8    9    0.000738    0.015000    0.005951
TEDX    8    9    0.000738    0.015000    0.005951
TEDY    6    7   -0.000310    0.015000    0.005950
TEDX    6    7   -0.000310    0.015000    0.005950

Nominal Merit Function    :      0.009049
Estimated change          :      0.020653
Estimated Merit Function  :      0.029702

Merit Statistics:
Mean                 :         0.012472
Standard Deviation   :         0.002770

Compensator Statistics:
Thickness Surf 5:
Nominal              :         0.038753
Minimum              :         0.033703
Maximum              :         0.043121
Mean                 :         0.036991
Standard Deviation   :         0.001857
```

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```
Monte Carlo Analysis:
Number of trials: 20

The Monte Carlo analysis includes the following tolerances:
TRAD TCUR TFRN TTHI TCON
TSDX TSDY TSTX TSTY TIRR
TEDV TPAR TIND TIRX TIRY
TUDX TUDY TUTX TUTY TUTZ
TEDX TEDY TETX TETY

Statistics: Normal Distribution

  Trial       Merit       Change
      1 Lens cannot be traced, tolerances may be too loose!
      2   0.015513    0.006463
 Thickness   5:                      3.95450E-002
      3   0.032647    0.023598
 Thickness   5:                      4.14721E-002
      4   0.014084    0.005034
 Thickness   5:                      4.34018E-002
      5   0.034290    0.025240
 Thickness   5:                      3.39097E-002
      6   0.021378    0.012329
 Thickness   5:                      3.49749E-002
      7   0.017825    0.008776
 Thickness   5:                      4.29862E-002
      8   0.029666    0.020616
 Thickness   5:                      3.32403E-002
      9   0.043048    0.033998
 Thickness   5:                      3.60354E-002
     10   0.027819    0.018770
 Thickness   5:                      4.13343E-002
     11   0.014713    0.005663
 Thickness   5:                      3.34936E-002
     12 Lens cannot be traced, tolerances may be too loose!
     13   0.010518    0.001469
 Thickness   5:                      3.63611E-002
     14   0.029394    0.020345
 Thickness   5:                      3.38907E-002
     15 Lens cannot be traced, tolerances may be too loose!
     16   0.026178    0.017128
 Thickness   5:                      3.38113E-002
     17   0.031413    0.022364
 Thickness   5:                      3.33203E-002
     18   0.019514    0.010465
 Thickness   5:                      4.10124E-002
     19   0.022356    0.013307
 Thickness   5:                      3.34138E-002
     20   0.007538   -0.001512
 Thickness   5:                      4.07788E-002

Nominal    0.009049
Best       0.007538
Worst      0.043048
Mean       0.023406
Std Dev    0.009236

Compensator Statistics:
Thickness Surf 5:
Nominal              :        0.038753
Minimum              :        0.033240
Maximum              :        0.043402
Mean                 :        0.037234
Standard Deviation   :        0.003751


90% of Monte Carlo lenses have a merit function below 0.032647.
50% of Monte Carlo lenses have a merit function below 0.021378.
10% of Monte Carlo lenses have a merit function below 0.007538.

End of Run.
```

Back-end

Prescription

System/Prescription Data

File : \\Betelgeuse\c\CALUNIT\ZEMAX\Cubacktl2.ZMX
Title: Cal Unit : Section #2, tolerance analysis
Date : THU OCT 30 1997

GENERAL LENS DATA:

```
Surfaces         :              53
Stop             :               7
System Aperture : Float By Stop Size = 0.005
Ray aiming      : Real Reference, cache on
 X Pupil shift  :   0.0000000E+000
 Y Pupil shift  :   0.0000000E+000
 Z Pupil shift  :   0.0000000E+000
Apodization     :Uniform, factor =   0.00000E+000
Eff. Focal Len. : -1.61671E-001 (in air)
Eff. Focal Len. : -1.61671E-001 (in image space)
Total Track     :  5.28978E-001
Image Space F/# :  9.82442E+000
Para. Wrkng F/# :  1.00114E+001
Working F/#     :  1.00068E+001
Obj. Space N.A. :  8.02117E-002
Stop Radius     :  5.00000E-003
Parax. Ima. Hgt.:  1.11563E-002
Parax. Mag.     :  1.61126E+000
Entr. Pup. Dia. :  1.64560E-002
Entr. Pup. Pos. :  7.38534E-002
Exit Pupil Dia. :  1.39304E+000
Exit Pupil Pos. : -1.39547E+001
Field Type      : Object height in Meters
Maximum Field   :  6.92400E-003
Primary Wave    :  2.20000E+000
Lens Units      :        Meters
Angular Mag.    : -1.18130E-002
```

```
Fields         : 5
Field Type: Object height in Meters
#       X-Value         Y-Value          Weight
 1      0.000000        0.000000        1.000000
 2      0.000000        0.006924        1.000000
 3      0.000000       -0.006924        1.000000
 4      0.006920        0.000000        1.000000
 5     -0.006920        0.000000        1.000000
```

```
Vignetting Factors
#      VDX       VDY       VCX       VCY
1  0.000000  0.000000  0.000000  0.000000
2  0.000000  0.000000  0.000000  0.000000
3  0.000000  0.000000  0.000000  0.000000
4  0.000000  0.000000  0.000000  0.000000
5  0.000000  0.000000  0.000000  0.000000
```

```
Wavelengths    : 7
Units: Microns
#        Value       Weight
 1      1.000000    1.000000
 2      1.250000    1.000000
 3      1.650000    1.000000
 4      2.200000    1.000000
 5      2.500000    1.000000
 6      3.700000    1.000000
 7      5.000000    1.000000
```

SURFACE DATA SUMMARY:

Surf	Type	Comment	Radius	Thickness	Glass	Diameter	Conic
OBJ	STANDARD		Infinity	2.8394899E-002		1.3848000E-002	0
1	STANDARD		-1.3920000E-002	7.8000000E-003	CAFL	2.2000000E-002	0
2	STANDARD		-1.7960000E-002	1.2232286E-002		2.2000000E-002	0
3	STANDARD		1.3183000E-001	2.5000000E-003	LIF	2.4000000E-002	0
4	STANDARD		2.1580000E-002	1.9651939E-003		2.4000000E-002	0

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		Radius	Thickness	Glass	Semi-Diameter	Conic
5	STANDARD	2.6300000E-002	9.8000000E-003	CAFL	2.4000000E-002	0
6	STANDARD	-3.2280000E-002	4.0404115E-002		2.4000000E-002	0
STO	STANDARD	Infinity	1.1292021E-001		1.0000000E-002	0
8	STANDARD	Infinity	-8.0000000E-004		3.5704595E-002	0
9	STANDARD	5.1250000E-002	7.9000000E-003	CAFL	4.0000000E-002	0
10	STANDARD	-1.1077000E-001	1.8313495E-003		4.0000000E-002	0
11	STANDARD	4.6890000E-002	5.0000000E-003	LIF	4.0000000E-002	0
12	STANDARD	2.2180000E-002	5.2316350E-002		4.0000000E-002	0
13	STANDARD	-3.8040000E-002	6.6000000E-003	CAFL	4.4000000E-002	0
14	STANDARD	-2.9990000E-002	1.0328926E-001		4.4000000E-002	0
15	STANDARD	Infinity	3.0633360E-002		3.3580666E-002	0
16	STANDARD	Infinity	7.5000000E-003	CAFL	3.5718962E-002	0
17	STANDARD	Infinity	6.0000000E-002		3.6093073E-002	0
18	COORDBRK	-	0	-	-	-
19	COORDBRK	-	0	-	-	-
20	COORDBRK	-	0	-	-	-
21	STANDARD	Infinity	0	MIRROR	6.2497022E-002	0
22	COORDBRK	-	-3.0408495E-001	-	-	-
23	COORDBRK	-	0	-	-	-
24	COORDBRK	-	0	-	-	-
25	COORDBRK	-	0	-	-	-
26	COORDBRK	-	-4.0849500E-003	-	-	-
27	COORDBRK	-	0	-	-	-
28	STANDARD	7.9183010E-001	0	MIRROR	2.2230697E-001	-1.0000000E+000
29	COORDBRK	-	4.0849500E-003	-	-	-
30	COORDBRK	-	3.0408495E-001	-	-	-
31	COORDBRK	-	0	-	-	-
32	STANDARD	Infinity	0	MIRROR	5.5663475E-002	0
33	COORDBRK	-	-1.0364647E-001	-	-	-
34	COORDBRK	-	0	-	-	-
35	STANDARD	Infinity	-2.0000000E-003	CAF2_77X	2.7825120E-002	0
36	STANDARD	Infinity	-4.8000000E-002		2.7706390E-002	0
37	COORDBRK	-	0	-	-	-
38	COORDBRK	-	0	-	-	-
39	STANDARD	Infinity	2.1800155E-001	MIRROR	4.8854727E-002	0
40	COORDBRK	-	2.1800155E-001	-	-	-
41	COORDBRK	-	0	-	-	-
42	COORDBRK	-	2.7308900E-003	-	-	-
43	STANDARD	-5.2935822E-001	0	MIRROR	1.5665772E-001	-1.0000000E+000
44	COORDBRK	-	-2.7308900E-003	-	-	-
45	COORDBRK	-	0	-	-	-
46	COORDBRK	-	0	-	-	-
47	COORDBRK	-	-2.1800155E-001	-	-	-
48	COORDBRK	-	0	-	-	-
49	STANDARD	Infinity	0	MIRROR	4.3193216E-002	0
50	COORDBRK	-	4.9431661E-002	-	-	-
51	COORDBRK	-	0	-	-	-
52	COORDBRK	-	0	-	-	-
IMA	STANDARD	Infinity			2.2719494E-002	0

SURFACE DATA DETAIL:

```
Surface OBJ    : STANDARD
Surface   1    : STANDARD
Surface   2    : STANDARD
Surface   3    : STANDARD
Surface   4    : STANDARD
Surface   5    : STANDARD
Surface   6    : STANDARD
Surface STO    : STANDARD
Surface   8    : STANDARD
Surface   9    : STANDARD
Surface  10    : STANDARD
Surface  11    : STANDARD
Surface  12    : STANDARD
Surface  13    : STANDARD
Surface  14    : STANDARD
Surface  15    : STANDARD
Surface  16    : STANDARD
 Aperture      : Circular Aperture
 Minimum Radius :          0
 Maximum Radius :      0.026
Surface  17    : STANDARD
 Aperture      : Circular Aperture
 Minimum Radius :          0
 Maximum Radius :      0.026
Surface  18    : COORDBRK
 Decenter X    :  0.00000000E+000
 Decenter Y    :  0.00000000E+000
 Tilt About X  :  0.00000000E+000
 Tilt About Y  :  0.00000000E+000
 Tilt About Z  :  1.80000000E+002
 Order         : Decenter then tilt
```

```
Surface  19      : COORDBRK
 Decenter X      :  0.00000000E+000
 Decenter Y      :  0.00000000E+000
 Tilt About X    :  0.00000000E+000
 Tilt About Y    :  0.00000000E+000
 Tilt About Z    :  0.00000000E+000
 Order           : Decenter then tilt
Surface  20      : COORDBRK
 Decenter X      :  0.00000000E+000
 Decenter Y      :  0.00000000E+000
 Tilt About X    : -4.79000000E+001
 Tilt About Y    :  0.00000000E+000
 Tilt About Z    :  0.00000000E+000
 Order           : Decenter then tilt
Surface  21      : STANDARD
 Aperture        : Rectangular Aperture
 X Half Width    :        0.02905
 Y Half Width    :         0.0448
Surface  22      : COORDBRK
 Decenter X      :  0.00000000E+000
 Decenter Y      :  0.00000000E+000
 Tilt About X    : -4.79000000E+001
 Tilt About Y    :  0.00000000E+000
 Tilt About Z    :  0.00000000E+000
 Order           : Decenter then tilt
Surface  23      : COORDBRK
 Decenter X      :  0.00000000E+000
 Decenter Y      :  0.00000000E+000
 Tilt About X    :  0.00000000E+000
 Tilt About Y    :  0.00000000E+000
 Tilt About Z    :  0.00000000E+000
 Order           : Decenter then tilt
Surface  24      : COORDBRK
 Decenter X      :  0.00000000E+000
 Decenter Y      :  0.00000000E+000
 Tilt About X    :  1.16000000E+001
 Tilt About Y    :  0.00000000E+000
 Tilt About Z    :  0.00000000E+000
 Order           : Decenter then tilt
Surface  25      : COORDBRK
 Decenter X      :  0.00000000E+000
 Decenter Y      :  8.04311685E-002
 Tilt About X    :  0.00000000E+000
 Tilt About Y    :  0.00000000E+000
 Tilt About Z    :  0.00000000E+000
 Order           : Decenter then tilt
Surface  26      : COORDBRK
 Decenter X      :  0.00000000E+000
 Decenter Y      :  0.00000000E+000
 Tilt About X    :  0.00000000E+000
 Tilt About Y    :  0.00000000E+000
 Tilt About Z    :  0.00000000E+000
 Order           : Decenter then tilt
Surface  27      : COORDBRK
 Decenter X      :  0.00000000E+000
 Decenter Y      :  0.00000000E+000
 Tilt About X    :  0.00000000E+000
 Tilt About Y    :  0.00000000E+000
 Tilt About Z    :  0.00000000E+000
 Order           : Decenter then tilt
Surface  28      : STANDARD
 Aperture        : Circular Aperture
 Minimum Radius  :              0
 Maximum Radius  :         0.0396
 Y- Decenter     :     -0.0804312
Surface  29      : COORDBRK
 Decenter X      :  0.00000000E+000
 Decenter Y      : -8.04311685E-002
 Tilt About X    :  0.00000000E+000
 Tilt About Y    :  0.00000000E+000
 Tilt About Z    :  0.00000000E+000
 Order           : Decenter then tilt
Surface  30      : COORDBRK
 Decenter X      :  0.00000000E+000
 Decenter Y      :  0.00000000E+000
 Tilt About X    :  0.00000000E+000
 Tilt About Y    :  0.00000000E+000
```

```
 Tilt About Z   :  0.00000000E+000
 Order          : Decenter then tilt
Surface  31     : COORDBRK
 Decenter X     :  0.00000000E+000
 Decenter Y     :  0.00000000E+000
 Tilt About X   : -4.79000000E+001
 Tilt About Y   :  0.00000000E+000
 Tilt About Z   :  0.00000000E+000
 Order          : Decenter then tilt
Surface  32     : STANDARD
 Aperture       : Rectangular Aperture
 X Half Width   :       0.02015
 Y Half Width   :        0.034
Surface  33     : COORDBRK
 Decenter X     :  0.00000000E+000
 Decenter Y     :  0.00000000E+000
 Tilt About X   : -4.79000000E+001
 Tilt About Y   :  0.00000000E+000
 Tilt About Z   :  0.00000000E+000
 Order          : Decenter then tilt
Surface  34     : COORDBRK
 Decenter X     :  0.00000000E+000
 Decenter Y     :  0.00000000E+000
 Tilt About X   :  0.00000000E+000
 Tilt About Y   :  0.00000000E+000
 Tilt About Z   :  0.00000000E+000
 Order          : Decenter then tilt
Surface  35     : STANDARD
 Aperture       : Circular Aperture
 Minimum Radius :             0
 Maximum Radius :        0.015
Surface  36     : STANDARD
 Aperture       : Circular Aperture
 Minimum Radius :             0
 Maximum Radius :        0.015
Surface  37     : COORDBRK
 Decenter X     :  0.00000000E+000
 Decenter Y     :  0.00000000E+000
 Tilt About X   :  0.00000000E+000
 Tilt About Y   :  0.00000000E+000
 Tilt About Z   :  0.00000000E+000
 Order          : Decenter then tilt
Surface  38     : COORDBRK
 Decenter X     :  0.00000000E+000
 Decenter Y     :  0.00000000E+000
 Tilt About X   : -4.79000000E+001
 Tilt About Y   :  0.00000000E+000
 Tilt About Z   :  0.00000000E+000
 Order          : Decenter then tilt
Surface  39     : STANDARD
 Aperture       : Rectangular Aperture
 X Half Width   :       0.01745
 Y Half Width   :       0.02732
Surface  40     : COORDBRK
 Decenter X     :  0.00000000E+000
 Decenter Y     :  0.00000000E+000
 Tilt About X   : -4.79000000E+001
 Tilt About Y   :  0.00000000E+000
 Tilt About Z   :  0.00000000E+000
 Order          : Decenter then tilt
Surface  41     : COORDBRK
 Decenter X     :  0.00000000E+000
 Decenter Y     :  5.37702469E-002
 Tilt About X   :  0.00000000E+000
 Tilt About Y   :  0.00000000E+000
 Tilt About Z   :  0.00000000E+000
 Order          : Decenter then tilt
Surface  42     : COORDBRK
 Decenter X     :  0.00000000E+000
 Decenter Y     :  0.00000000E+000
 Tilt About X   :  0.00000000E+000
 Tilt About Y   :  0.00000000E+000
 Tilt About Z   :  0.00000000E+000
 Order          : Decenter then tilt
Surface  43     : STANDARD
 Aperture       : Circular Aperture
 Minimum Radius :             0
```

```
 Maximum Radius :        0.03153
 Y- Decenter    :      -0.0537703
Surface  44      : COORDBRK
 Decenter X     :   0.00000000E+000
 Decenter Y     :   0.00000000E+000
 Tilt About X   :   0.00000000E+000
 Tilt About Y   :   0.00000000E+000
 Tilt About Z   :   0.00000000E+000
 Order          : Decenter then tilt
Surface  45      : COORDBRK
 Decenter X     :   0.00000000E+000
 Decenter Y     :  -5.37702469E-002
 Tilt About X   :   0.00000000E+000
 Tilt About Y   :   0.00000000E+000
 Tilt About Z   :   0.00000000E+000
 Order          : Decenter then tilt
Surface  46      : COORDBRK
 Decenter X     :   0.00000000E+000
 Decenter Y     :   0.00000000E+000
 Tilt About X   :   1.16000000E+001
 Tilt About Y   :   0.00000000E+000
 Tilt About Z   :   0.00000000E+000
 Order          : Decenter then tilt
Surface  47      : COORDBRK
 Decenter X     :   0.00000000E+000
 Decenter Y     :   0.00000000E+000
 Tilt About X   :   0.00000000E+000
 Tilt About Y   :   0.00000000E+000
 Tilt About Z   :   0.00000000E+000
 Order          : Decenter then tilt
Surface  48      : COORDBRK
 Decenter X     :   0.00000000E+000
 Decenter Y     :   0.00000000E+000
 Tilt About X   :  -4.79000000E+001
 Tilt About Y   :   0.00000000E+000
 Tilt About Z   :   0.00000000E+000
 Order          : Decenter then tilt
Surface  49      : STANDARD
 Aperture       : Rectangular Aperture
 X Half Width   :        0.0163
 Y Half Width   :        0.0248
Surface  50      : COORDBRK
 Decenter X     :   0.00000000E+000
 Decenter Y     :   0.00000000E+000
 Tilt About X   :  -4.79000000E+001
 Tilt About Y   :   0.00000000E+000
 Tilt About Z   :   0.00000000E+000
 Order          : Decenter then tilt
Surface  51      : COORDBRK
 Decenter X     :   0.00000000E+000
 Decenter Y     :   0.00000000E+000
 Tilt About X   :   0.00000000E+000
 Tilt About Y   :   0.00000000E+000
 Tilt About Z   :   0.00000000E+000
 Order          : Decenter then tilt
Surface  52      : COORDBRK
 Decenter X     :   0.00000000E+000
 Decenter Y     :   0.00000000E+000
 Tilt About X   :   0.00000000E+000
 Tilt About Y   :   0.00000000E+000
 Tilt About Z   :   1.80000000E+002
 Order          : Decenter then tilt
Surface IMA      : STANDARD

EDGE THICKNESS DATA:

Surf        X-Edge          Y-Edge
 OBJ       0.026551        0.026551
   1       0.009427        0.009427
   2       0.016455        0.016455
   3       0.005597        0.005597
   4       0.001218        0.001218
   5       0.004589        0.004589
   6       0.042717        0.042717
 STO       0.112920        0.112920
   8       0.002410        0.002410
   9       0.002016        0.002016
```

```
10         0.008131          0.008131
11         0.013112          0.013112
12         0.034044          0.034044
13         0.003998          0.003998
14         0.112898          0.112898
15         0.030633          0.030633
16         0.007500          0.007500
17         0.060000          0.060000
18         0.000000          0.000000
19         0.000000          0.000000
20         0.000000          0.000000
21         0.000000          0.000000
22        -0.304085         -0.304085
23         0.000000          0.000000
24         0.000000          0.000000
25         0.000000          0.000000
26        -0.004085         -0.004085
27         0.000000          0.000000
28        -0.007802         -0.007802
29         0.004085          0.004085
30         0.304085          0.304085
31         0.000000          0.000000
32         0.000000          0.000000
33        -0.103646         -0.103646
34         0.000000          0.000000
35        -0.002000         -0.002000
36        -0.048000         -0.048000
37         0.000000          0.000000
38         0.000000          0.000000
39         0.000000          0.000000
40         0.218002          0.218002
41         0.000000          0.000000
42         0.002731          0.002731
43         0.005795          0.005795
44        -0.002731         -0.002731
45         0.000000          0.000000
46         0.000000          0.000000
47        -0.218002         -0.218002
48         0.000000          0.000000
49         0.000000          0.000000
50         0.049432          0.049432
51         0.000000          0.000000
52         0.000000          0.000000
IMA        0.000000          0.000000
```

SOLVE AND VARIABLE DATA:

```
Semi Diameter   1      : Fixed
Semi Diameter   2      : Fixed
Semi Diameter   3      : Fixed
Semi Diameter   4      : Fixed
Semi Diameter   5      : Fixed
Semi Diameter   6      : Fixed
Semi Diameter   7      : Fixed
Semi Diameter   9      : Fixed
Semi Diameter  10      : Fixed
Semi Diameter  11      : Fixed
Semi Diameter  12      : Fixed
Semi Diameter  13      : Fixed
Semi Diameter  14      : Fixed
```

INDEX OF REFRACTION DATA:

Surf	Glass	1.000000	1.250000	1.650000	2.200000	2.500000
0		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
1	CAFL	1.42888268	1.42746016	1.42555631	1.42280773	1.42110201
2		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
3	LIF	1.38876646	1.38685568	1.38345741	1.37766731	1.37390429
4		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
5	CAFL	1.42888268	1.42746016	1.42555631	1.42280773	1.42110201
6		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
7		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
8		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
9	CAFL	1.42888268	1.42746016	1.42555631	1.42280773	1.42110201
10		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
11	LIF	1.38876646	1.38685568	1.38345741	1.37766731	1.37390429
12		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000

```
13      CAFL    1.42888268  1.42746016  1.42555631  1.42280773  1.42110201
14              1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
15              1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
16      CAFL    1.42888268  1.42746016  1.42555631  1.42280773  1.42110201
17              1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
18 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
19 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
20 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
21      MIRROR  1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
22 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
23 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
24 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
25 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
26 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
27 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
28      MIRROR  1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
29 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
30 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
31 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
32      MIRROR  1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
33 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
34 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
35    CAF2_77X  1.43090401  1.42954573  1.42770030  1.42499297  1.42330012
36              1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
37 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
38 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
39      MIRROR  1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
40 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
41 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
42 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
43      MIRROR  1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
44 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
45 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
46 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
47 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
48 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
49      MIRROR  1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
50 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
51 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
52 <CRD BRK>    1.00000000  1.00000000  1.00000000  1.00000000  1.00000000
53              1.00000000  1.00000000  1.00000000  1.00000000  1.00000000


Surf      Glass    3.700000    5.000000
   0              1.00000000  1.00000000
   1      CAFL    1.41235319  1.39895815
   2              1.00000000  1.00000000
   3       LIF    1.35450219  1.32561903
   4              1.00000000  1.00000000
   5      CAFL    1.41235319  1.39895815
   6              1.00000000  1.00000000
   7              1.00000000  1.00000000
   8              1.00000000  1.00000000
   9      CAFL    1.41235319  1.39895815
  10              1.00000000  1.00000000
  11       LIF    1.35450219  1.32561903
  12              1.00000000  1.00000000
  13      CAFL    1.41235319  1.39895815
  14              1.00000000  1.00000000
  15              1.00000000  1.00000000
  16      CAFL    1.41235319  1.39895815
  17              1.00000000  1.00000000
  18 <CRD BRK>    1.00000000  1.00000000
  19 <CRD BRK>    1.00000000  1.00000000
  20 <CRD BRK>    1.00000000  1.00000000
  21      MIRROR  1.00000000  1.00000000
  22 <CRD BRK>    1.00000000  1.00000000
  23 <CRD BRK>    1.00000000  1.00000000
  24 <CRD BRK>    1.00000000  1.00000000
  25 <CRD BRK>    1.00000000  1.00000000
  26 <CRD BRK>    1.00000000  1.00000000
  27 <CRD BRK>    1.00000000  1.00000000
  28      MIRROR  1.00000000  1.00000000
  29 <CRD BRK>    1.00000000  1.00000000
  30 <CRD BRK>    1.00000000  1.00000000
  31 <CRD BRK>    1.00000000  1.00000000
  32      MIRROR  1.00000000  1.00000000
```

```
33 <CRD BRK>     1.00000000  1.00000000
34 <CRD BRK>     1.00000000  1.00000000
35  CAF2_77X     1.41455993  1.40112380
36                1.00000000  1.00000000
37 <CRD BRK>     1.00000000  1.00000000
38 <CRD BRK>     1.00000000  1.00000000
39    MIRROR     1.00000000  1.00000000
40 <CRD BRK>     1.00000000  1.00000000
41 <CRD BRK>     1.00000000  1.00000000
42 <CRD BRK>     1.00000000  1.00000000
43    MIRROR     1.00000000  1.00000000
44 <CRD BRK>     1.00000000  1.00000000
45 <CRD BRK>     1.00000000  1.00000000
46 <CRD BRK>     1.00000000  1.00000000
47 <CRD BRK>     1.00000000  1.00000000
48 <CRD BRK>     1.00000000  1.00000000
49    MIRROR     1.00000000  1.00000000
50 <CRD BRK>     1.00000000  1.00000000
51 <CRD BRK>     1.00000000  1.00000000
52 <CRD BRK>     1.00000000  1.00000000
53                1.00000000  1.00000000

THERMAL COEFFICIENT OF EXPANSION DATA:

Surf      Glass        TCE
   0                 0.00000000
   1      CAFL       0.00000000
   2                 0.00000000
   3       LIF       0.00000000
   4                 0.00000000
   5      CAFL       0.00000000
   6                 0.00000000
   7                 0.00000000
   8                 0.00000000
   9      CAFL       0.00000000
  10                 0.00000000
  11       LIF       0.00000000
  12                 0.00000000
  13      CAFL       0.00000000
  14                 0.00000000
  15                 0.00000000
  16      CAFL       0.00000000
  17                 0.00000000
  18 <CRD BRK>       0.00000000
  19 <CRD BRK>       0.00000000
  20 <CRD BRK>       0.00000000
  21    MIRROR       0.00000000
  22 <CRD BRK>       0.00000000
  23 <CRD BRK>       0.00000000
  24 <CRD BRK>       0.00000000
  25 <CRD BRK>       0.00000000
  26 <CRD BRK>       0.00000000
  27 <CRD BRK>       0.00000000
  28    MIRROR       0.00000000
  29 <CRD BRK>       0.00000000
  30 <CRD BRK>       0.00000000
  31 <CRD BRK>       0.00000000
  32    MIRROR       0.00000000
  33 <CRD BRK>       0.00000000
  34 <CRD BRK>       0.00000000
  35  CAF2_77X       0.00000000
  36                 0.00000000
  37 <CRD BRK>       0.00000000
  38 <CRD BRK>       0.00000000
  39    MIRROR       0.00000000
  40 <CRD BRK>       0.00000000
  41 <CRD BRK>       0.00000000
  42 <CRD BRK>       0.00000000
  43    MIRROR       0.00000000
  44 <CRD BRK>       0.00000000
  45 <CRD BRK>       0.00000000
  46 <CRD BRK>       0.00000000
  47 <CRD BRK>       0.00000000
  48 <CRD BRK>       0.00000000
  49    MIRROR       0.00000000
  50 <CRD BRK>       0.00000000
  51 <CRD BRK>       0.00000000
```

```
   52 <CRD BRK>    0.00000000
   53               0.00000000
```

F/# DATA:

F/# calculations consider vignetting factors and ignore surface apertures.

		Wavelength:	1.000000		1.250000		1.650000	
#	Field	Tan	Sag	Tan	Sag	Tan	Sag	
1	0.0000, 0.0000 M:	9.9808	9.9808	10.0024	10.0024	10.0125	10.0125
2	0.0000, 0.0069 M:	10.1188	9.9752	10.1576	10.0002	10.1904	10.0145
3	0.0000, -0.0069 M:	9.7803	9.9744	9.8179	9.9998	9.8496	10.0144
4	0.0069, 0.0000 M:	9.9741	9.9474	9.9993	9.9855	10.0137	10.0177
5	-0.0069, 0.0000 M:	9.9741	9.9474	9.9993	9.9855	10.0137	10.0177

		Wavelength:	2.200000		2.500000		3.700000	
#	Field	Tan	Sag	Tan	Sag	Tan	Sag	
1	0.0000, 0.0000 M:	10.0068	10.0068	9.9991	9.9991	9.9548	9.9548
2	0.0000, 0.0069 M:	10.2163	10.0140	10.2276	10.0093	10.2742	9.9779
3	0.0000, -0.0069 M:	9.8744	10.0140	9.8853	10.0094	9.9294	9.9779
4	0.0069, 0.0000 M:	10.0133	10.0430	10.0086	10.0540	9.9771	10.0991
5	-0.0069, 0.0000 M:	10.0133	10.0430	10.0086	10.0540	9.9771	10.0991

		Wavelength:	5.000000	
#	Field	Tan	Sag	
1	0.0000, 0.0000 M:	9.8968	9.8968
2	0.0000, 0.0069 M:	10.3347	9.9326
3	0.0000, -0.0069 M:	9.9869	9.9327
4	0.0069, 0.0000 M:	9.9319	10.1576
5	-0.0069, 0.0000 M:	9.9319	10.1576

GLOBAL VERTEX COORDINATES AND DIRECTIONS:

Surf	X coord	Y coord	Z coord	X direc	Y direc	Z direc
1	0.000000	0.000000	0.028395	0.000000	0.000000	1.000000
2	0.000000	0.000000	0.036195	0.000000	0.000000	1.000000
3	0.000000	0.000000	0.048427	0.000000	0.000000	1.000000
4	0.000000	0.000000	0.050927	0.000000	0.000000	1.000000
5	0.000000	0.000000	0.052892	0.000000	0.000000	1.000000
6	0.000000	0.000000	0.062692	0.000000	0.000000	1.000000
7	0.000000	0.000000	0.103096	0.000000	0.000000	1.000000
8	0.000000	0.000000	0.216017	0.000000	0.000000	1.000000
9	0.000000	0.000000	0.215217	0.000000	0.000000	1.000000
10	0.000000	0.000000	0.223117	0.000000	0.000000	1.000000
11	0.000000	0.000000	0.224948	0.000000	0.000000	1.000000
12	0.000000	0.000000	0.229948	0.000000	0.000000	1.000000
13	0.000000	0.000000	0.282264	0.000000	0.000000	1.000000
14	0.000000	0.000000	0.288864	0.000000	0.000000	1.000000
15	0.000000	0.000000	0.392154	0.000000	0.000000	1.000000
16	0.000000	0.000000	0.422787	0.000000	0.000000	1.000000
17	0.000000	0.000000	0.430287	0.000000	0.000000	1.000000
18	0.000000	0.000000	0.490287	0.000000	0.000000	1.000000
19	0.000000	0.000000	0.490287	0.000000	0.000000	1.000000
20	0.000000	0.000000	0.490287	0.000000	-0.741976	0.670427
21	0.000000	0.000000	0.490287	0.000000	-0.741976	0.670427
22	0.000000	0.000000	0.490287	0.000000	-0.994881	-0.101056
23	-0.000000	0.302528	0.521017	0.000000	-0.994881	-0.101056
24	-0.000000	0.302528	0.521017	0.000000	-0.994881	0.101056
25	-0.000000	0.294400	0.440997	0.000000	-0.994881	0.101056
26	-0.000000	0.294400	0.440997	0.000000	-0.994881	0.101056
27	-0.000000	0.298464	0.440584	0.000000	-0.994881	0.101056
28	-0.000000	0.298464	0.440584	0.000000	-0.994881	0.101056
29	-0.000000	0.306592	0.520604	0.000000	-0.994881	0.101056
30	-0.000000	0.302528	0.521017	0.000000	-0.994881	0.101056
31	0.000000	-0.000000	0.551746	0.000000	-0.741976	-0.670427
32	0.000000	-0.000000	0.551746	0.000000	-0.741976	-0.670427
33	0.000000	-0.000000	0.551746	-0.000000	0.000000	-1.000000
34	0.000000	-0.000000	0.655393	-0.000000	0.000000	-1.000000
35	0.000000	-0.000000	0.655393	-0.000000	0.000000	-1.000000
36	0.000000	-0.000000	0.657393	-0.000000	0.000000	-1.000000
37	0.000000	-0.000000	0.705393	-0.000000	0.000000	-1.000000
38	0.000000	-0.000000	0.705393	-0.000000	0.741976	-0.670427
39	0.000000	-0.000000	0.705393	-0.000000	0.741976	-0.670427
40	0.000000	-0.000000	0.705393	-0.000000	0.994881	0.101056
41	-0.000000	0.211452	0.780918	-0.000000	0.994881	0.101056
42	-0.000000	0.211452	0.780918	-0.000000	0.994881	0.101056
43	-0.000000	0.214169	0.781194	-0.000000	0.994881	0.101056

```
44      -0.000000       0.214169       0.781194 -0.000000  0.994881  0.101056
45      -0.000000       0.216886       0.727423 -0.000000  0.994881  0.101056
46      -0.000000       0.216886       0.727423 -0.000000  0.994881 -0.101056
47      -0.000000       0.216886       0.727423 -0.000000  0.994881 -0.101056
48       0.000000      -0.000000       0.749454 -0.000000  0.741976  0.670427
49       0.000000      -0.000000       0.749454 -0.000000  0.741976  0.670427
50       0.000000      -0.000000       0.749454  0.000000 -0.000000  1.000000
51       0.000000      -0.000000       0.798885  0.000000 -0.000000  1.000000
52       0.000000      -0.000000       0.798885  0.000000 -0.000000  1.000000
53       0.000000      -0.000000       0.798885  0.000000 -0.000000  1.000000
```

ELEMENT VOLUME DATA:

Values are only accurate for plane and spherical surfaces.
Element volumes are computed by assuming edges are squared up
to the larger of the front and back radial aperture.

```
                         Volume cc   Density g/cc       Mass g
Element surf   1 to   2   3.220176     0.000000       0.000000
Element surf   3 to   4   1.806203     0.000000       0.000000
Element surf   5 to   6   3.274021     0.000000       0.000000
Element surf   9 to  10   6.268675     0.000000       0.000000
Element surf  11 to  12  10.381786     0.000000       0.000000
Element surf  13 to  14   8.341996     0.000000       0.000000
Element surf  16 to  17   7.673595     0.000000       0.000000
Element surf  35 to  36   1.216169     0.000000       0.000000
Total Mass:                                           0.000000
```

CARDINAL POINTS:

Object space positions are measured with respect to surface 1.
Image space positions are measured with respect to the image surface.
The index in both the object space and image space is considered.

```
                          Object Space       Image Space
W = 1.000000
Principal Planes  :        -0.090474         -0.109201
Nodal Planes      :        -0.090474         -0.109201
Focal Planes      :         0.073243         -0.272919
Anti-Nodal Planes :         0.236961         -0.436636

W = 1.250000
Principal Planes  :        -0.090013         -0.108012
Nodal Planes      :        -0.090013         -0.108012
Focal Planes      :         0.072332         -0.270357
Anti-Nodal Planes :         0.234678         -0.432702

W = 1.650000
Principal Planes  :        -0.089749         -0.107309
Nodal Planes      :        -0.089749         -0.107309
Focal Planes      :         0.071857         -0.268915
Anti-Nodal Planes :         0.233463         -0.430520

W = 2.200000 (Primary)
Principal Planes  :        -0.089727         -0.107211
Nodal Planes      :        -0.089727         -0.107211
Focal Planes      :         0.071944         -0.268882
Anti-Nodal Planes :         0.233615         -0.430553

W = 2.500000
Principal Planes  :        -0.089785         -0.107330
Nodal Planes      :        -0.089785         -0.107330
Focal Planes      :         0.072153         -0.269268
Anti-Nodal Planes :         0.234092         -0.431207

W = 3.700000
Principal Planes  :        -0.090173         -0.108136
Nodal Planes      :        -0.090173         -0.108136
Focal Planes      :         0.073456         -0.271765
Anti-Nodal Planes :         0.237086         -0.435395

W = 5.000000
Principal Planes  :        -0.090590         -0.108811
Nodal Planes      :        -0.090590         -0.108811
Focal Planes      :         0.075171         -0.274572
Anti-Nodal Planes :         0.240932         -0.440333
```

Back-end

Merit Funciton

Merit Function Listing

File : \\Betelgeuse\c\CALUNIT\ZEMAX\Cubacktl2.ZMX
Title: Cal Unit : Section #2, tolerance analysis
Date : FRI OCT 31 1997

Merit Function Value: 0.00000000E+000

Num	Type	Int1	Int2	Hx	Hy	Px	Py	Target	Weight	Value	% Cont
1	REAY	35	1	0.0000	0.0000	0.0000	1.0000	0.00000E+000	0	1.33816E-002	0.000
2	REAY	35	1	1.0000	0.0000	0.0000	1.0000	0.00000E+000	0	1.33580E-002	0.000
3	REAY	35	1	-1.0000	0.0000	0.0000	1.0000	0.00000E+000	0	1.33580E-002	0.000
4	REAY	35	1	0.0000	1.0000	0.0000	1.0000	0.00000E+000	0	1.30858E-002	0.000
5	REAY	35	1	0.0000	-1.0000	0.0000	1.0000	0.00000E+000	0	1.35865E-002	0.000
6	REAY	35	4	0.0000	0.0000	0.0000	1.0000	0.00000E+000	0	1.33473E-002	0.000
7	REAY	35	4	1.0000	0.0000	0.0000	1.0000	0.00000E+000	0	1.33059E-002	0.000
8	REAY	35	4	-1.0000	0.0000	0.0000	1.0000	0.00000E+000	0	1.33059E-002	0.000
9	REAY	35	4	0.0000	1.0000	0.0000	1.0000	0.00000E+000	0	1.32669E-002	0.000
10	REAY	35	4	0.0000	-1.0000	0.0000	1.0000	0.00000E+000	0	1.31424E-002	0.000
11	CONS							1.33779E-002	0	1.33779E-002	0.000
12	DIFF	1	11					0.00000E+000	0	3.70666E-006	0.000
13	DIFF	2	11					0.00000E+000	0	-1.98959E-005	0.000
14	DIFF	3	11					0.00000E+000	0	-1.98959E-005	0.000
15	DIFF	4	11					0.00000E+000	0	-2.92087E-004	0.000
16	DIFF	5	11					0.00000E+000	0	2.08604E-004	0.000
17	DIFF	6	11					0.00000E+000	0	-3.06129E-005	0.000
18	DIFF	7	11					0.00000E+000	0	-7.19782E-005	0.000
19	DIFF	8	11					0.00000E+000	0	-7.19782E-005	0.000
20	DIFF	9	11					0.00000E+000	0	-1.10955E-004	0.000
21	DIFF	10	11					0.00000E+000	0	-2.35519E-004	0.000
22	EQUA	12	21					0.00000E+000	0	9.24423E-004	0.000
23	CONS							1.00000E+001	0	1.00000E+001	0.000
24	DIVI	22	23					0.00000E+000	0	9.24423E-005	0.000
25	DIVI	24	11					0.00000E+000	0	6.91008E-003	0.000
26	CONS							1.00000E+002	0	1.00000E+002	0.000
27	PROD	25	26					0.00000E+000	0	6.91008E-001	0.000
28	CONS							2.00000E+000	0	2.00000E+000	0.000
29	DIVI	27	28					0.00000E+000	0	3.45504E-001	0.000
30	OPLT	29						1.00000E+000	1	1.00000E+000	0.000
31	RWCE	5	4	0.0000	0.0000			0.00000E+000	0	8.06255E-002	0.000
32	RWCE	5	4	1.0000	0.0000			0.00000E+000	0	9.21067E-002	0.000
33	RWCE	5	4	-1.0000	0.0000			0.00000E+000	0	9.21067E-002	0.000
34	RWCE	5	4	0.0000	1.0000			0.00000E+000	0	9.06786E-002	0.000
35	RWCE	5	4	0.0000	-1.0000			0.00000E+000	0	9.38193E-002	0.000
36	EQUA	31	35					1.20000E-001	0	1.20000E-001	0.000
37	CONS							1.20000E-001	0	1.20000E-001	0.000
38	DIFF	36	37					0.00000E+000	0	0.00000E+000	0.000
39	DIVI	38	37					0.00000E+000	0	0.00000E+000	0.000
40	CONS							1.00000E+002	0	1.00000E+002	0.000
41	PROD	40	39					0.00000E+000	0	0.00000E+000	0.000
42	OPLT	41						1.00000E+000	1	1.00000E+000	0.000

Back-end

Tolerance Listing

Tolerance Data Listing - before running inverse sensitivity

File : \\Betelgeuse\c\CALUNIT\ZEMAX\Cubacktl2.ZMX
Title: Cal Unit : Section #2, tolerance analysis
Date : THU OCT 30 1997

Num	Type	Int1	Int2	Min	Max
1	(COMP)	7	0	-5.00000E-003	5.00000E-003
2	(TTHI)	0	0	-3.00000E-003	3.00000E-003
3	(TTHI)	2	2	-3.00000E-003	3.00000E-003
4	(TTHI)	4	4	-3.00000E-003	3.00000E-003
5	(TTHI)	6	6	-3.00000E-003	3.00000E-003
6	(TTHI)	7	7	-3.00000E-003	3.00000E-003
7	(TTHI)	10	10	-3.00000E-003	3.00000E-003
8	(TTHI)	12	12	-3.00000E-003	3.00000E-003
9	(TTHI)	14	14	-3.00000E-003	3.00000E-003
10	(TETX)	1	2	-5.00000E-001	5.00000E-001
11	(TETX)	3	4	-5.00000E-001	5.00000E-001
12	(TETX)	5	6	-5.00000E-001	5.00000E-001
13	(TETX)	9	10	-5.00000E-001	5.00000E-001
14	(TETX)	11	12	-5.00000E-001	5.00000E-001
15	(TETX)	13	14	-5.00000E-001	5.00000E-001
16	(TEDX)	1	2	-3.00000E-003	3.00000E-003
17	(TEDX)	3	4	-3.00000E-003	3.00000E-003
18	(TEDX)	5	6	-3.00000E-003	3.00000E-003
19	(TEDX)	9	10	-3.00000E-003	3.00000E-003
20	(TEDX)	11	12	-3.00000E-003	3.00000E-003
21	(TEDX)	13	14	-3.00000E-003	3.00000E-003
22	(TETY)	1	2	-5.00000E-001	5.00000E-001
23	(TETY)	3	4	-5.00000E-001	5.00000E-001
24	(TETY)	5	6	-5.00000E-001	5.00000E-001
25	(TETY)	9	10	-5.00000E-001	5.00000E-001
26	(TETY)	11	12	-5.00000E-001	5.00000E-001
27	(TETY)	13	14	-5.00000E-001	5.00000E-001
28	(TEDY)	1	2	-3.00000E-003	3.00000E-003
29	(TEDY)	3	4	-3.00000E-003	3.00000E-003
30	(TEDY)	5	6	-3.00000E-003	3.00000E-003
31	(TEDY)	9	10	-3.00000E-003	3.00000E-003
32	(TEDY)	11	12	-3.00000E-003	3.00000E-003
33	(TEDY)	13	14	-3.00000E-003	3.00000E-003

Tolerance Data Listing - after running inverse sensitivity

File : \\Betelgeuse\c\CALUNIT\ZEMAX\Cubacktl2.ZMX
Title: Cal Unit : Section #2, tolerance analysis
Date : FRI OCT 31 1997

Num	Type	Int1	Int2	Min	Max
1	(COMP)	7	0	-5.00000E-003	5.00000E-003
2	(TTHI)	0	0	-3.00000E-003	3.00000E-003
3	(TTHI)	2	2	-3.00000E-003	3.00000E-003
4	(TTHI)	4	4	-7.53251E-004	3.77182E-004
5	(TTHI)	6	6	-3.00000E-003	3.00000E-003
6	(TTHI)	7	7	-3.00000E-003	3.00000E-003
7	(TTHI)	10	10	-3.00000E-003	7.81141E-004
8	(TTHI)	12	12	-1.96551E-003	1.50031E-003
9	(TTHI)	14	14	-3.00000E-003	3.00000E-003
10	(TETX)	1	2	-5.00000E-001	5.00000E-001
11	(TETX)	3	4	-5.00000E-001	2.50060E-001
12	(TETX)	5	6	-5.00000E-001	5.00000E-001
13	(TETX)	9	10	-5.00000E-001	5.00000E-001
14	(TETX)	11	12	-2.50052E-001	2.55499E-001
15	(TETX)	13	14	-5.00000E-001	5.00000E-001
16	(TEDX)	1	2	-3.00000E-003	3.00000E-003
17	(TEDX)	3	4	-1.87514E-004	1.87514E-004
18	(TEDX)	5	6	-1.87528E-004	1.87528E-004
19	(TEDX)	9	10	-3.75072E-004	7.50051E-004
20	(TEDX)	11	12	-1.87514E-004	1.87514E-004
21	(TEDX)	13	14	-1.87536E-004	1.87520E-004

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22 (TETY)    1    2 -5.00000E-001  5.00000E-001
23 (TETY)    3    4 -5.00000E-001  5.00000E-001
24 (TETY)    5    6 -5.00000E-001  5.00000E-001
25 (TETY)    9   10 -5.00000E-001  5.00000E-001
26 (TETY)   11   12 -5.00000E-001  5.00000E-001
27 (TETY)   13   14 -5.00000E-001  5.00000E-001
28 (TEDY)    1    2 -3.00000E-003  3.00000E-003
29 (TEDY)    3    4 -9.37701E-005  1.87516E-004
30 (TEDY)    5    6 -1.87520E-004  1.87523E-004
31 (TEDY)    9   10 -3.75071E-004  7.50058E-004
32 (TEDY)   11   12 -1.87528E-004  9.64735E-005
33 (TEDY)   13   14 -1.87511E-004  1.87539E-004
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Tolerance Output

Analysis of Tolerances


File : \\Betelgeuse\c\CALUNIT\ZEMAX\Cubacktl2.ZMX
Title: Cal Unit :  Section #2, tolerance analysis
Date : FRI OCT 31 1997


Units are Meters.
Element tilts are in degrees; surface tilts are in fringes.


Mnemonics:
TRAD: Tolerance on radius of curvature.
TCUR: Tolerance on curvature (inverse length).
TFRN: Tolerance on curvature in fringes.
TTHI: Tolerance on thickness.
TCON: Tolerance on conic.
TSDX: Tolerance on surface decentering in x.
TSDY: Tolerance on surface decentering in y.
TSTX: Tolerance on surface tilt in x (fringes).
TSTY: Tolerance on surface tilt in y (fringes).
TIRX: Tolerance on surface total indicator runout in x.
TIRY: Tolerance on surface total indicator runout in y.
TIRR: Tolerance on irregularity (fringes).
TIND: Tolerance on index of refraction.
TPAR: Tolerance on parameter.
TEDV: Tolerance on extra data value.
TEDX: Tolerance on element decentering in x.
TEDY: Tolerance on element decentering in y.
TETX: Tolerance on element tilt in x (degrees).
TETY: Tolerance on element tilt in y (degrees).
TUDX: Tolerance on user surface decentering in x.
TUDY: Tolerance on user surface decentering in y.
TUTX: Tolerance on user surface tilt (degrees) around the x-axis.
TUTY: Tolerance on user surface tilt (degrees) around the y-axis.
TUTZ: Tolerance on user surface tilt (degrees) around the z-axis.


Compensator: Thickness 7, Min = -0.0050, Max = 0.0050
Mode: Inverse Sensitivities
Maximum Merit Value is 0.00100000
Merit: User defined merit function


Nominal Merit Function (MF) is 0.00000000



Fields: User Defined Object height in Meters
  #     X-Field       Y-Field       Weight     VDX     VDY     VCX     VCY
  1   0.000E+000    0.000E+000    1.000E+000   0.000   0.000   0.000   0.000
  2   0.000E+000    6.924E-003    1.000E+000   0.000   0.000   0.000   0.000
  3   0.000E+000   -6.924E-003    1.000E+000   0.000   0.000   0.000   0.000
  4   6.920E-003    0.000E+000    1.000E+000   0.000   0.000   0.000   0.000
  5  -6.920E-003    0.000E+000    1.000E+000   0.000   0.000   0.000   0.000


Sensitivity Analysis:

              |------------ Minimum ------------|  |------------ Maximum ------------|
Type Sf1 Sf2        Value        MF        Change        Value        MF        Change
Thickness tolerance on surface 0
TTHI   0   0   -0.003000    0.000000    0.000000    0.003000    0.000000    0.000000
 Thickness    7:                     1.12920E-001                     1.12920E-001
Thickness tolerance on surface 2
TTHI   2   2   -0.003000    0.000000    0.000000    0.003000    0.000000    0.000000
 Thickness    7:                     1.12920E-001                     1.12920E-001
Thickness tolerance on surface 4
TTHI   4   4   -0.000753    0.000000    0.000000    0.000377    0.000000    0.000000
 Thickness    7:                     1.12920E-001                     1.12920E-001
Thickness tolerance on surface 6
TTHI   6   6   -0.003000    0.000000    0.000000    0.003000    0.000000    0.000000
 Thickness    7:                     1.12920E-001                     1.12920E-001
Thickness tolerance on surface 7
TTHI   7   7   -0.003000    0.000000    0.000000    0.003000    0.000000    0.000000
 Thickness    7:                     1.10615E-001                     1.14451E-001
Thickness tolerance on surface 10
TTHI  10  10   -0.003000    0.000000    0.000000    0.000781    0.000000    0.000000
 Thickness    7:                     1.12920E-001                     1.12920E-001
```

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Thickness tolerance on surface 12
TTHI  12  12   -0.001966   0.000000   0.000000   0.001500   0.000000   0.000000
  Thickness     7:                    1.13634E-001                    1.12573E-001
Thickness tolerance on surface 14
TTHI  14  14   -0.003000   0.000000   0.000000   0.003000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Tilt X tolerance on surfaces 1 through 2 (degrees)
TETX   1   2   -0.500000   0.000000   0.000000   0.500000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Tilt X tolerance on surfaces 3 through 4 (degrees)
TETX   3   4   -0.500000   0.000000   0.000000   0.250060   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Tilt X tolerance on surfaces 5 through 6 (degrees)
TETX   5   6   -0.500000   0.000000   0.000000   0.500000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Tilt X tolerance on surfaces 9 through 10 (degrees)
TETX   9  10   -0.500000   0.000000   0.000000   0.500000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Tilt X tolerance on surfaces 11 through 12 (degrees)
TETX  11  12   -0.250052   0.000000   0.000000   0.255499   0.000000   0.000000
  Thickness     7:                    1.11189E-001                    1.12920E-001
Tilt X tolerance on surfaces 13 through 14 (degrees)
TETX  13  14   -0.500000   0.000000   0.000000   0.500000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Decenter X tolerance on surfaces 1 through 2
TEDX   1   2   -0.003000   0.000000   0.000000   0.003000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Decenter X tolerance on surfaces 3 through 4
TEDX   3   4   -0.000188   0.000000   0.000000   0.000188   0.000000   0.000000
  Thickness     7:                    1.11789E-001                    1.12920E-001
Decenter X tolerance on surfaces 5 through 6
TEDX   5   6   -0.000188   0.000000   0.000000   0.000188   0.000000   0.000000
  Thickness     7:                    1.12509E-001                    1.12920E-001
Decenter X tolerance on surfaces 9 through 10
TEDX   9  10   -0.000375   0.000000   0.000000   0.000750   0.000000   0.000000
  Thickness     7:                    1.10734E-001                    1.12920E-001
Decenter X tolerance on surfaces 11 through 12
TEDX  11  12   -0.000188   0.000000   0.000000   0.000188   0.000000   0.000000
  Thickness     7:                    1.13114E-001                    1.12920E-001
Decenter X tolerance on surfaces 13 through 14
TEDX  13  14   -0.000188   0.000000   0.000000   0.000188   0.000000   0.000000
  Thickness     7:                    1.12926E-001                    1.12920E-001
Tilt Y tolerance on surfaces 1 through 2 (degrees)
TETY   1   2   -0.500000   0.000000   0.000000   0.500000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Tilt Y tolerance on surfaces 3 through 4 (degrees)
TETY   3   4   -0.500000   0.000000   0.000000   0.500000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Tilt Y tolerance on surfaces 5 through 6 (degrees)
TETY   5   6   -0.500000   0.000000   0.000000   0.500000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Tilt Y tolerance on surfaces 9 through 10 (degrees)
TETY   9  10   -0.500000   0.000000   0.000000   0.500000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Tilt Y tolerance on surfaces 11 through 12 (degrees)
TETY  11  12   -0.500000   0.000000   0.000000   0.500000   0.000000   0.000000
  Thickness     7:                    1.10854E-001                    1.10854E-001
Tilt Y tolerance on surfaces 13 through 14 (degrees)
TETY  13  14   -0.500000   0.000000   0.000000   0.500000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Decenter Y tolerance on surfaces 1 through 2
TEDY   1   2   -0.003000   0.000000   0.000000   0.003000   0.000000   0.000000
  Thickness     7:                    1.12920E-001                    1.12920E-001
Decenter Y tolerance on surfaces 3 through 4
TEDY   3   4   -0.000094   0.000000   0.000000   0.000188   0.000000   0.000000
  Thickness     7:                    1.10767E-001                    1.12920E-001
Decenter Y tolerance on surfaces 5 through 6
TEDY   5   6   -0.000188   0.000000   0.000000   0.000188   0.000000   0.000000
  Thickness     7:                    1.12207E-001                    1.12920E-001
Decenter Y tolerance on surfaces 9 through 10
TEDY   9  10   -0.000375   0.000000   0.000000   0.000750   0.000000   0.000000
  Thickness     7:                    1.10072E-001                    1.12920E-001
Decenter Y tolerance on surfaces 11 through 12
TEDY  11  12   -0.000188   0.000000   0.000000   0.000096   0.000000   0.000000
  Thickness     7:                    1.13124E-001                    1.12920E-001
Decenter Y tolerance on surfaces 13 through 14
TEDY  13  14   -0.000188   0.000000   0.000000   0.000188   0.000000   0.000000
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Thickness   7:                          1.11008E-001                          1.12920E-001

Worst offenders:
Type Sf1 Sf2      Value       MF         Change
TTHI  0   0  -0.003000   0.000000    0.000000
TTHI  0   0   0.003000   0.000000    0.000000
TTHI  2   2  -0.003000   0.000000    0.000000
TTHI  2   2   0.003000   0.000000    0.000000
TTHI  4   4  -0.000753   0.000000    0.000000
TTHI  4   4   0.000377   0.000000    0.000000
TTHI  6   6  -0.003000   0.000000    0.000000
TTHI  6   6   0.003000   0.000000    0.000000
TTHI  7   7  -0.003000   0.000000    0.000000
TTHI  7   7   0.003000   0.000000    0.000000


Nominal Merit Function  :      0.000000
Estimated change        :      0.000000
Estimated Merit Function :     0.000000

Merit Statistics:
Mean                :       0.000000
Standard Deviation :       0.000000

Compensator Statistics:
Thickness Surf 7:
Nominal             :       0.112920
Minimum             :       0.110072
Maximum             :       0.114451
Mean                :       0.112651
Standard Deviation :       0.000775



Monte Carlo Analysis:
Number of trials: 20

The Monte Carlo analysis includes the following tolerances:
TRAD TCUR TFRN TTHI TCON
TSDX TSDY TSTX TSTY TIRR
TEDV TPAR TIND TIRX TIRY
TUDX TUDY TUTX TUTY TUTZ
TEDX TEDY TETX TETY

Statistics: Normal Distribution

  Trial      Merit       Change
     1   0.000000    0.000000
 Thickness   7:                          1.14344E-001
     2   1.450338    1.450338
 Thickness   7:                          1.06171E-001
     3  89.258271   89.258271
 Thickness   7:                          9.54871E-002
     4  93.919404   93.919404
 Thickness   7:                          8.29197E-002
     5   0.000000    0.000000
 Thickness   7:                          1.11611E-001
     6   0.000000    0.000000
 Thickness   7:                          1.13828E-001
     7   4.068062    4.068062
 Thickness   7:                          9.70921E-002
     8  175.163736  175.163736
 Thickness   7:                          1.30829E-001
     9   0.000000    0.000000
 Thickness   7:                          1.10393E-001
    10   9.508243    9.508243
 Thickness   7:                          8.02363E-002
    11   0.000000    0.000000
 Thickness   7:                          1.13824E-001
    12   0.000000    0.000000
 Thickness   7:                          1.12659E-001
    13   0.580415    0.580415
 Thickness   7:                          1.09040E-001
    14   0.000000    0.000000
 Thickness   7:                          1.12426E-001
    15   2.125131    2.125131
 Thickness   7:                          1.06666E-001
    16   5.536834    5.536834
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Thickness    7:                        9.36499E-002
    17   3.906879    3.906879
Thickness    7:                        9.84341E-002
    18   0.000000    0.000000
Thickness    7:                        1.13478E-001
    19   2.503249    2.503249
Thickness    7:                        1.04105E-001
    20   0.000000    0.000000
Thickness    7:                        1.14083E-001


Nominal    0.000000
Best       0.000000
Worst    175.163736
Mean      19.401028
Std Dev   44.781876

Compensator Statistics:
Thickness Surf 7:
Nominal             :          0.112920
Minimum             :          0.080236
Maximum             :          0.130829
Mean                :          0.106064
Standard Deviation  :          0.011566


90% of Monte Carlo lenses have a merit function below 89.258271.
50% of Monte Carlo lenses have a merit function below 0.580415.
10% of Monte Carlo lenses have a merit function below 0.000000.

End of Run.
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