Design for a new Prime Focus Corrector on the Wyoming InfraRed Observatory (WIRO) 2.3 m Telescope

Final Pre-fabrication design of 12 January, 2004

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Overview

This document describes the specifications for the fabrication of a new prime focus corrector for the 2.3 m f/2.03 Wyoming Infrared Observatory (WIRO) telescope on Mt. Jelm. This WIRO Prime Focus Corrector (WIROPFC) will consist of 4 fused silica lenses in a common mount. It will greatly enhance the capabilities of the telescope by enabling imaging over wide fields of view with modern optical detectors while preserving the capability for infrared imaging as well. The plate scale at the f/2.1 focus is 44”/mm or 0.044”/micron. Modern optical arrays such as the current WIRO Marconi 2k x 2k CCD have 13.5 micron pixels and focal planes which are 27.6 mm on a side, resulting in a 20.5' field of view. A future upgrade to a 4kx4k detector will yield a 41' field of view for the same pixel size. WIROPFC must correct the abberations from the parabolic primary (mostly coma) over at least this 40' field of view (field angles of up to 20' in X and Y), and must have excellent transmissivity over a broad wavelength range from the blue wavelength limit of optical CCDs near 0.37 microns to the red wavelength limit of CCDs near 1.0 microns. We also wish to preserve future prime focus imaging ability in the near infrared (1.0 - 1.6 microns), so the corrector should produce reasonable images and allow high throughput at these wavelengths. This consideration requires that the lenses be made from fused silica, the least expensive option for high IR transmissivity.

WIROPFC must deliver an intrinsic point source spot size which is small compared to the typical seeing disk at the Mt Jelm site. For these purposes, we have set the design goals such that the mean field-averaged RMS spot size radius delivered by WIROPFC should ideally be smaller than 5 microns, i.e., less than half of 10 microns, which is the RMS radius of the typical 1” FWHM (σ=FWHM/2.35=0.42”= 9.5 micron) seeing at optical wavelengths. The best design described in this document produces images comparable to the 1” seeing at most wavelengths and field angles, although better images may be obtained over a restricted field of view and for particular wavelengths by tuning the focus.

Section I of this document describes the preliminary design and performance for WIROPFC.

Section II of this document includes detailed manufacturing specifications intended as a request for quote (RFQ) from fabricators. The manufacturing process is divided into three distinct jobs.

Job	Tentative Vendor Selected
A. silica lens blanks	W. David Navan, Corning Inc., 334 County Rt. 16, Canton NY, 14831 ph: 315-379-3661 fax: 315-379-3317
B. Spherical Lens fabrication/coating	Harold Johnson Optical Labs, 1826 W. 169th St., Gardena, CA, 90247 ph: 310-327-3051 fax: 310-327-6179
C. Opto-mechanical design/mounting	J. Alan Schier/The Pilot Group, 128 W. Walnut Ave, Unit C. Monrovia, CA 91016 ph: 626-599-9422

I. WIROPFC Design

A. Optical material

The design for WIROPFC was performed in the ZEMAX software. Fused silica was chosen as the glass due its high transmissivity across the entire wavelength range of operation. Figure 1 below shows a typical transmissivity curve for fused silica, including 3-4% reflectivity losses at each surface reflectivity losses. Actual transmission values will be provided by vendors.

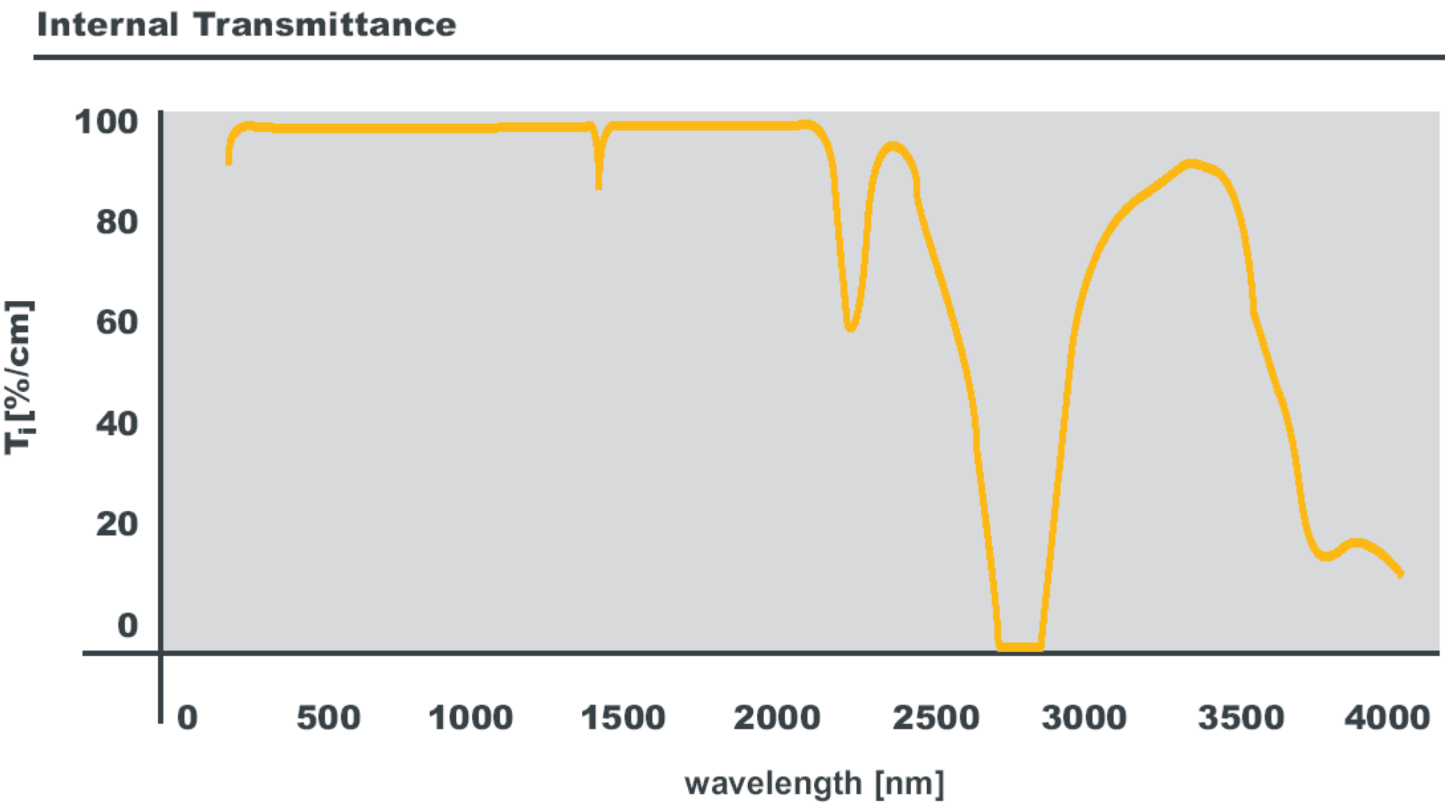


Figure 1: Transmissivity of Fused silica (from Corning)

B. Optical Configuration

Initially, we searched for all-spherical 4-element design based on the existing 4-element Wynn derivative corrector now at WIRO. A ZEMAX optimization was performed to find an initial lens design that minimized the RMS spot size at wavelengths of 0.37 um, 0.55 um, 1.0 um, at six field angles of 0 degrees, 7' (i.e., 5' in X and Y), 14' (10' in XY), 17' (12' in XY), 20' (14' in XY), and 27' (19' in XY). For ease of manufacture and mounting, all lens surfaces were assumed to have spherical figures.

The design was optimized for minimum RMS spot radius subject to the additional merit function constraints that the minimum center glass thickness be 4 mm, the minimum glass thickness at the edge of the lens be 6 mm, the maximum glass thickness at the center of the lens be 25 mm, and the back focal distance be very close to 70 mm to allow for a filter wheel between the last surface and the detector.

The thickness, radius of curvature, and position of each surface, including the focal plane, was allowed to vary within the stated limits. A suitable configuration was found that produced a wavelength-averaged RMS spot size of 6.7 microns at most wavelengths averaged over the six field angles. Figure 2 below shows the 4-element design with a filter and dewar window also shown.

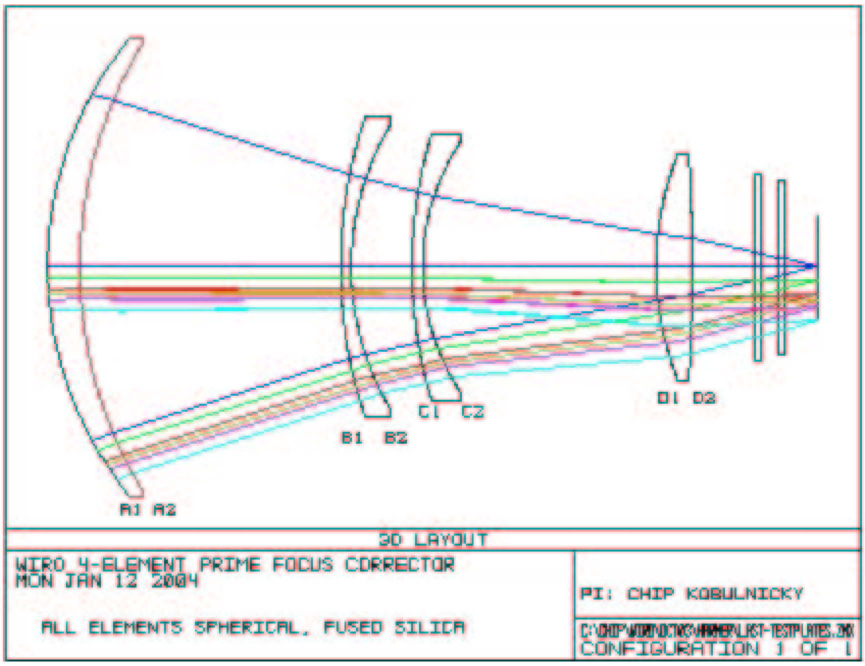


Figure 2: Schematic of the 3-element WIROPFC with filter, dewar window and focal plane shown.

Next, we searched for HJOL testplates matching the radii of spherical surfaces. Close matches were found for nearly all surfaces. After fixing the radii of curvature for these surfaces to the radii of the testplates, the design was reoptimized, allowing only the element thicknesses and the radii of D1 to vary. Surface D1 is designated as the pickup surface and will be custom fabricated and designed after the other 7 surfaces are completed. The full lens prescription is included in Appendix A. Table 1 below contains a summary of the lens prescription. **Bold text** in Table 1 indicates radii with existing testplates in the HJOL testplate list. Only surface D1 will require a custom testplate.

TABLE 1: SURFACE DATA SUMMARY (units in mm)

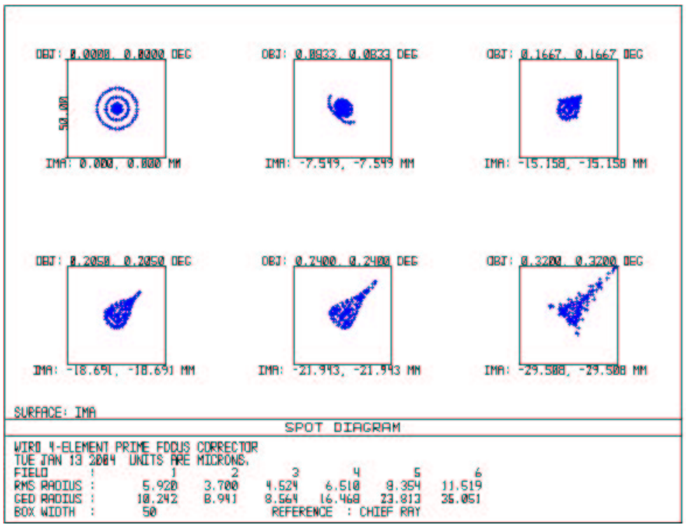
Surf	Shape	Radius	Thickness	material	Diam
A1	sphere	**193.675**	17.92	F_SILICA	248
A2	sphere	**230.861**	145.20	air	244
B1	sphere	**250.408**	6.00	F_SILICA	164
B2	sphere	**149.530**	33.71	air	156
C1	sphere	**245.900**	6.00	F_SILICA	146
C2	sphere	**120.650**	130.10	air	138
D1	sphere	165.677	20.00	F_SILICA	124
D2	sphere	**-949.123**		air	122

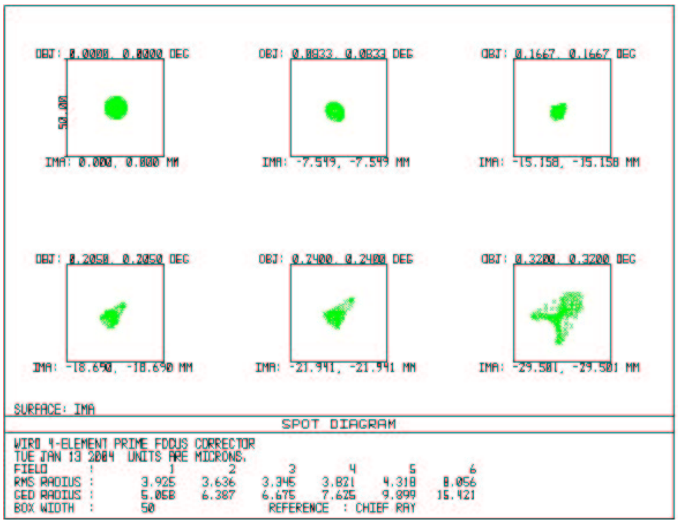
The mass of glass in all 4 elements is 2.98 kg.

C. Optical Performance

The panels of Figure 3 below show the spot diagrams for the WIROPFC at 4 field angles at 3 wavelengths: .37 microns, 0.55 microns, and 1.0 microns.   The size of the scale box is 50 microns or 2.2”.   The back focal distance is varied to minimize the spot size at each wavelength. In every case, the geometrical size of the image diameter fits within the nominal 50 micron (4 pixels for 13.5 micron pixels) box.

Figure 3: WIROPFC spot diagrams at 3 wavelengths. Six field angles are shown in each panel.





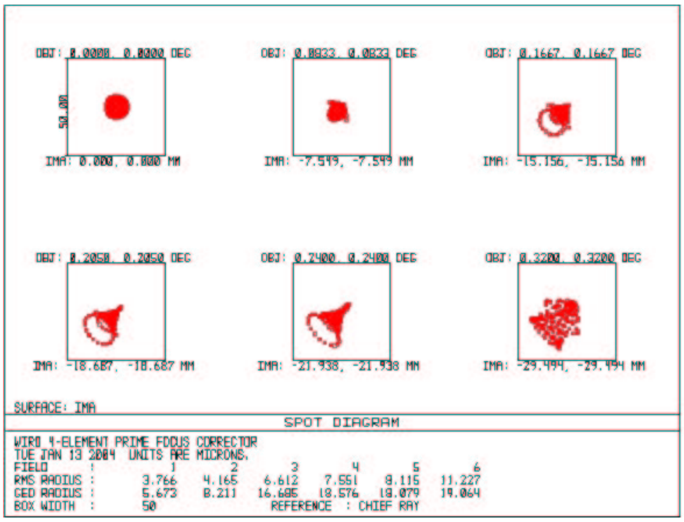


Figure 4 illustrates the encircled energy as a function of radius for each of the 6 field angles at 0.55 microns, 0.55 microns, and 1.0 microns with the new WIROPFC.

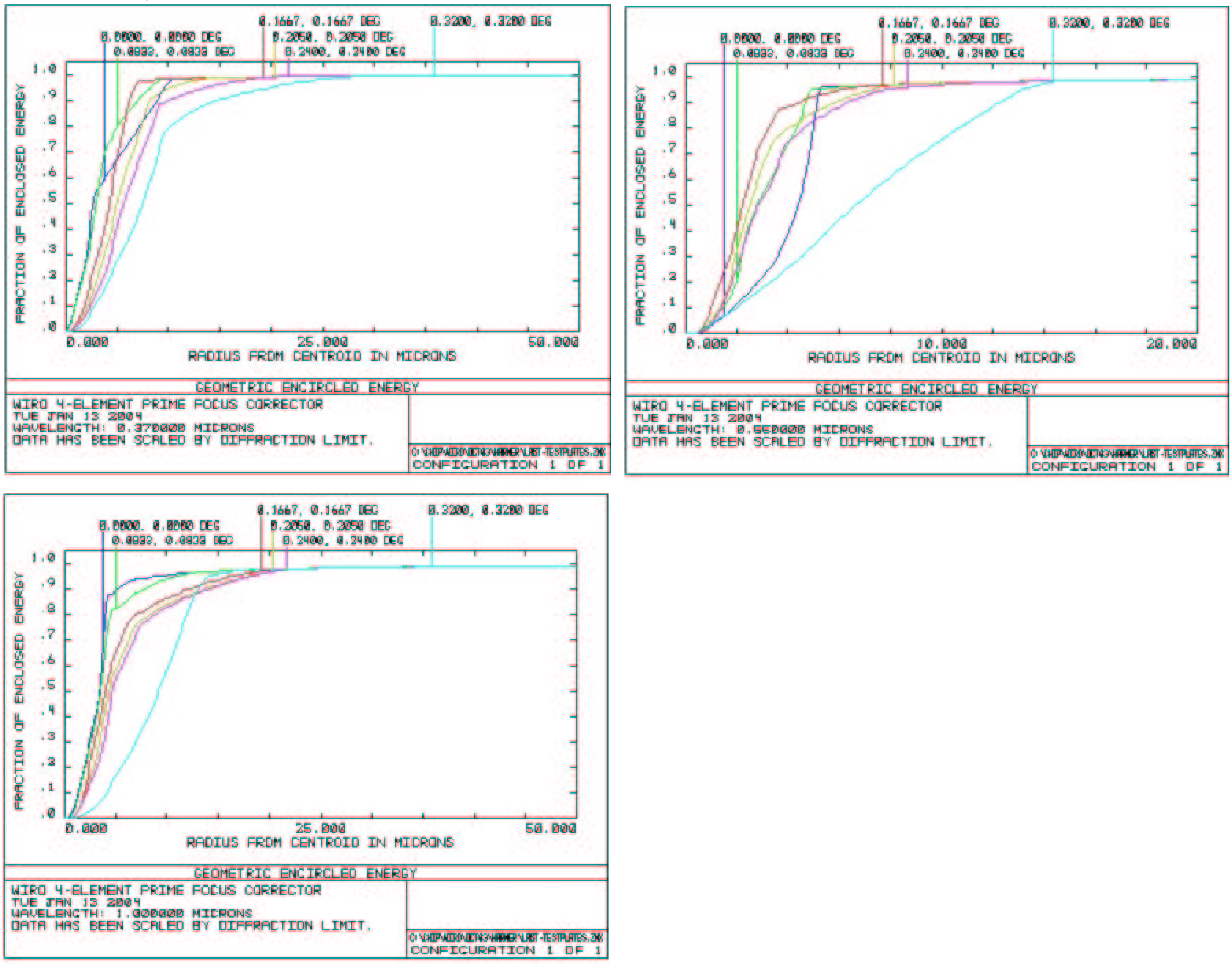


Figure 4: A comparison of the encircled energy at six field angles for 0.37 microns (upper left), 0.55 microns (right) and 1.0 microns (lower left).

Figure 5 shows a spot diagram through focus indicating minimal field curvature. The right panel shows the chromatic focal shift as a function of wavelength.

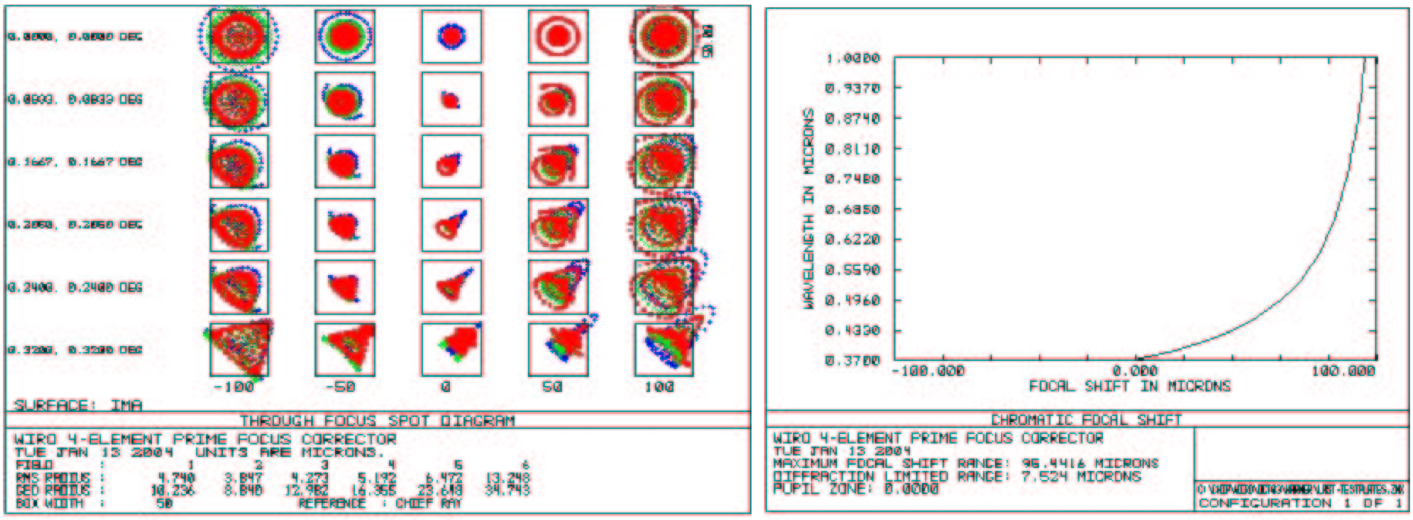


Figure 5: Spot diagrams through focus as a function of field angle (left) and chromatic focal shift (right).

Figure 6 shows the degree of field curvature (left) and distortion (plate scale change) across the field. There is a significant amount of barrel distortion, with a maximum of 1.0% at the edge of the field. Overall, however, the corrector has only a small amount of negative power, producing an image space focal number of 2.15 on axis and 2.19 at a maximum field angle of 28' (20' in X,Y), compared to the uncorrected prime focus which is f/2.03.

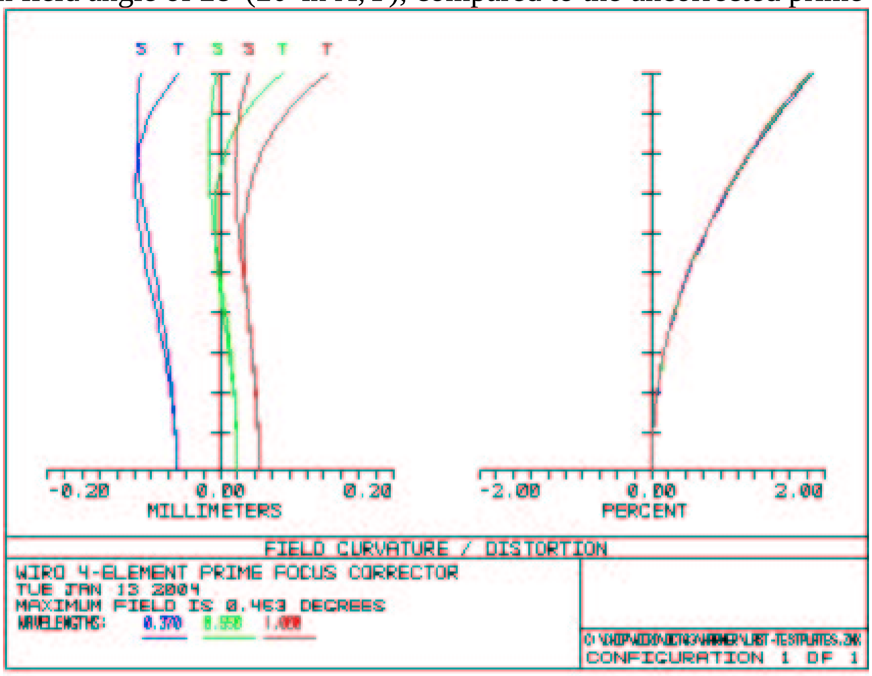


Figure 6: Field curvature (left) at three wavelengths and distortion (right) as a function of field distance.

D. Tolerance Analysis

In order to understand the effects of lens manufacturing and mounting errors on optical performance, a ZEMAX tolerancing analysis was performed. This is done by performing a Monte-Carlo simulations which varies the radii of curvature, tilt, and centering, and thickness of each lens surface within a user-specified range. In general, the maximum allowed deviations from design specs were set as follows, based on an understanding of the precision achievable with careful conventional machining techniques.

	Tolerance Type	***Default Tolerance***
TRAD	Tolerance on radius of curvature (mm)	0.1% of radius
TETX/Y	Tolerance on element tilt in X and Y	0.017 degrees = 1 arcmin
TEDX/Y	Tolerance on element decenter in X and Y	0.1 mm
TSDX/Y	Tolerance on surface decenter in X and Y	0.1 mm
TTHI	Tolerance on total thickness of a surface	0.1 mm
TIND	Tolerance on index of refraction variations	2.00E-005
TABBE	Tolerance on Abbe value	0.2

Only 1 surface, A1, requires more exacting manufacture in order that the RMS spot size not exceed the 9 micron radius expected from the site seeing. Optical performance was found to be particularly sensitive to the radius of curvature on the the surfaces of Lens A. To achieve acceptable imaging performance requires that the radius of curvature on surface A1 be accurate to 0.10 mm (0.05%).   In order to mitigate the restrictive tolerances on the radius of surfaces of surface A1, we allowed the radius of surface D1 to vary as a compensating factor. Surface D1 will be fabricated last.

Appendix B shows the tolerance report for the 0.55 micron wavelength. The notable results of this analysis are that the expected RMS spot size averaged over all fields and wavelengths based upon 40 Monte-Carlo simulations is 8.2 microns, i.e., 1.5 microns larger than the nominal error-free spot radius of 6.7 microns. This is still less than the RMS seeing radius of 9.6 microns (1”/2.35=0.42”) at optical wavelengths.

E. Thermal Sensitivity Analysis

WIROPFC must operate under a wide range of temperature conditions from 20 C, characteristic of manufacturing environments and warm summer evenings on Mt. Jelm, to -40 C, characteristic of cold winter nights, without performance degradation. Thermal expansion and contraction of the fused silica and mounting material must not introduce abberations other than defocus, which can be corrected by varying the back focal distance. The coefficient of thermal expansion (CTE) of fused silica is quite small at 0.51e-6. ZEMAX was used to perform a thermal analysis at temperatures of 20 C, 10 C, -15 C, and -40 C. In each case, the back focal distance is used compensate for defocus. Thermal analysis of the optical system mounted on an aluminum (CTE=23.5E-6) optical bench showed no significant spot size increase when the system temperature dropped below 0 C. Figure 7 below shows the spot diagrams at 20 C and -40 C when the mount is constructed of aluminum.

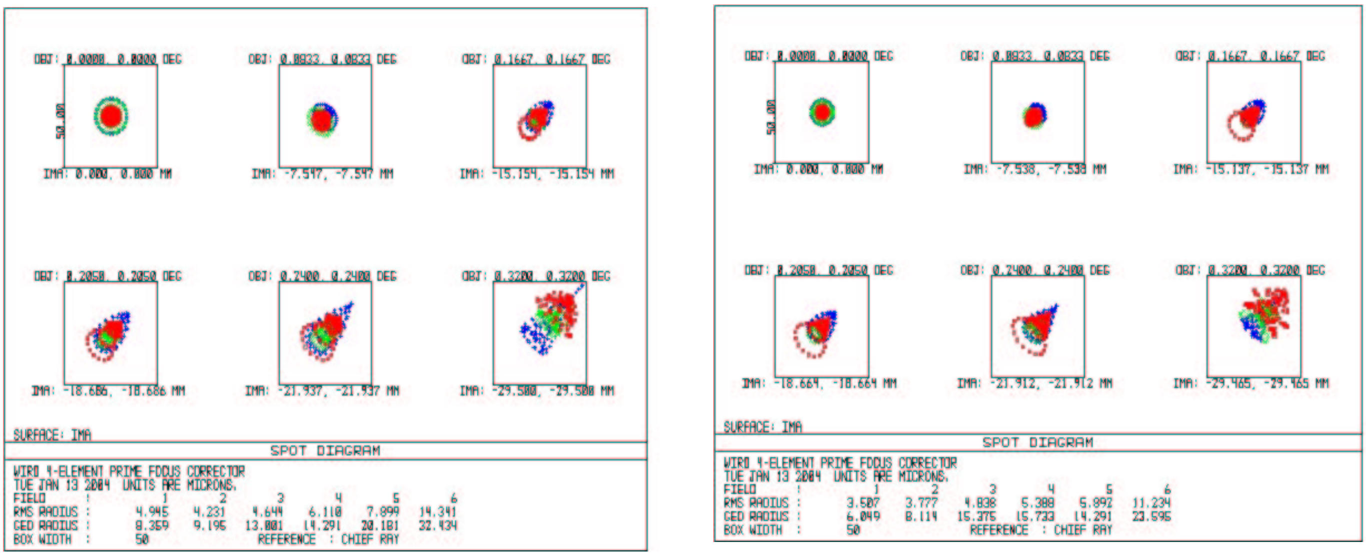


Figure 7: Comparison of spot size when at the design temperature of 20 C (left) versus operating at -40 C (right) when aluminum is used as the optical bench.

<u>Spot diagrams show only a marginal degredation over the range 20 C to -40 C, so we conclude that aluminum is a suitable material for the optical bench.</u>

F. Anti-reflection Coating Options

At each air-glass interface, the typical reflective loss is 3-4%. If left uncoated, the 8 air-glass interfaces in WIROPFC would reduce the efficiency of the entire optical system to 0.72. With anti-reflection coatings, the losses can be reduced to between 0% and 2% for each surface. If the reflectivity could be reduced to 2% per surface, the efficiency of WIROPFC would be 0.85.

Most anti-reflection coatings are effective over a limited range of wavelengths. There are several commonly-used types of anti-reflection coatings for astronomical applications. Magnesium Fluoride (MgF_2) has been a standard for many years because it is cheap and durable. More efficient alternatives (multi-layer and SolGel coatings) are both more expensive and more easily damaged. We have elected to use simple MgF_2 coatings optimized for minimal reflectivity at 0.45 microns.

G. Known Risks

No major risks known or reported initially by vendors.

II. Manufacturing Specifications for the WIRO Prime Focus Corrector

A. Fused Silica Blanks

These optical blanks will be used to construct a Prime Focus corrector for the Wyoming InfraRed Observatory 2.3 m telescope.

Material: Corning 7980 HPFS Standard Grade F2 fused silica: inclusion class 2 (<0.25 mm^2 per 100 cm^3 with maximum inclusion size 0.50 mm), index homogeneity class F (<5 ppm index variation over surface).

Fused silica optical blanks. Index (N_d): 1.458464+/-0.0002 Abbe (V_d): 67.8214 +/-0.2

Lens	*Diameter(mm)*	*Thickness (mm)*
A	255	59
B	170	34
C	152	34
D	128	25

OH content: < 100 ppm
All properties at 20 C.

Desired delivery timescale: flexible, but prefer 4 weeks.

B. Lens Fabrication and analysis

The optical blanks will either be supplied by the customer. The blanks will be oversized by 4 mm in thickness and 6 mm in diameter.

1. Fabricator will provide a finished optical elements meeting the physical specifications below. Fabricator will document the final surface figures on each surface.

2. Fabricator will work with the customer to make maximal use of existing test places and implement changes that the fabricator might suggest to facilitate production and mitigate problems. One surface out of the 8 surfaces will be designated as a pickup surface and be fabricated last to compensate for the final figures on the initial 7 surfaces. All surfaces are spherical. All dimensions are in mm. Physical properties are stated at 20 C.
3. Surface finish.
    a. Shape: spherical Pitch polish to test place within ±0.5 fringe at 555 nm. Document and report final figure.
    b. Radius tolerance: ±0.1% unless indicated. Document and report.
    c. Surface finish: 1 nm RMS or better. Document and report measured values.
    d. Diameter and thickness: ±0.1 mm unless otherwise indicated. Report to 0.05 mm.
    e. Wedge: <20 microns edge thickness difference
    f. Bevel edges 1mm at 45 deg: 1.4 mm max face width

C. Anti-reflection Coating

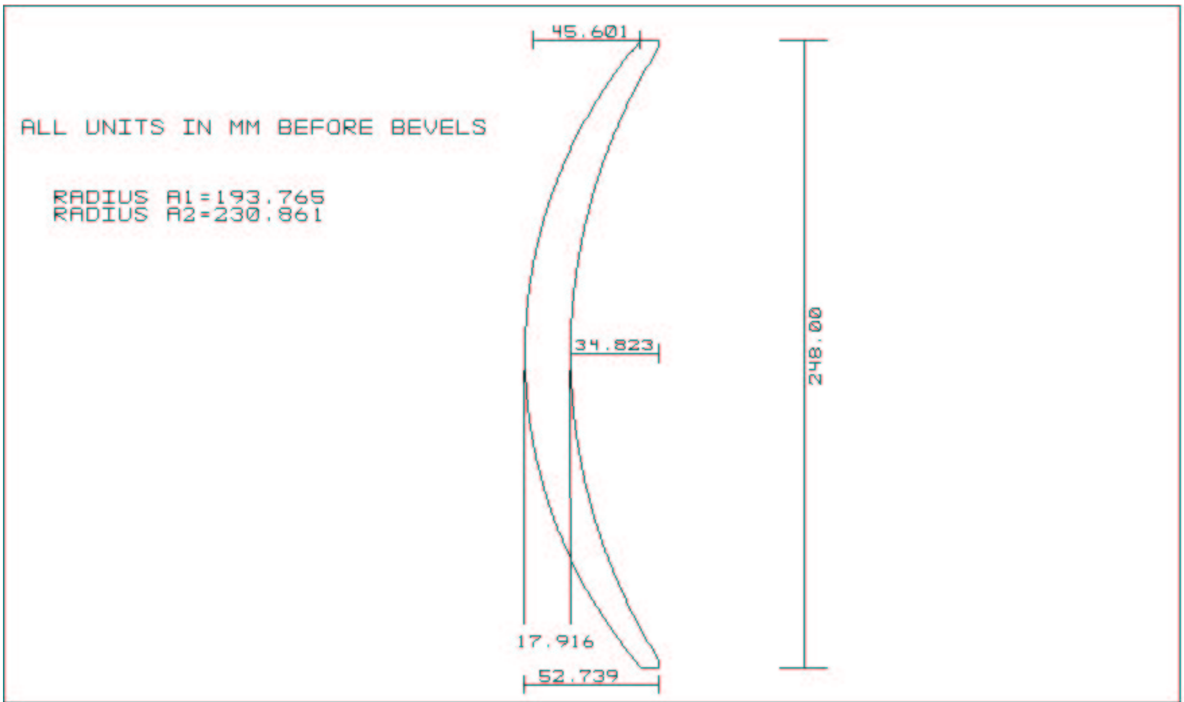
Vendor will provide a plot of transmissivity per surface over the wavelength range 0.37 microns to 1.0 microns. Vendor will document coating thickness and reflectivity across each element.

D. Opto-mechanical Mounting

Vendor will provide initial mechanical design and work with customer to arrive at final design. Vendor will fabricate assembly from aluminum or other specified material as agreed with customer, mount the elements, and document final tip/tilt, spacing, and centering achieved for each element.

E. Delivery timescale

Vendors will indicate delivery timescale for each job.

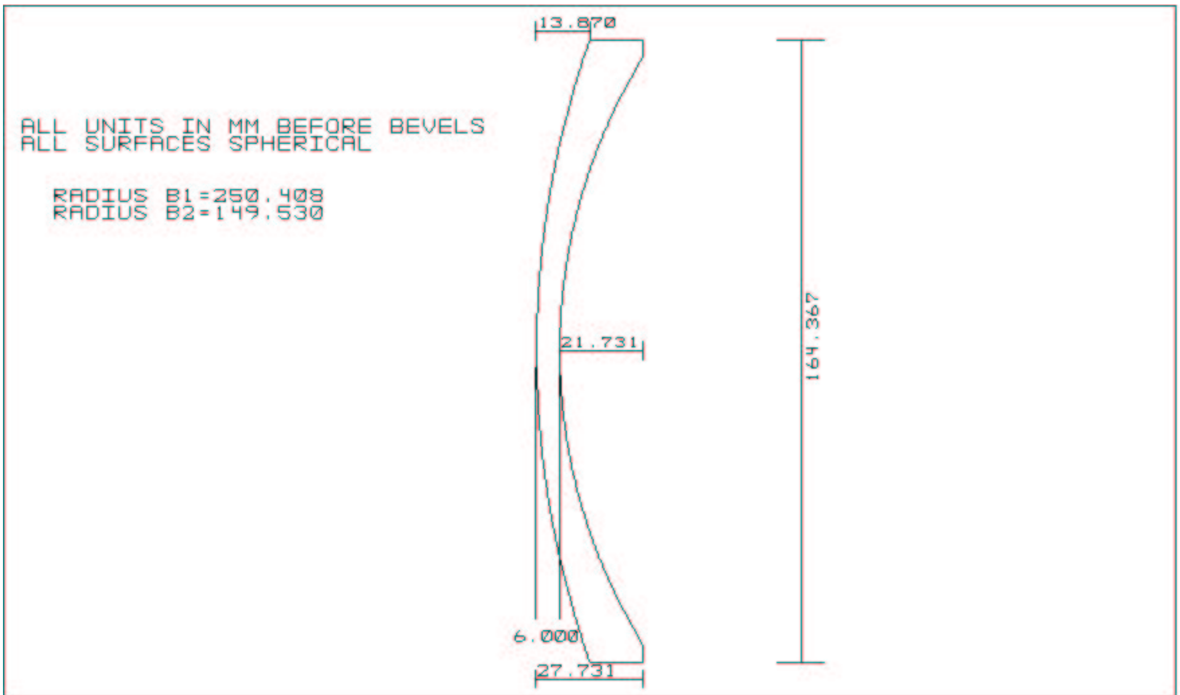


3D LAYOUT

WIRO 4-ELEMENT PRIME FOCUS CORRECTOR
MON MAR 1 2004

ELEMENT A - FUSED SILICA

C:\CHIP\WIRO\OCT03\HARMER\LAST-TESTPLATES_ELEMENTS.ZMX
CONFIGURATION 1 OF 1

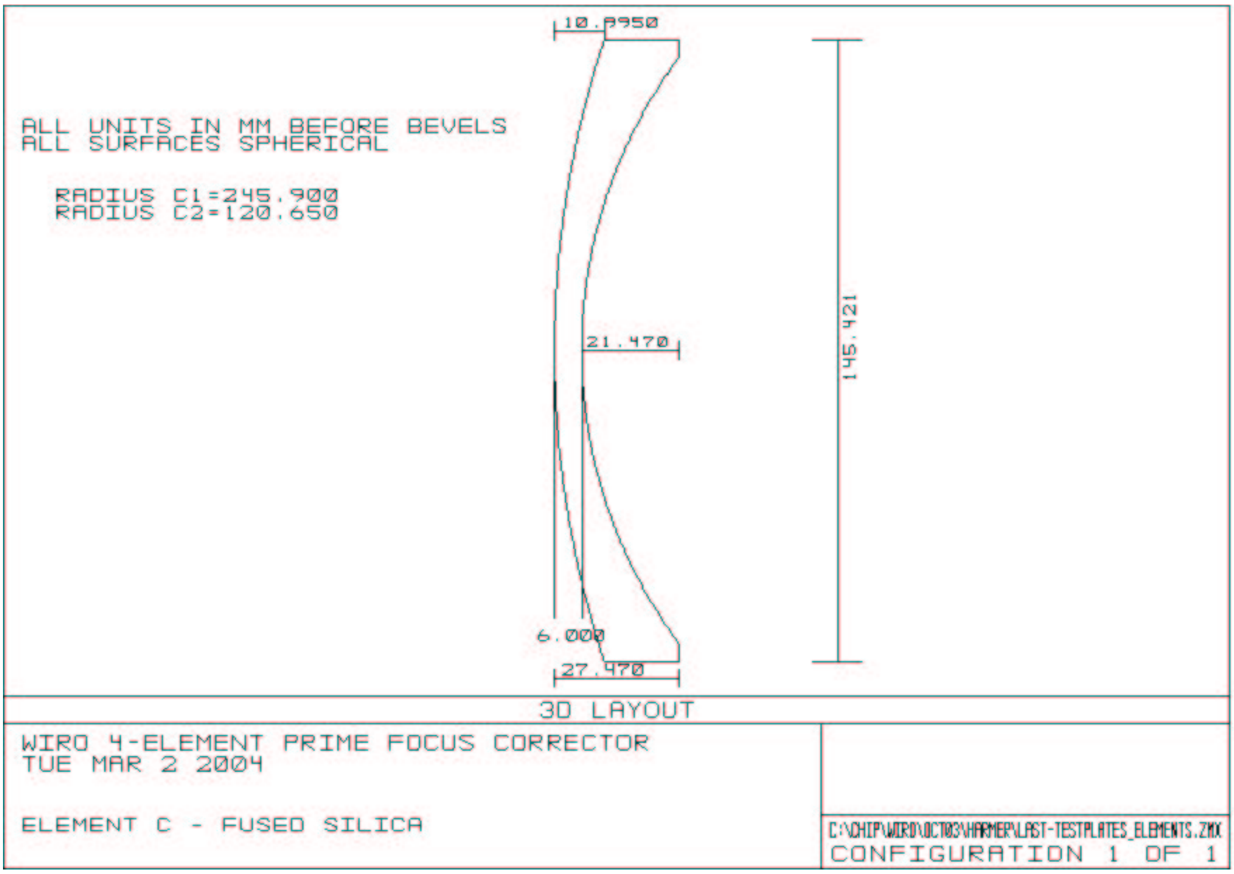


3D LAYOUT

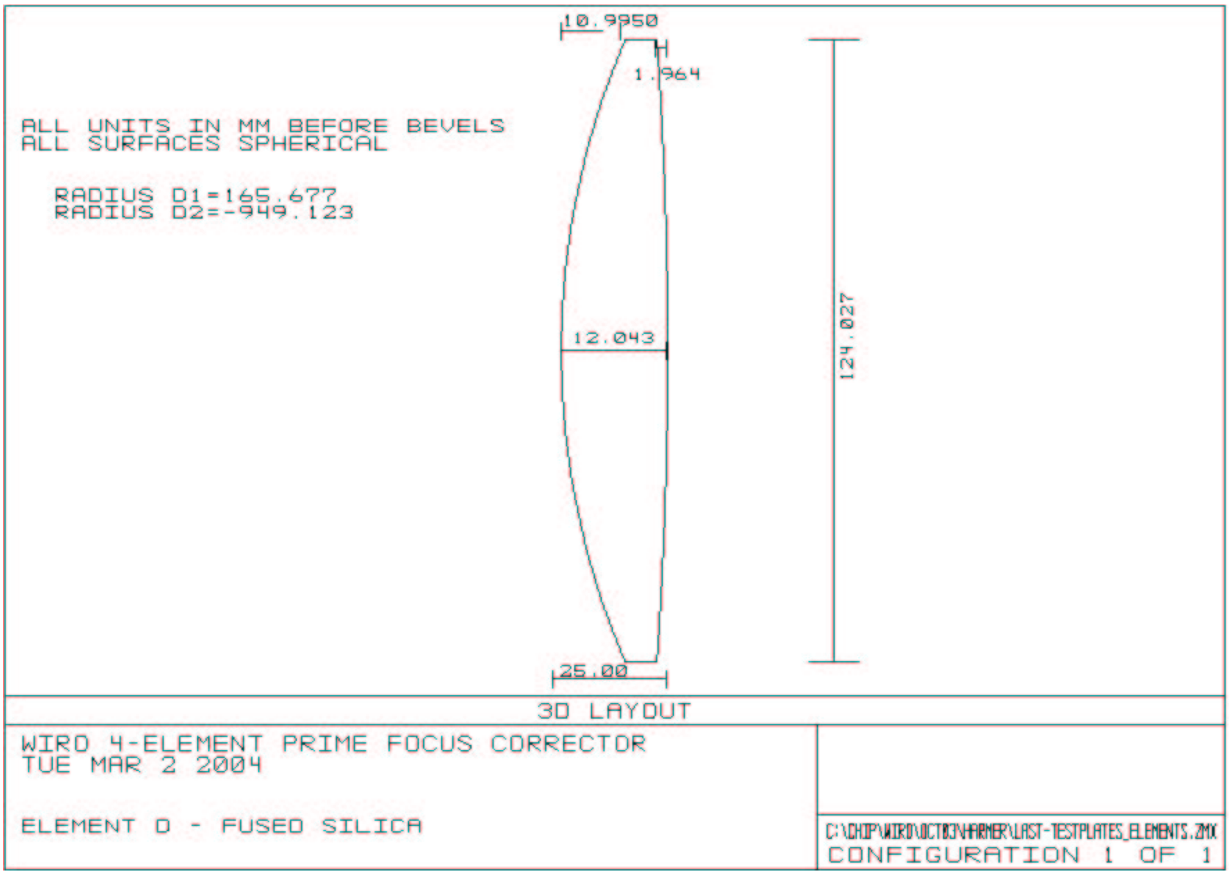
WIRO 4-ELEMENT PRIME FOCUS CORRECTOR
TUE MAR 2 2004

ELEMENT B - FUSED SILICA

C:\CHIP\WIRO\OCT03\HARMER\LAST-TESTPLATES_ELEMENTS.ZMX
CONFIGURATION 1 OF 1



ALL UNITS IN MM BEFORE BEVELS
ALL SURFACES SPHERICAL
RADIUS C1=245.900
RADIUS C2=120.650
10.9950
21.470
145.421
6.000
27.470
3D LAYOUT
WIRO 4-ELEMENT PRIME FOCUS CORRECTOR
TUE MAR 2 2004
ELEMENT C - FUSED SILICA
C:\CHIP\WIRO\OCT03\HARMER\LAST-TESTPLATES_ELEMENTS.ZMX
CONFIGURATION 1 OF 1



10.9950
1.964
ALL UNITS IN MM BEFORE BEVELS
ALL SURFACES SPHERICAL
RADIUS D1=165.677
RADIUS D2=-949.123
12.043
124.027
25.00
3D LAYOUT
WIRO 4-ELEMENT PRIME FOCUS CORRECTOR
TUE MAR 2 2004
ELEMENT D - FUSED SILICA
C:\CHIP\WIRO\OCT03\HARMER\LAST-TESTPLATES_ELEMENTS.ZMX
CONFIGURATION 1 OF 1

APPENDIX A: Lens Prescription

System/Prescription Data

File : C:\Chip\WIRO\Oct03\Harmer\Last-testplates.ZMX
Title: WIRO 4-element Prime Focus Corrector
Date : TUE JAN 13 2004

LENS NOTES:

PI: Chip Kobulnicky

GENERAL LENS DATA:

Surfaces	: 14
Stop	: 1
System Aperture	: Entrance Pupil Diameter = 2300
Glass Catalogs	: Schott OHARA INFRARED PFIS_0211
Ray Aiming	: Off
Apodization	:Uniform, factor = 0.00000E+000
Temperature (C)	: 2.00000E+001
Pressure (ATM)	: 1.00000E+000
Effective Focal Length	: -5186.469 (in air at system temperature and pressure)
Effective Focal Length	: -5186.469 (in image space)
Back Focal Length	: -19.05083
Total Track	: 4695.991
Image Space F/#	: 2.254987
Paraxial Working F/#	: 2.254987
Working F/#	: 2.254674
Image Space NA	: 0.2164733
Object Space NA	: 1.15e-007
Stop Radius	: 1150
Paraxial Image Height	: 40.96596
Paraxial Magnification	: 0
Entrance Pupil Diameter	: 2300
Entrance Pupil Position	: 0
Exit Pupil Diameter	: 335.7365
Exit Pupil Position	: 757.0304
Field Type	: Angle in degrees
Maximum Field	: 0.4525483
Primary Wave	: 0.37
Lens Units	: Millimeters
Angular Magnification	: 6.850611

Fields : 6
Field Type: Angle in degrees

#	X-Value	Y-Value	Weight
1	0.000000	0.000000	1.000000
2	0.083300	0.083300	1.000000
3	0.166670	0.166670	1.000000
4	0.205000	0.205000	1.000000
5	0.240000	0.240000	1.000000
6	0.320000	0.320000	1.000000

Vignetting Factors

#	VDX	VDY	VCX	VCY	VAN
1	0.000000	0.000000	0.000000	0.000000	0.000000
2	0.000000	0.000000	0.000000	0.000000	0.000000
3	0.000000	0.000000	0.000000	0.000000	0.000000
4	0.000000	0.000000	0.000000	0.000000	0.000000
5	0.000000	0.000000	0.000000	0.000000	0.000000
6	0.000000	0.000000	0.000000	0.000000	0.000000

Wavelengths : 3
Units: Microns

#	Value	Weight
1	0.370000	1.000000
2	0.550000	1.000000
3	1.000000	1.000000

SURFACE DATA SUMMARY:

Surf	Type	Comment	Radius	Thickness	Glass	Diameter	Conic
OBJ	STANDARD		Infinity	Infinity		0	
STO	STANDARD	PRIMARY	9340	4267.048	MIRROR	2300	-1
2	STANDARD	LENS1	193.675	17.91557	F_SILICA	249.672	
3	STANDARD		230.861	145.2021		243.8516	
4	STANDARD	LENSE2	250.408	6	F_SILICA	164.3676	
5	STANDARD		149.53	33.71835		155.2643	
6	STANDARD	LENS3	245.9	5.999998	F_SILICA	145.4206	
7	STANDARD		120.65	130.0982		137.4021	
8	STANDARD	LENS4	165.6778	20.00865	F_SILICA	124.0271	
9	STANDARD		-949.123	35		122.0849	
10	STANDARD	FILTER	Infinity	3	BK7	101.6	
11	STANDARD		Infinity	10		101.6	
12	STANDARD	WINDOW	Infinity	3	BK7	94.9856	
13	STANDARD		Infinity	19		93.92548	
IMA	STANDARD		Infinity			55.2	

SURFACE DATA DETAIL:

```
Surface OBJ     : STANDARD
Surface STO     : STANDARD PRIMARY
 Aperture       : Floating Aperture
 Maximum Radius :          1150
Surface   2     : STANDARD LENS1
 Aperture       : Floating Aperture
 Maximum Radius :       124.836
Surface   3     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :      121.9258
Surface   4     : STANDARD LENSE2
 Aperture       : Floating Aperture
 Maximum Radius :      82.18378
Surface   5     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :      77.63217
Surface   6     : STANDARD LENS3
 Aperture       : Floating Aperture
 Maximum Radius :      72.71029
Surface   7     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :      68.70106
Surface   8     : STANDARD LENS4
 Aperture       : Floating Aperture
 Maximum Radius :      62.01357
Surface   9     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :      61.04243
Surface  10     : STANDARD FILTER
 Aperture       : Floating Aperture
 Maximum Radius :          50.8
Surface  11     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :          50.8
Surface  12     : STANDARD WINDOW
Surface  13     : STANDARD
Surface IMA     : STANDARD
```

COATING DEFINITIONS:

PHYSICAL OPTICS PROPAGATION SETTINGS SUMMARY:

```
 OBJ STANDARD
    Use Rays To Propagate To Next Surface  : Off
    Recompute Pilot Beam                   : Off
    Do Not Rescale Beam Size Using Ray Data: Off
    Use Angular Spectrum Propagator        : Off
    Reference Radius                       : Best Fit
 STO STANDARD              PRIMARY
    Use Rays To Propagate To Next Surface  : Off
```

```
  Recompute Pilot Beam                     : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
 2 STANDARD                LENS1
  Use Rays To Propagate To Next Surface  : Off
  Recompute Pilot Beam                   : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
 3 STANDARD
  Use Rays To Propagate To Next Surface  : Off
  Recompute Pilot Beam                   : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
 4 STANDARD               LENSE2
  Use Rays To Propagate To Next Surface  : Off
  Recompute Pilot Beam                   : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
 5 STANDARD
  Use Rays To Propagate To Next Surface  : Off
  Recompute Pilot Beam                   : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
 6 STANDARD                LENS3
  Use Rays To Propagate To Next Surface  : Off
  Recompute Pilot Beam                   : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
 7 STANDARD
  Use Rays To Propagate To Next Surface  : Off
  Recompute Pilot Beam                   : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
 8 STANDARD                LENS4
  Use Rays To Propagate To Next Surface  : Off
  Recompute Pilot Beam                   : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
 9 STANDARD
  Use Rays To Propagate To Next Surface  : Off
  Recompute Pilot Beam                   : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
10 STANDARD               FILTER
  Use Rays To Propagate To Next Surface  : Off
  Recompute Pilot Beam                   : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
11 STANDARD
  Use Rays To Propagate To Next Surface  : Off
  Recompute Pilot Beam                   : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
12 STANDARD               WINDOW
  Use Rays To Propagate To Next Surface  : Off
  Recompute Pilot Beam                   : Off
  Do Not Rescale Beam Size Using Ray Data: Off
  Use Angular Spectrum Propagator        : Off
  Reference Radius                       : Best Fit
13 STANDARD
  Use Rays To Propagate To Next Surface  : Off
```

Recompute Pilot Beam : Off
Do Not Rescale Beam Size Using Ray Data: Off
Use Angular Spectrum Propagator : Off
Reference Radius : Best Fit

IMA STANDARD

Use Rays To Propagate To Next Surface : Off
Recompute Pilot Beam : Off
Do Not Rescale Beam Size Using Ray Data: Off
Use Angular Spectrum Propagator : Off
Reference Radius : Best Fit

EDGE THICKNESS DATA:

Surf	X-Edge	Y-Edge
STO	4241.851600	4241.851600
2	7.137803	7.137803
3	124.249616	124.249616
4	13.860967	13.860967
5	22.982607	22.982607
6	16.474717	16.474717
7	120.671383	120.671383
8	5.999999	5.999999
9	36.964993	36.964993
10	3.000000	3.000000
11	10.000000	10.000000
12	3.000000	3.000000
13	19.000000	19.000000
IMA	0.000000	0.000000

SOLVE AND VARIABLE DATA:

Thickness of 1 : Variable
Semi Diameter 1 : Fixed
Thickness of 2 : Variable
Thickness of 3 : Variable
Thickness of 4 : Variable
Thickness of 5 : Variable
Thickness of 6 : Variable
Thickness of 7 : Variable
Curvature of 8 : Variable
Thickness of 8 : Variable
Semi Diameter 10 : Fixed
Semi Diameter 11 : Fixed
Thickness of 13 : Variable
Semi Diameter 14 : Fixed

INDEX OF REFRACTION DATA:

System Temperature: 20.00
System Pressure : 1.00

Surf	Glass	Temp	Pres	0.370000	0.550000	1.000000
0		20.00	1.00	1.00000000	1.00000000	1.00000000
1	MIRROR	20.00	1.00	1.00000000	1.00000000	1.00000000
2	F_SILICA	20.00	1.00	1.47382578	1.45991089	1.45041741
3		20.00	1.00	1.00000000	1.00000000	1.00000000
4	F_SILICA	20.00	1.00	1.47382578	1.45991089	1.45041741
5		20.00	1.00	1.00000000	1.00000000	1.00000000
6	F_SILICA	20.00	1.00	1.47382578	1.45991089	1.45041741
7		20.00	1.00	1.00000000	1.00000000	1.00000000
8	F_SILICA	20.00	1.00	1.47382578	1.45991089	1.45041741
9		20.00	1.00	1.00000000	1.00000000	1.00000000
10	BK7	20.00	1.00	1.53539019	1.51852239	1.50750220
11		20.00	1.00	1.00000000	1.00000000	1.00000000
12	BK7	20.00	1.00	1.53539019	1.51852239	1.50750220
13		20.00	1.00	1.00000000	1.00000000	1.00000000
14		20.00	1.00	1.00000000	1.00000000	1.00000000

THERMAL COEFFICIENT OF EXPANSION DATA:

Surf	Glass	TCE *10E-6
0		0.00000000

1	MIRROR	23.50000000
2	F_SILICA	0.51000000
3		1.00000000
4	F_SILICA	0.51000000
5		1.00000000
6	F_SILICA	0.51000000
7		1.00000000
8	F_SILICA	0.51000000
9		23.50000000
10	BK7	7.10000000
11		23.50000000
12	BK7	7.10000000
13		23.50000000
14		0.00000000

F/# DATA:

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

	Wavelength:	0.370000		0.550000		1.000000	
#	Field	Tan	Sag	Tan	Sag	Tan	Sag
1	0.0000, 0.0000 deg:	2.2547	2.2547	2.2553	2.2553	2.2557	2.2557
2	0.0833, 0.0833 deg:	2.2598	2.2598	2.2604	2.2604	2.2607	2.2607
3	0.1667, 0.1667 deg:	2.2757	2.2757	2.2761	2.2761	2.2762	2.2762
4	0.2050, 0.2050 deg:	2.2870	2.2870	2.2872	2.2872	2.2873	2.2873
5	0.2400, 0.2400 deg:	2.2998	2.2998	2.2999	2.2999	2.2998	2.2998
6	0.3200, 0.3200 deg:	2.3395	2.3395	2.3390	2.3390	2.3385	2.3385

GLOBAL VERTEX COORDINATES, ORIENTATIONS, AND ROTATION/OFFSET MATRICES:

Reference Surface: 1

Surf	R11	R12	R13	X	
	R21	R22	R23	Y	
	R31	R32	R33	Z	
1	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	PRIMARY
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	0.000000000E+000	
2	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	LENS1
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.267048494E+003	
3	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.284964062E+003	
4	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	LENSE2
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.430166171E+003	
5	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.436166171E+003	
6	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	LENS3
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.469884525E+003	
7	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.475884523E+003	
8	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	LENS4
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.605982683E+003	
9	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.625991329E+003	

10	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	FILTER
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.660991329E+003	
11	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.663991329E+003	
12	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	WINDOW
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.673991329E+003	
13	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.676991329E+003	
14	1.0000000000	0.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	1.0000000000	0.0000000000	0.000000000E+000	
	0.0000000000	0.0000000000	1.0000000000	4.695991329E+003	

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.
Single elements that are duplicated in the Lens Data Editor
for ray tracing purposes may be listed more than once yielding
incorrect total mass estimates.

	Volume cc	Density g/cc	Mass g
Element surf 2 to 3	680.109901	2.200000	1496.241783
Element surf 4 to 5	231.568202	2.200000	509.450045
Element surf 6 to 7	201.275036	2.200000	442.805079
Element surf 8 to 9	157.662444	2.200000	346.857376
Element surf 10 to 11	24.321959	2.510000	61.048117
Element surf 12 to 13	21.258207	2.510000	53.358101
Total Mass:			2909.760502

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 = 0.370000 (Primary)		
Focal Length :	5186.468967	5186.468967
Focal Planes :	35530.482486	-0.050830
Principal Planes :	30344.013519	-5186.519797
Anti-Principal Planes :	40716.951452	5186.418137
Nodal Planes :	40716.951452	5186.418137
Anti-Nodal Planes :	30344.013519	-5186.519797
W = 0.550000		
Focal Length :	5186.280426	5186.280426
Focal Planes :	33660.213361	0.019974
Principal Planes :	28473.932935	-5186.260451
Anti-Principal Planes :	38846.493787	5186.300400
Nodal Planes :	38846.493787	5186.300400
Anti-Nodal Planes :	28473.932935	-5186.260451
W = 1.000000		
Focal Length :	5185.902027	5185.902027
Focal Planes :	32402.551475	0.044612
Principal Planes :	27216.649448	-5185.857415
Anti-Principal Planes :	37588.453502	5185.946638
Nodal Planes :	37588.453502	5185.946638
Anti-Nodal Planes :	27216.649448	-5185.857415

APPENDIX B: Tolerance Analysis at 0.55 microns

Analysis of Tolerances

File : C:\Chip\WIRO\Oct03\Harmer\Last-testplates.ZMX
Title: WIRO 4-element Prime Focus Corrector
Date : TUE JAN 13 2004

Units are Millimeters.

Fast tolerancing mode is on. In this mode, all
compensators are ignored, except back focus error.

WARNING: RAY AIMING IS OFF. Very loose tolerances may not be computed accurately.

WARNING: Boundary constraints on compensators are ignored when
using fast mode or user-defined merit functions.

Mode : Sensitivities
Sampling : 3
Optimization Cycles : Automatic mode

Merit: RMS Spot Radius in Millimeters

Nominal Merit Function (MF) is 0.00675554

Test wavelength: 0.6328

Fields: XY Symmetric Angle in degrees

#	X-Field	Y-Field	Weight	VDX	VDY	VCX	VCY
1	0.000E+000	0.000E+000	4.000E+000	0.000	0.000	0.000	0.000
2	0.000E+000	3.168E-001	1.000E+000	0.000	0.000	0.000	0.000
3	0.000E+000	-3.168E-001	1.000E+000	0.000	0.000	0.000	0.000
4	0.000E+000	4.525E-001	1.000E+000	0.000	0.000	0.000	0.000
5	0.000E+000	-4.525E-001	1.000E+000	0.000	0.000	0.000	0.000
6	3.168E-001	0.000E+000	1.000E+000	0.000	0.000	0.000	0.000
7	-3.168E-001	0.000E+000	1.000E+000	0.000	0.000	0.000	0.000
8	4.525E-001	0.000E+000	1.000E+000	0.000	0.000	0.000	0.000
9	-4.525E-001	0.000E+000	1.000E+000	0.000	0.000	0.000	0.000

Sensitivity Analysis:

			Minimum			Maximum		
Type			Value	MF	Change	Value	MF	Change
TRAD	2		-0.100000	0.007223	0.000468	0.100000	0.007311	0.000556
TRAD	3		-0.110000	0.006905	0.000149	0.110000	0.006956	0.000201
TRAD	4		-0.242000	0.006746	-0.000010	0.242000	0.006858	0.000103
TRAD	5		-0.146000	0.006972	0.000217	0.146000	0.006811	0.000056
TRAD	6		-0.248000	0.006736	-0.000020	0.248000	0.006803	0.000047
TRAD	7		-0.120000	0.007249	0.000493	0.120000	0.006884	0.000129
TRAD	8		-0.163000	0.006761	0.000005	0.163000	0.006758	0.000002
TRAD	9		-0.941000	0.006770	0.000015	0.941000	0.006743	-0.000013
TFRN	10		-1.000000	0.006757	0.000001	1.000000	0.006754	-0.000001
TFRN	11		-1.000000	0.006754	-0.000001	1.000000	0.006757	0.000001
TFRN	12		-1.000000	0.006757	0.000001	1.000000	0.006754	-0.000001
TFRN	13		-1.000000	0.006754	-0.000001	1.000000	0.006757	0.000001
TTHI	2	3	-0.100000	0.006857	0.000102	0.100000	0.006923	0.000167
TTHI	3	5	-0.100000	0.006789	0.000033	0.100000	0.006781	0.000026
TTHI	4	5	-0.100000	0.006847	0.000092	0.100000	0.006768	0.000012
TTHI	5	7	-0.100000	0.006838	0.000083	0.100000	0.006761	0.000006
TTHI	6	7	-0.100000	0.006879	0.000124	0.100000	0.006756	0.000000
TTHI	7	9	-0.100000	0.006750	-0.000006	0.100000	0.006768	0.000012
TTHI	8	9	-0.100000	0.006749	-0.000006	0.100000	0.006765	0.000009
TTHI	9	11	-0.100000	0.006756	-0.000000	0.100000	0.006756	-0.000000
TTHI	10	11	-0.100000	0.006758	0.000002	0.100000	0.006755	-0.000001
TTHI	11	13	-0.100000	0.006756	-0.000000	0.100000	0.006756	0.000000
TTHI	12	13	-0.100000	0.006758	0.000002	0.100000	0.006755	-0.000001
TSDX	2		-0.100000	0.007500	0.000745	0.100000	0.007500	0.000745
TSDX	3		-0.100000	0.007222	0.000467	0.100000	0.007222	0.000467

TSDX	4		-0.100000	0.006813	0.000058	0.100000	0.006813	0.000058
TSDX	5		-0.100000	0.006925	0.000170	0.100000	0.006925	0.000170
TSDX	6		-0.100000	0.006791	0.000035	0.100000	0.006791	0.000035
TSDX	7		-0.100000	0.006943	0.000188	0.100000	0.006943	0.000188
TSDX	8		-0.100000	0.006796	0.000041	0.100000	0.006796	0.000041
TSDX	9		-0.100000	0.006761	0.000005	0.100000	0.006761	0.000005
TSDX	10		-0.100000	0.006756	0.000000	0.100000	0.006756	0.000000
TSDX	11		-0.100000	0.006756	0.000000	0.100000	0.006756	0.000000
TSDX	12		-0.100000	0.006756	0.000000	0.100000	0.006756	0.000000
TSDX	13		-0.100000	0.006756	0.000000	0.100000	0.006756	-0.000000
TSDY	2		-0.100000	0.007500	0.000745	0.100000	0.007500	0.000745
TSDY	3		-0.100000	0.007222	0.000467	0.100000	0.007222	0.000467
TSDY	4		-0.100000	0.006813	0.000058	0.100000	0.006813	0.000058
TSDY	5		-0.100000	0.006925	0.000170	0.100000	0.006925	0.000170
TSDY	6		-0.100000	0.006791	0.000035	0.100000	0.006791	0.000035
TSDY	7		-0.100000	0.006943	0.000188	0.100000	0.006943	0.000188
TSDY	8		-0.100000	0.006796	0.000041	0.100000	0.006796	0.000041
TSDY	9		-0.100000	0.006761	0.000005	0.100000	0.006761	0.000005
TSDY	10		-0.100000	0.006756	0.000000	0.100000	0.006756	0.000000
TSDY	11		-0.100000	0.006756	0.000000	0.100000	0.006756	0.000000
TSDY	12		-0.100000	0.006756	0.000000	0.100000	0.006756	0.000000
TSDY	13		-0.100000	0.006756	0.000000	0.100000	0.006756	0.000000
TSTX	2		-0.017000	0.007010	0.000254	0.017000	0.007010	0.000254
TSTX	3		-0.017000	0.006979	0.000223	0.017000	0.006979	0.000223
TSTX	4		-0.017000	0.006787	0.000032	0.017000	0.006787	0.000032
TSTX	5		-0.017000	0.006789	0.000034	0.017000	0.006789	0.000034
TSTX	6		-0.017000	0.006774	0.000019	0.017000	0.006774	0.000019
TSTX	7		-0.017000	0.006780	0.000024	0.017000	0.006780	0.000024
TSTX	8		-0.017000	0.006765	0.000010	0.017000	0.006765	0.000010
TSTX	9		-0.017000	0.006795	0.000040	0.017000	0.006795	0.000040
TSTX	10		-0.017000	0.006771	0.000015	0.017000	0.006771	0.000015
TSTX	11		-0.017000	0.006770	0.000015	0.017000	0.006770	0.000015
TSTX	12		-0.017000	0.006768	0.000012	0.017000	0.006768	0.000012
TSTX	13		-0.017000	0.006767	0.000012	0.017000	0.006767	0.000012
TSTY	2		-0.017000	0.007010	0.000254	0.017000	0.007010	0.000254
TSTY	3		-0.017000	0.006979	0.000223	0.017000	0.006979	0.000223
TSTY	4		-0.017000	0.006787	0.000032	0.017000	0.006787	0.000032
TSTY	5		-0.017000	0.006789	0.000034	0.017000	0.006789	0.000034
TSTY	6		-0.017000	0.006774	0.000019	0.017000	0.006774	0.000019
TSTY	7		-0.017000	0.006780	0.000024	0.017000	0.006780	0.000024
TSTY	8		-0.017000	0.006765	0.000010	0.017000	0.006765	0.000010
TSTY	9		-0.017000	0.006795	0.000040	0.017000	0.006795	0.000040
TSTY	10		-0.017000	0.006771	0.000015	0.017000	0.006771	0.000015
TSTY	11		-0.017000	0.006770	0.000015	0.017000	0.006770	0.000015
TSTY	12		-0.017000	0.006768	0.000012	0.017000	0.006768	0.000012
TSTY	13		-0.017000	0.006767	0.000012	0.017000	0.006767	0.000012
TIRR	2		-0.200000	0.006764	0.000009	0.200000	0.006748	-0.000008
TIRR	3		-0.200000	0.006748	-0.000008	0.200000	0.006764	0.000008
TIRR	4		-0.200000	0.006761	0.000006	0.200000	0.006750	-0.000005
TIRR	5		-0.200000	0.006750	-0.000006	0.200000	0.006761	0.000006
TIRR	6		-0.200000	0.006761	0.000005	0.200000	0.006751	-0.000005
TIRR	7		-0.200000	0.006751	-0.000005	0.200000	0.006761	0.000005
TIRR	8		-0.200000	0.006757	0.000002	0.200000	0.006754	-0.000002
TIRR	9		-0.200000	0.006754	-0.000002	0.200000	0.006757	0.000002
TIRR	10		-0.200000	0.006756	0.000001	0.200000	0.006755	-0.000001
TIRR	11		-0.200000	0.006755	-0.000001	0.200000	0.006756	0.000001
TIRR	12		-0.200000	0.006756	0.000001	0.200000	0.006755	-0.000001
TIRR	13		-0.200000	0.006755	-0.000001	0.200000	0.006756	0.000001
TEDX	2	3	-0.100000	0.006867	0.000112	0.100000	0.006867	0.000112
TEDX	4	5	-0.100000	0.006828	0.000073	0.100000	0.006828	0.000073
TEDX	6	7	-0.100000	0.006875	0.000119	0.100000	0.006875	0.000119
TEDX	8	9	-0.100000	0.006801	0.000045	0.100000	0.006801	0.000045
TEDX	10	11	-0.100000	0.006756	0.000000	0.100000	0.006756	0.000000
TEDX	12	13	-0.100000	0.006756	0.000000	0.100000	0.006756	0.000000
TEDY	2	3	-0.100000	0.006867	0.000112	0.100000	0.006867	0.000112
TEDY	4	5	-0.100000	0.006828	0.000073	0.100000	0.006828	0.000073
TEDY	6	7	-0.100000	0.006875	0.000119	0.100000	0.006875	0.000119
TEDY	8	9	-0.100000	0.006801	0.000045	0.100000	0.006801	0.000045
TEDY	10	11	-0.100000	0.006756	0.000000	0.100000	0.006756	0.000000
TEDY	12	13	-0.100000	0.006756	0.000000	0.100000	0.006756	0.000000
TETX	2	3	-0.017000	0.006788	0.000032	0.017000	0.006788	0.000032
TETX	4	5	-0.017000	0.006770	0.000015	0.017000	0.006770	0.000015

TETX	6	7	-0.017000	0.006772	0.000017	0.017000	0.006772	0.000017
TETX	8	9	-0.017000	0.006804	0.000048	0.017000	0.006804	0.000048
TETX	10	11	-0.017000	0.006756	0.000000	0.017000	0.006756	0.000000
TETX	12	13	-0.017000	0.006756	0.000000	0.017000	0.006756	0.000000
TETY	2	3	-0.017000	0.006788	0.000032	0.017000	0.006788	0.000032
TETY	4	5	-0.017000	0.006770	0.000015	0.017000	0.006770	0.000015
TETY	6	7	-0.017000	0.006772	0.000017	0.017000	0.006772	0.000017
TETY	8	9	-0.017000	0.006804	0.000048	0.017000	0.006804	0.000048
TETY	10	11	-0.017000	0.006756	0.000000	0.017000	0.006756	0.000000
TETY	12	13	-0.017000	0.006756	0.000000	0.017000	0.006756	0.000000
TIND	2		-0.000200	0.006760	0.000004	0.000200	0.006779	0.000024
TIND	4		-0.000200	0.006748	-0.000007	0.000200	0.006769	0.000013
TIND	6		-0.000200	0.006743	-0.000012	0.000200	0.006774	0.000019
TIND	8		-0.000200	0.006769	0.000014	0.000200	0.006744	-0.000011
TIND	10		-0.000200	0.006756	0.000000	0.000200	0.006756	-0.000000
TIND	12		-0.000200	0.006756	0.000000	0.000200	0.006756	-0.000000
TABB	2		-0.200000	0.007234	0.000479	0.200000	0.006797	0.000042
TABB	6		-0.200000	0.006769	0.000014	0.200000	0.006949	0.000193
TABB	8		-0.200000	0.006773	0.000018	0.200000	0.006798	0.000042
TABB	10		-0.200000	0.006754	-0.000002	0.200000	0.006757	0.000002
TABB	12		-0.200000	0.006754	-0.000002	0.200000	0.006757	0.000002
TABB	4		-0.200000	0.006745	-0.000010	0.200000	0.006943	0.000188

Worst offenders:

Type		Value	MF	Change
TSDX	2	-0.100000	0.007500	0.000745
TSDX	2	0.100000	0.007500	0.000745
TSDY	2	-0.100000	0.007500	0.000745
TSDY	2	0.100000	0.007500	0.000745
TRAD	2	0.100000	0.007311	0.000556
TRAD	7	-0.120000	0.007249	0.000493
TABB	2	-0.200000	0.007234	0.000479
TRAD	2	-0.100000	0.007223	0.000468
TSDX	3	0.100000	0.007222	0.000467
TSDX	3	-0.100000	0.007222	0.000467
TSDY	3	0.100000	0.007222	0.000467
TSDY	3	-0.100000	0.007222	0.000467
TSTY	2	0.017000	0.007010	0.000254
TSTY	2	-0.017000	0.007010	0.000254
TSTX	2	0.017000	0.007010	0.000254
TSTX	2	-0.017000	0.007010	0.000254
TSTY	3	0.017000	0.006979	0.000223
TSTY	3	-0.017000	0.006979	0.000223
TSTX	3	-0.017000	0.006979	0.000223
TSTX	3	0.017000	0.006979	0.000223

Nominal RMS Spot Radius : 0.006756
Estimated change : 0.001627
Estimated RMS Spot Radius: 0.008383

Merit Statistics:
Mean : 0.006821
Standard Deviation : 0.000134

Compensator Statistics:
Change in back focus:
Minimum : -0.253078
Maximum : 0.252883
Mean : 0.000003
Standard Deviation : 0.041053

Monte Carlo Analysis:
Number of trials: 20

Initial Statistics: Normal Distribution

Trial	Merit	Change
1	0.007982	0.001227
2	0.008041	0.001285
3	0.007633	0.000878
4	0.010318	0.003563

5	0.007872	0.001116
6	0.007251	0.000495
7	0.008359	0.001603
8	0.008139	0.001383
9	0.010247	0.003491
10	0.007073	0.000317
11	0.007422	0.000667
12	0.007498	0.000743
13	0.008504	0.001749
14	0.007816	0.001060
15	0.008169	0.001414
16	0.008087	0.001331
17	0.010190	0.003435
18	0.007747	0.000992
19	0.007911	0.001155
20	0.007774	0.001018

Nominal	0.006756
Best	0.007073
Worst	0.010318
Mean	0.008202
Std Dev	0.000926

Compensator Statistics:
Change in back focus:

Minimum	:	-0.362155
Maximum	:	0.266009
Mean	:	-0.006209
Standard Deviation	:	0.177164

90% of Monte Carlo lenses have a merit function below 0.010190.
50% of Monte Carlo lenses have a merit function below 0.007911.
10% of Monte Carlo lenses have a merit function below 0.007251.

End of Run.