NIRSPEC

UCLA Astrophysics Program **U.C. Berkeley** **W.M. Keck Observatory**

Samuel B. Larson **August 19, 1998**

NIRSPEC Optics Design Note 3.02
Slit-Viewing Camera

Description

NIRSPEC will contain a separate cryogenic camera that images the slit plane. This slit-viewing camera (SCAM) serves several purposes. It provides a convenient way to focus the telescope and center the astronomical target in the slit, and it allows the observer to obtain deep near-infrared images of the field around the spectroscopic target simultaneously with the spectra. In addition, the SCAM may be used as a guider camera when observing in heavily extincted regions or when the desired spectroscopic accuracy is extremely high.

SCAM receives the diverging f/10 beam from the front end of NIRSPEC that has been reflected from the slit surface. SCAM re-images this beam onto a Rockwell 256x256 NICMOS3 array. In this way, SCAM obtains an image of the field with the slit area missing in spectroscopy mode, or a complete image in imaging mode.

Design Constraints

The SCAM design was constrained by scientific goals as well as manufacturability and assembly issues. The following list outlines the most important of these constraints.

1. 46" x 46" field of view. This requires a plate scale of 0.18 arcsec/pixel, or an f/4.59 imager for a 10m aperture and 40 µm pixels.
2. achromatic from 1 - 2.5 µm so that no refocus is needed from band to band, with the performance optimized for the astronomical wavebands centered at 1.25, 1.65 and 2.2 µm.
3. 80% of the light captured in 1 pixel everywhere on the array for all three wavebands.
4. minimal image distortion. Based on intermediate designs and published specifications from other instruments, the goal was set at 0.5% distortion everywhere on the array.
5. minimal number of elements for highest throughput and lowest cost, and minimal number of aspheric surfaces for lowest cost and highest manufacturability.
6. first element $ 110 mm from the slit plane to clear the NIRSPEC f/converter optics.
7. total track # 400 mm so that the SCAM would neither constrain the size of the dewar nor require a fold.
8. element thicknesses greater than 10% of their diameter but less than 10 mm. Discussions with Janos led to the minimum limit to ease manufacturability, and cost issues drive the maximum limit.
9. surface curvatures allow for 10 mm oversizing of element diameters. This gives 5 mm on the edge of the elements for mounting, which previous experience shows is desirable.
10. last surface must be convex to reduce ghosting.

Note that the design was not constrained to provide an accurate pupil image, allow access for a filter wheel, or present a telecentric beam to the array. While these features are necessary in most astronomical cameras, they are not required in this application. A pupil image is formed upstream of the SCAM optics where a Lyot stop is placed. Telecentricity is not required because SCAM is to re-image the slit surface. Since the distance between the slit surface and the detector is fixed, telecentricity offers no advantages.

Optical Design

All design work was performed using the Zemax ray-tracing program, initially feeding the design an ideal f/10 beam. Final optimizations were run with the real NIRSPEC front-end feeding the design. The final SCAM design consists of three elements and is shown in Figure 1. Three field points (center and two opposite corners) are traced with three rays per field. The second surface has a conic constant, and the rest are spherical. The first element is made of BaF_2, and it forms a rough pupil

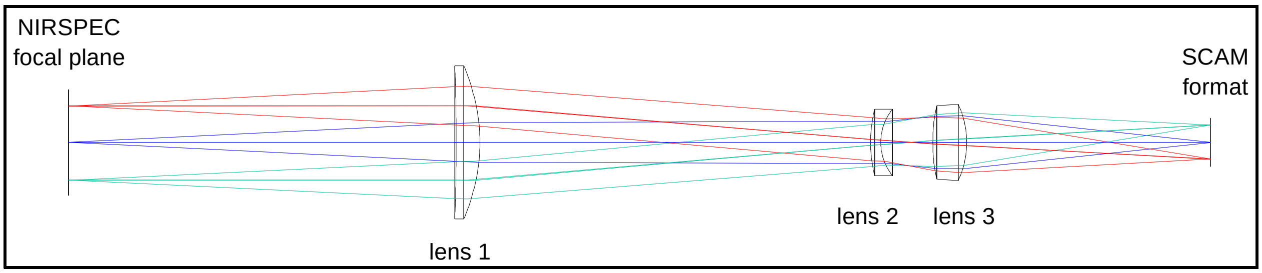

Figure 1. SCAM Ray Trace

image but does not collimate the beam. The other two elements, LiF and BaF_2, act as a doublet and provide an f/4.59 focus onto the array. The operating (77 K) optical prescription data of the best design is shown in Table 1. Negative radii indicate concave surfaces from the perspective of the incoming beam. Note that these numbers may differ from actual Zemax prescriptions in sign.

Table 1. SCAM Operating (77K) Prescription

Surface	Material	Radius (mm)	Conic	Min. clear aperture diam. (mm)	Center Thickness (mm)	Distance (mm)
F.P.	-	-	-	-	-	114.100
Lens 1	BaF_2	-571.016	0	40.541	7.000	-
		-54.853	-1.399	40.813	-	116.436
Lens 2	LiF	42.246	0	15.116	3.000	-
		16.192	0	14.250	-	15.441
Lens 3	BaF_2	53.046	0	17.138	10.000	-
		-27.530	0	18.356	-	72.633

Four-element designs were pursued in an attempt to eliminate the asphere, but no designs were found with acceptable optical performace. Rather than have five or more elements, we have decided to accept the risk inherent in the manufacture of aspheric lenses.

All SCAM ray trace designs can be found in the *altair/c/zmx404/nirspec/scam* directory. The relevant final designs are as follows:

15sc23.zmx	end-to-end final design: Keck II to SCAM array (units=meters)
15sc23mm.zmx	15sc23.zmx with units=millimeters (shown in Table 1)
15sc23bf.zmx	15sc23mm.zmx with baffle surfaces
15sc23is.zmx	15sc23mm.zmx fed by ideal f/10 beam instead of NIRSPEC
15sc23ip.zmx	15sc23mm.zmx matched to ISP test plates
15sc23jp.zmx	15sc23mm.zmx matched to Janos test plates
15sc23tl.zmx	tolernace analysis of 15sc23mm.zmx

Lenses were matched to test plates by thermally expanding the most sensitive surface to room temperature, matching it to the nearest test plate, contracting it back to operating temperature, reoptimizing the remaining surfaces, and repeating until the least sensitive element was matched to the closest plate. Thermal calculations were performed using expansion values of $\Delta L/L_0$ = -0.319% for BaF_2 and $\Delta L/L_0$ = -0.472% for LiF, corresponding to cooling from 293 K to 75 K (Touloukian et al. 1977, Thermophysical Properties of Matter, vol. 13). The aspheric surface cannot be matched to a test plate, so it was reoptimized as a final step.

Room temperature lenses matched to the test plates of International Scientific Products (ISP) are provided in Table 2. The surfaces must be complete out to the specified minimum clear aperture. The lenses are oversized to the specified total diameter to accomodate mounting and baffling. Note that the prescription in Table 2 does not match the values in Table 1 when cooled, as Table 1 contains the best design before matching to test plates.

Table 2. SCAM Lenses at Room Temperature: ISP Test Plates

Surface	Material	Radius (mm)	Conic	Min. clear aperture diam. (mm)	Total diameter (mm)	Center Thickness (mm)
Lens 1	BaF_2	-1128.600	0	41.2	50.0	7.022
		-56.466	-1.524	41.5	50.0	
Lens 2	LiF	42.760	0	15.7	25.0	3.014
		16.220	0	14.9	25.0	
Lens 3	BaF_2	50.230	0	17.7	28.0	10.032
		-27.670	0	19.0	28.0	

Optical Tolerances

Our performance goal is to capture at least 80% diffraction ensquared energy in one 40 μm pixel at the SCAM format. The current design meets this goal from 1.05 to 2.4 μm for all field points (in the nominal image rotator position). Table 3 shows the optical tolerances that must be met to ensure that this performance is preserved.

Table 3. SCAM Optical Tolerances

Tolerance	Units	Lens 1 (BaF_2)		Lens 2 (LiF)		Lens 3 (BaF_2)	
		surf 1	surf 2	surf 1	surf 2	surf 1	surf 2
thickness	mm	0.25	-	0.25	-	0.2	-
radii	mm	1	0.1	0.1	0.025	0.1	0.025
surface irregularity	$\lambda_{632.8nm}$ rms	1/4	1/4	1/4	1/4	1/4	1/4
conic	-	-	0.01	-	-	-	-

Also of concern is the uncertainty in the refractive indices of the chosen materials. Our adopted 77K indices are shown in Table 4 (Figer 1994, private communication). Tolerance analysis shows that the indices should not vary by more than 0.1%. The change in refractive indices from room temperature to 77K is only 0.2-0.3% with these materials and wavelengths, so this tolerance is more likely to be violated by random batch-to-batch variances in the materials than by errors in the thermal calculation. In fact, independent cryogenic indices (SPIE Optical Engineering, May 1995, vol. 34, #5) differ by less than .05% from our adopted values.

Table 4. Refractive indices @ 77 K

Material	1.00 μm	1.25 μm	1.65 μm	2.20 μm	2.50 μm
BaF_2	1.47195678	1.47063594	1.46922392	1.46757507	1.46664037
LiF	1.39066980	1.38871969	1.38551364	1.38025957	1.37677560
CaF_2	1.43090400	1.42954573	1.42770030	1.42499297	1.42330011

Feeding the SCAM

Because the slit surface is so close to the f/converter optics, SCAM cannot look directly at the slit without tilting the slit surface an unreasonable amount. The solution is to tilt the slit surface a smaller amount so that the reflecting beam comes back onto the last flat in the f/converter and then off to the side of that module. This layout is shown in Figure 2.

The slit surface is tilted 12/ out of the image plane (such that the long vertical slits for low-res mode remain in the image plane). This causes a 24/ deflection in the SCAM beam away from the f/converter K-mirror as it reflects off the f/converter flat and up beside the K-mirror, allowing room for the SCAM lenses.

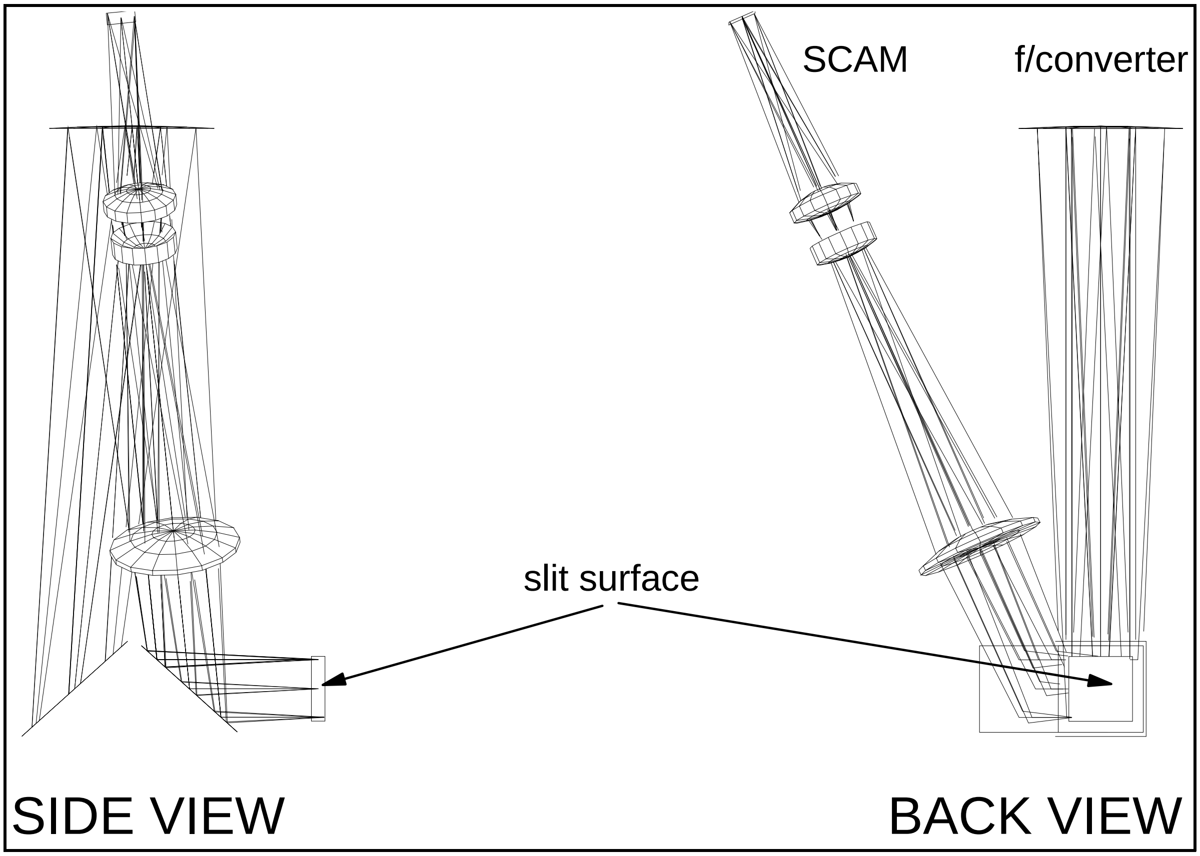

Figure 2. SCAM Layout

Optical Performance

The optical performance of the SCAM is difficult to describe in a general way, because it is dependent upon wavelength, field, and image rotator angle. First we will look at the performace at the nominal (0/) roator angle, and then examine how this performance degrades as the rotator swings away from its nominal position.

Spot diagrams and diffraction encircled energy plots for J, H and K astronomical passbands are shown in Figures 3, 4 and 5, respectively. These were produced by equally weighting the center and edge wavelengths of each band. Results shown are for center, worst edge, best corner and worst corner field points. Spots for each waveband and field point fit easily into one 40 μm pixel for all field points. Diffraction encircled energy plots show that about 90% of the light is captured within one pixel for each waveband out to the edge of the field, and over 80% is captured at the corners of the field. In fact, the SCAM performance is limited by the NIRSPEC front-end for most of the format even at the nominal image rotator angle.

Figure 7 plots the diffraction energy captured inside one SCAM pixel (“enpixelled” energy) versus wavelength for 4 image rotator angles: 0/, 22.5/, 45/, and 90/. Plotted are the diffraction limit, center field point, four edge points and four corners. Within 22.5/ of the nominal position, at least 80% of the light is captured in one pixel for all field points but one corner. Out to 45/, more than 80% of the light is captured in one pixel out to the edges of the array. Even at the worst rotator angle, 90/, at least 80% of the light goes into one pixel in the slit area.

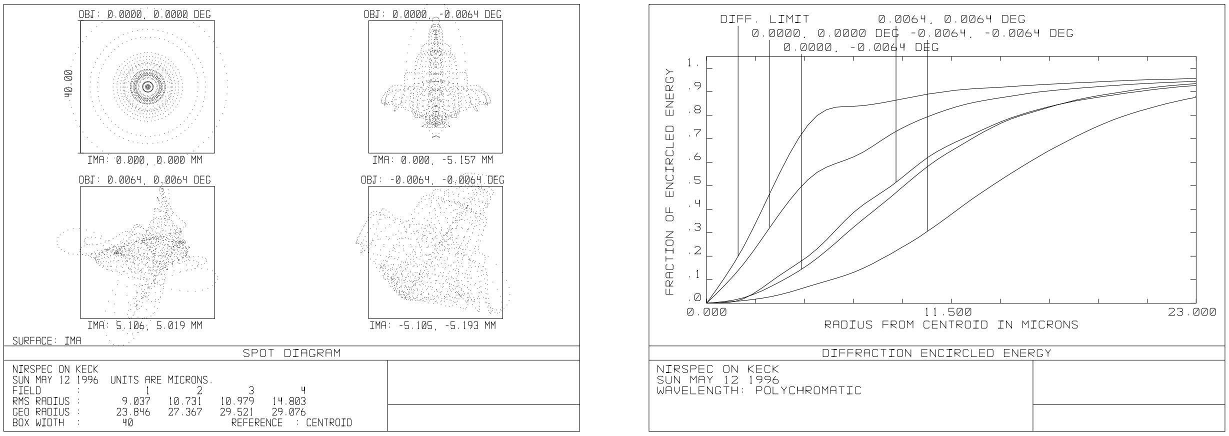

Figure 3. J band (1.1 - 1.4 μm) spot and encircled energy diagrams for center, edge and two corner field points. Box in spot diagram is 1 pixel, and edge of enc. energy plot is the energy in 1 pixel.

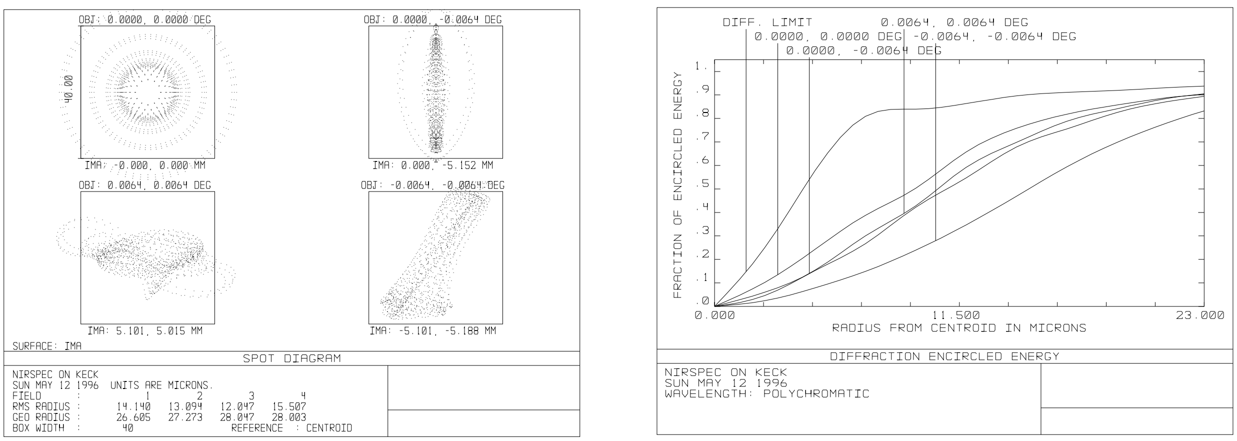

Figure 4. H band (1.5 - 1.8 μm) spot and encircled energy diagrams for center, edge and two corner field points. Box in spot diagram is 1 pixel, and edge of enc. energy plot is the energy in 1 pixel.

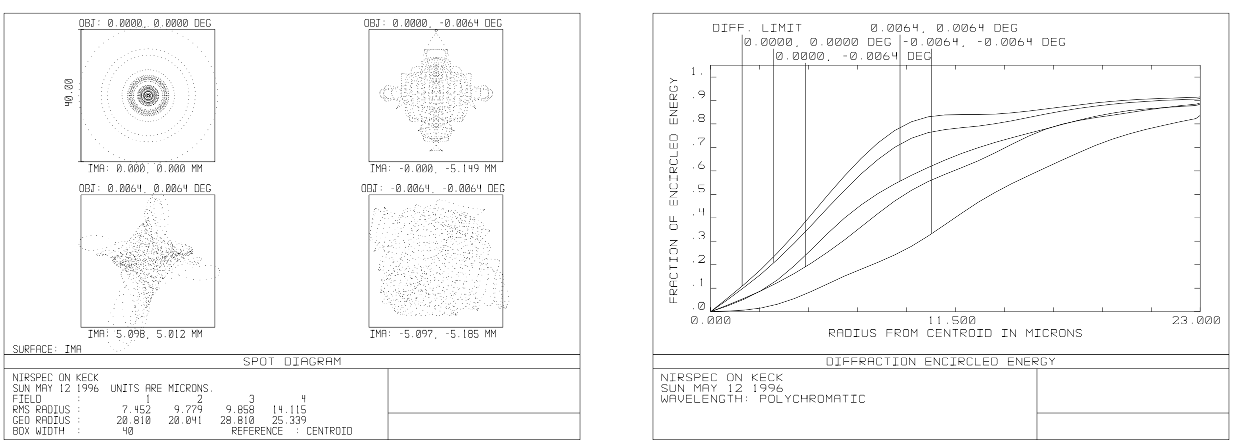

Figure 5. K band (2.0 - 2.4 μm) spot and encircled energy diagrams for center, edge and two corner field points. Box in spot diagram is 1 pixel, and edge of enc. energy plot is the energy in 1 pixel.

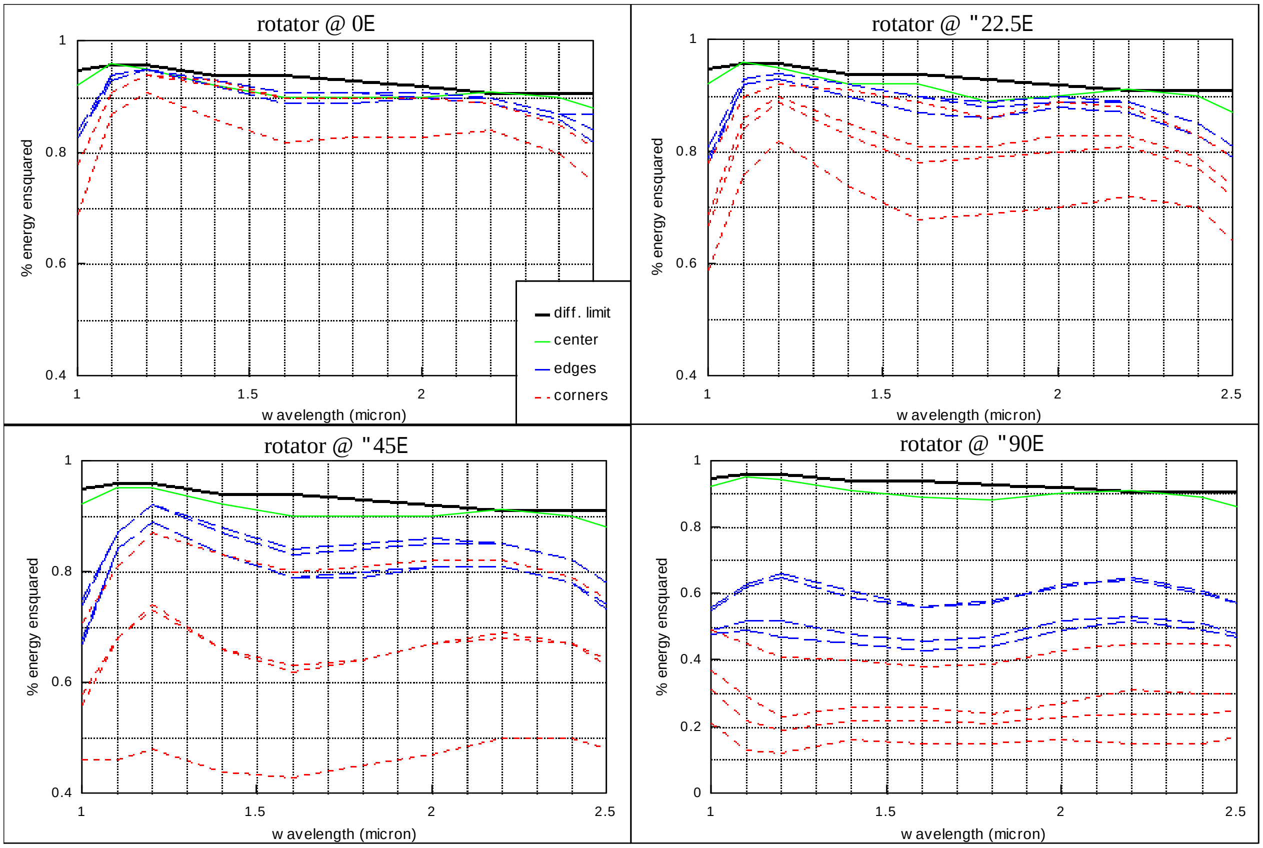

Figure 7. SCAM enpixelled energy vs. wavelength and image rotator angle. Note that the lower right graph (rotator=90 deg) has a different vertical scale than the others.

APPENDIX: Full Optical Prescription for the SCAM (Isolated from NIRSPEC)

System/Prescription Data

File : H:\ZMX404\NIRSPEC\SCAM\15SC23IS.ZMX
Title: NIRSPEC ON KECK
Date : TUE MAY 14 1996

GENERAL LENS DATA:

Surfaces	:	9
Stop	:	1
System Aperture	:	Entrance Pupil Diameter
Ray aiming	:	Off
Apodization	:	Uniform, factor = 0.000000
Eff. Focal Len.	:	-46033.6 (in air)
Eff. Focal Len.	:	-46033.6 (in image space)
Total Track	:	100339
Image Space F/#	:	4.60336
Working F/#	:	4.6084
Obj. Space N.A.	:	5e-007
Stop Radius	:	5000
Parax. Ima. Hgt.	:	7.24916
Parax. Mag.	:	0
Entr. Pup. Dia.	:	10000
Entr. Pup. Pos.	:	0
Exit Pupil Dia.	:	18.4905
Exit Pupil Pos.	:	-84.8326
Field Type	:	Angle in degrees
Maximum Field	:	0.00902268
Primary Wave	:	1.650000
Lens Units	:	Millimeters
Angular Mag.	:	-540.817

Fields : 7
Field Type: Angle in degrees

#	X-Value	Y-Value	Weight
1	0.000000	0.000000	2.000000
2	0.006380	0.006380	0.500000
3	0.006380	-0.006380	0.500000
4	-0.006380	0.006380	0.000000
5	-0.006380	-0.006380	0.000000
6	0.000000	0.006380	1.000000
7	0.000000	-0.006380	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
6	0.000000	0.000000	0.000000	0.000000
7	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	0.500000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity		0	0
STO	PARAXIAL	--------	100000		10000	--------
2	STANDARD	Infinity	114.1		31.4951	0
3	STANDARD	-571.0158	7	BAF2_77X	40.38279	0
4	STANDARD	-54.85268	116.4364		40.67242	-1.398713
5	STANDARD	42.24555	3	LIF_77X	14.93611	0
6	STANDARD	16.19168	15.44099		14.08746	0
7	STANDARD	53.04603	10	BAF2_77X	17.15014	0
8	STANDARD	-27.53026	72.57481		18.37579	0
IMA	STANDARD	Infinity	0		14.4151	0

SURFACE DATA DETAIL:

```
Surface OBJ     : STANDARD
Surface STO     : PARAXIAL
 Focal length   :         100000
Surface   2     : STANDARD
Surface   3     : STANDARD
 Aperture       : Circular Aperture
 Minimum Radius :              0
 Maximum Radius :             25
Surface   4     : STANDARD
 Aperture       : Circular Aperture
 Minimum Radius :              0
 Maximum Radius :             25
Surface   5     : STANDARD
 Aperture       : Circular Aperture
 Minimum Radius :              0
 Maximum Radius :           12.5
Surface   6     : STANDARD
 Aperture       : Circular Aperture
 Minimum Radius :              0
 Maximum Radius :           12.5
Surface   7     : STANDARD
 Aperture       : Circular Aperture
 Minimum Radius :              0
 Maximum Radius :             14
Surface   8     : STANDARD
 Aperture       : Circular Aperture
 Minimum Radius :              0
 Maximum Radius :             14
Surface IMA     : STANDARD
 Aperture       : Rectangular Aperture
 X Half Width   :            5.5
 Y Half Width   :            5.5
```

SOLVE AND VARIABLE DATA:

Thickness of   8   : Variable

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		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
2		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
3	BAF2_77X	1.47195678	1.47063594	1.46922392	1.46757507	1.46664037
4		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
5	LIF_77X	1.39066980	1.38871969	1.38551364	1.38025957	1.37677560
6		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
7	BAF2_77X	1.47195678	1.47063594	1.46922392	1.46757507	1.46664037
8		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
9		1.00000000	1.00000000	1.00000000	1.00000000	1.00000000

F/# DATA:

	Wavelength:	1.000000		1.250000		1.650000	
#	Field	Tan	Sag	Tan	Sag	Tan	Sag
1	0.0000, 0.0000 deg:	4.6026	4.6026	4.6085	4.6085	4.6084	4.6084
2	0.0064, 0.0064 deg:	4.5530	4.5530	4.5594	4.5594	4.5600	4.5600
3	0.0064, -0.0064 deg:	4.5530	4.5530	4.5594	4.5594	4.5600	4.5600
4	-0.0064, 0.0064 deg:	4.5530	4.5530	4.5594	4.5594	4.5600	4.5600
5	-0.0064, -0.0064 deg:	4.5530	4.5530	4.5594	4.5594	4.5600	4.5600
6	0.0000, 0.0064 deg:	4.5712	4.5917	4.5774	4.5976	4.5778	4.5976
7	0.0000, -0.0064 deg:	4.5712	4.5917	4.5774	4.5976	4.5778	4.5976

	Wavelength:	2.200000		2.500000	
#	Field	Tan	Sag	Tan	Sag
1	0.0000, 0.0000 deg:	4.5994	4.5994	4.5913	4.5913
2	0.0064, 0.0064 deg:	4.5521	4.5521	4.5446	4.5446
3	0.0064, -0.0064 deg:	4.5521	4.5521	4.5446	4.5446
4	-0.0064, 0.0064 deg:	4.5521	4.5521	4.5446	4.5446
5	-0.0064, -0.0064 deg:	4.5521	4.5521	4.5446	4.5446
6	0.0000, 0.0064 deg:	4.5695	4.5887	4.5618	4.5807
7	0.0000, -0.0064 deg:	4.5695	4.5887	4.5618	4.5807

GLOBAL VERTEX COORDINATES AND DIRECTIONS:

Surf	X coord	Y coord	Z coord	X direc	Y direc	Z direc
1	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2	0.000000	0.000000	100000.000000	0.000000	0.000000	1.000000
3	0.000000	0.000000	100114.100000	0.000000	0.000000	1.000000

4	0.000000	0.000000	100121.100000	0.000000	0.000000	1.000000
5	0.000000	0.000000	100237.536417	0.000000	0.000000	1.000000
6	0.000000	0.000000	100240.536417	0.000000	0.000000	1.000000
7	0.000000	0.000000	100255.977404	0.000000	0.000000	1.000000
8	0.000000	0.000000	100265.977404	0.000000	0.000000	1.000000
9	0.000000	0.000000	100338.552214	0.000000	0.000000	1.000000

ELEMENT VOLUME DATA:

```
Units are cubic cm.
Values are only accurate for plane and spherical surfaces.
Element surf   3 to   4 volume :       6.789981
Element surf   5 to   6 volume :       0.583423
Element surf   7 to   8 volume :       2.206193
```