NIRSPEC

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

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NIRSPEC Optics Design Note 2.02
Guider Camera

Introduction

Observations using NIRSPEC must be guided to ensure that the target does not wander on scales larger than the desired spectroscopic resolution. We cannot rely completely on the slit-viewing camera for this task because its field of view (46" x 46") is too small to guarantee capturing a suitable guide star. Therefore, a separate camera with a larger field of view must be provided.

Guider systems can be quite intricate and expensive. In this application, at least three motions may be required: one to scan along the available field in search of a star, one to rotate the camera to follow the star as the image rotates, and one to focus the image to compensate for the telescope field curvature. The extreme guiding accuracy imposed by the NIRSPEC science goals adds to the complexity of this instrument. Given our limited budget and sampower, we want to select the simplest design that meets our performance requirements.

This document describes the simplest design concept, justifies its performance capabilities, and presents the full optical design and layout of the system.

Performance Requirements

There are several requirements that our guider must satisfy. Finding a guide star must not be cumbersome, and once found, it must be held in the guider field for the duration of the observation. The odds of finding no stars suitable for guiding must be very low (around the 1% level). Finally, the centroid of the guide star must be calculated to a certain accuracy. The highest possible resolution of a spectometer is 1/20 of a critically or better sampled resolution element (the slit width), which is obtained by centroiding on the spectral features (J. R. Graham 1994, priv. comm.; D. F. Figer 1995, Ph.D. Thesis). If the atmospheric seeing is about the same size as the slit width or smaller, then changes in the position of the target (along the width) will introduce errors in the wavelength calibration. The requirements placed on the guider are thus dependent on the science being done and the size of the seeing with respect to the chosen slit width. For NIRSPEC, the nominal slit width is 0.4", so ideally the guider should be able to provide guide star images that can be centroided to 0.02".

Design Motivation

The drive for simplicity means eliminating as many moving parts as possible. Instead of imaging a fraction of the available field of view, the simplest guider images the whole field, eliminating the need for a scanning mechanism. Also, intelligent software can track the guide star as the image rotates rather than physically rotating the guide camera.

Any part of the telescope field of view not used by NIRSPEC can be used for guiding, but it is natural to center the guider field on the optical axis. This way, guide stars will never move out of the field due to image rotation; guide stars will be closer to the rotation axis, minimizing their movement; guide star tracking will be unaffected by optical distortions since the aberrations are rotationally symmetric; and the distance between the science object and the guide star is minimized. Because rotational symmetry is preserved, it is also possible to design guider optics that correct the telescope field curvature, eliminating the need for a focus mechanism.

The guider design is shown in Figure 1, which traces two inner and two outer annulus field points. A flat pick-off mirror is placed just outside the NIRSPEC window, with a hole in the center to stay clear of NIRSPEC's field of view. The flat mirror sends light to a concave spherical mirror, which collimates the beam and redirects it through the hole in the flat mirror. A commercial lens then re-images the field onto a CCD. The available guide field becomes annular: the inner radius is no smaller than that which falls into NIRSPEC (23" x %2) and the outer radius is defined by the edge of the CCD. The corners of the CCD are not used since stars in these regions would fall out of the imaged area as the sky rotated. This reduces the size of the mirrors.

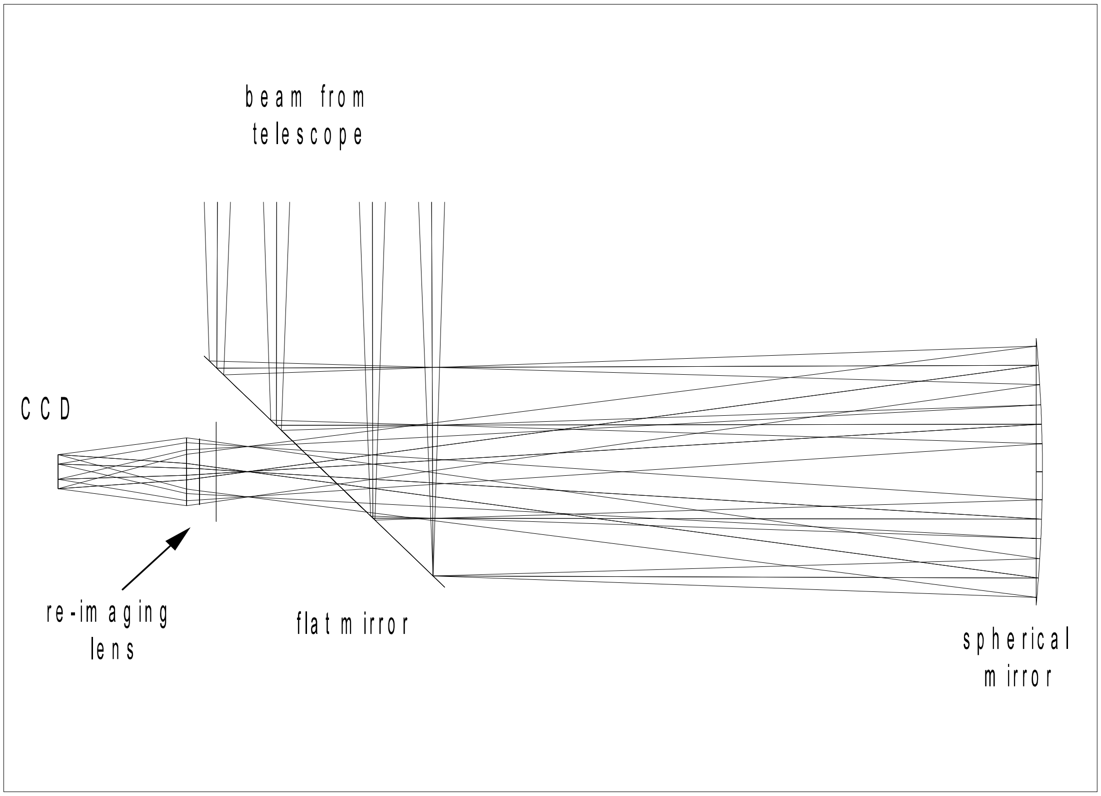


Figure 1. Fixed Guider Design

Field of View

We want the largest field of view possible to minimize the risk of not finding a guide star. Choosing a CCD plate scale that critically samples the smallest typical seeing disk of the guide star gives the maximum field of view allowable. From the R-band seeing histogram in NIRSPEC SLITS

(J. R. Graham 1996), the smallest FWHM is 0.4" which demands a plate scale of 0.2"/pixel. The size of the field is now governed by the size of the CCD.

The f/ratio of the camera can now be calculated using the equation

$$f/\# = 206265 \, \frac{d_{pix}}{D_{Tel}} \, \frac{1}{\theta_{pix}}$$

This gives f/1.5 for 15 µm pixels, and f/2.5 for 24 µm pixels. This camera requires a fast beam and it is important to get a CCD with large pixels. This is at cross-purposes with the need for a large CCD because pixel size generally decreases with larger CCDs.

For a 1024 x 1024 CCD, the total field of view would be 3.4' x 3.4'. The outer radius of the guiding annulus is then 1.7'. NIRSPEC must receive a radius of 23" x %2 = 0.54', so if the inner radius of the guide annulus is set to 0.7' (to allow an oversized field into the spectrometer), the total available field of view for guide stars is $\pi(1.7')^2 - \pi(0.7')^2 = 7.6$ square arcminutes.

Now we can get a rough estimate of the required size of the optical elements to capture this field of view. The guider is very near to the telescope focal plane, whose plate scale is 1.38"/mm. Capturing a field 3.4' across would require mirrors about 200 mm in diameter, fairly large for high-quality mirrors.

Guide Star Probability

The guider field of view determines the limiting magnitude necessary for guiding to ensure a reasonable chance of finding a guide star. For a worst-case scenario we will assume the observations are toward the galactic pole, where star counts are at a minimum. Note that some directions such as the “dark cloud” near the galactic center may be even worse. The density of stars at the galactic pole is taken from Allen, Astrophysical Quantities, 3rd Edition, scaled down by a factor of 0.73 according to Soniera and Bahcall (1981, NASA CP 3374). The probability of finding zero stars brighter than a given magnitude is calculated by

$$P(0) = e^{-\rho A}$$

where ρ is the density of stars and A is the field of view. Table 1 shows these probabilities for a 7.6 sq. arcmin area over a range of V magnitudes.

TABLE 1. Probability of Finding No Guide Stars.

Limiting V magnitude	ρ (stars/deg^2) at galactic pole	Prob. of finding no stars in 7.6 sq. arcmin
18	764	0.199
19	1157	0.087
20	1834	0.021
21	2308	0.008

Guiding down to 19th magnitude presents a 1 in 12 chance of not finding a suitable star at the galactic pole, which is a bit too risky. A 20th magnitude limit brings the probability down to 2%, which approaches an acceptable risk. We clearly must be able to guide accurately at least to 20th magnitude for this field of view to be acceptable.

Not included in these numbers are galaxies, which become prevalent at these magnitudes and can be used for guiding. Thus, the probabilities calculated above can be considered conservative.

Integration Times

Any guiding magnitude limit is reachable provided there is no upper limit on the integration times used. In this application integration times are limited because 1) the telescope open-loop tracking accuracy degrades over time, and 2) field rotation will cause the guide star to smear over the course of an exposure. Using the methodology found in Keck Observatory Report 164 (J. Nelson and J. Cohen 1987), this section calculates the integration time needed to centroid accurately on guide at the required V=20 limit defined previously.

The two-dimensional rms error in centroiding is given by the relation

$$\sigma_{cent} = 0.601\, FWHM \frac{\sigma_n}{n}$$

where σ_n is the total noise in the aperture used for centroiding, n is the number of electrons due to the star, and FWHM is the size of the seeing disk (King 1983, PASP 95, 163). The total noise is given by

$$\begin{aligned}\sigma_n^2 &= (e^-)_{star} + (e^-)_{sky} + (e^-)_{dark\ current} + (e^-)^2_{readnoise} \\ &= \varepsilon N_{20} t [10^{0.4(20-V_{star})} + A\,10^{0.4(20-V_{sky})}] + Dt\frac{A}{a^2} + R^2\frac{A}{a^2}\end{aligned}$$

where ε = total system throughput (incl. atmosphere and detector q.e.) in e^-/photon
t = integration time
V_{star} = V magnitude of guide star
V_{sky} = V magnitude of sky per arcsec^2
A = effective area used for centroid calculation in arcsec^2
a = size of pixel in arcsec
D = CCD dark current in e^-/sec/pixel
R = CCD readout noise in e^-/pixel
N_{20} = 7100 photons/sec from a V=20 star hitting Keck aperture above atmosphere

Appendix 1 shows the centroid uncertainty (in arcsec) as a function of integration time for a V=20 star, assuming a total system throughput of 0.3, 0.7" seeing, the optimal aperture for centroiding 5.55 FWHM^2 (King 1983), full moon sky brightness (V=18), dark current of 1 e^-/sec/pix and readout noise of 25 e^-/pix.

Using these values, centroid accuracies of 1/20 slit width (0.02") are reached with 4.7 second exposures. However, centroid errors are highly dependent upon seeing. Using 1" seeing, it takes 16.3 seconds to reach the same accuracy. Note that when the moon is not full, these exposures are dominated by read noise. It is therefore important to use a CCD package with low read noise.

These times should be considered approximate at best, but they demonstrate that accurate centroiding down to 20th magnitude does not require unreasonable integration times. There is one other characteristic of this design that affects centroid accuracy, which is explored in the next section.

Guide Star Smear

Because this guider design does not compensate for image rotation, guide stars will move across the CCD during the course of an exposure. This will degrade the centroid performance by 1) elongating the star, and 2) distributing the starlight onto more pixels (noise). The second effect is probably the dominant one. Models of this effect show that increasing the exposure time improves the centroid accuracy, even though it allows the guide star to smear across even more pixels. In effect, the increased signal wins out over the increased noise. However, as the exposure time increases, the centroid accuracy asymptotically approaches some value. For a given observing situation it may not be possible to guide to the desired accuracy.

The allowable exposure time is also limited, as the telescope tracking rate needs to be corrected at finite intervals. Exposures cannot be longer than the telescope can track on its own to the desired accuracy. Predicted Keck open-loop tracking accuracies are as follows: 0.02 arcseconds rms over 10 seconds, 0.1 arcsec over 10 minutes and 0.5 arcsec over 1 hour (J. Nelson and J. Cohen 1987, Keck Observatory Report 164). Actual tracking slippage has been measured at 4.5 arcsec over 1100 seconds (Beth Klein 1995, private communication), but the conditions under which this rate was measured are unknown. If this slippage is typical, it indicates that the telescope cannot go unguided for any length of time, which is impossible to satisfy since it takes several seconds just to read out the CCD, perform the centroid calculation, and send a tracking correction to the telescope. For the sake of argument, we shall set 10 seconds as the maximum allowable exposure time.

Guide star smear models were derived by calculating the noise per pixel from calculations described earlier, then estimating how many pixels the star will move across during the exposure time, given a star speed across the CCD. A total noise was then calculated by multiplying the noise per pixel by the square root of the number of pixels the star inhabits. This total noise was fed into the centroid error calculation presented earlier to get a final centroid error.

Star speeds were calculated using equations from V. P. Yegorov and Yu. A. Sabinin (1971, New Techniques in Astronomy, ed. H. C. Ingrao, Chapter I-8). The field rotation rate in rad/sec is

$$\frac{dp}{dt} = \frac{\omega_0 \cos\phi \cos A}{\sin Z}$$

where A is the azimuth, Z is the zenith angle, ϕ is the local latitude (19.833° for Keck), and ω_0 is the sidereal rate (7.2925×10^{-5} rad/sec). This equation can be expressed in terms of hour angle and declination by using the following conversions.

$$A = \arctan \frac{\cos\delta \sin t}{\cos\delta \sin\phi \cos t - \sin\delta \cos\phi}$$

$$Z = \arctan \frac{\cos\delta \sin\phi \cos t - \sin\delta \cos\phi}{\cos A(\cos\phi \cos\delta \cos t + \sin\phi \sin\delta)}$$

where δ is the declination and t is the hour angle. The rotation rate (rad/sec) is multiplied by the star's distance from the rotation axis at the telescope focal plane (mm) and by the telescope's plate scale (arcsec/mm) to obtain the star's speed in field arcseconds per second.

Appendix 2 contains a velocity map around the zenith, the region of fastest image rotation, for a star on the outer edge of the guiding annulus (the worst position). Declination runs vertically and is defined by the apparent declination minus Keck’s latitude of 19.833/. Hour angle (in minutes of time) runs horizontally.

Earlier it was found that for 0.7" seeing and full moon background, a V=20 star needed 4.7 second exposures to reach a centroid accuracy of 0.02". This is only true if the star is stationary. A 10 second exposure will still allow 0.02" guiding accuracy for star speeds less than 0.2"/sec. If the star resides at the outer edge of the guiding annulus, then from Appendix 2 we see that this speed is exceeded for declinations within ± 2/ of zenith, extending at most 4.2 minutes on either side of the meridian. This means that near the zenith in this worst-case scenario, guiding could not be performed to this accuracy for as long as 8.4 minutes. Table 2 summarizes the size of this "poor guiding" region for seeing conditions of 0.4", 0.7" and 1.0" for a V=20 star in two cases: worst case (star on outer edge of annulus, full moon) and typical case (star in middle of annulus, moon half-illuminated), assuming 10 second maximum exposures.

TABLE 2. Region of Sky with Guiding Error Worse than 0.02" for V=20 Star

Seeing (FWHM)	Worst Case		Typical Case	
	dec: 19.833° ±	hour angle	dec: 19.833° ±	hour angle
0.4 arcsec	0.3°	± 0.3 min	(in blind spot)	(in blind spot)
0.7 arcsec	2.0°	± 4.2 min	1.5°	± 3.0 min
1.0 arcsec	(all sky)	(all sky)	(all sky)	(all sky)

At 0.4" seeing in the typical case, the poor guiding region is completely encompassed by the Keck blind spot (± 0.22/ dec within zenith, ± 1.4 minutes of hour angle). At 1" seeing, a 10 second exposure will not allow for 0.02" centroiding even with a stationary star. This is acceptable since 0.02" centroiding is only required during good seeing: poor seeing will either present a flat point spread function inside the nominal slit (making spectroscopy insensitive to target wander) or require a larger slit and thus a larger centroid error. For typical seeing (0.7"), even the worst case scenario makes guiding poor for only a few minutes for a very small range of declination.

Increasing the field of view to allow more V=19 stars only accepts stars further away from the rotation axis, leading to more smear. We cannot, for any reasonable magnitude star, completely eliminate the effect of guide star smear up to the Keck blind spot without physically rotating the guider camera. The issue, then, is whether the guider design be allowed to be driven by an area of sky this small. Eight minutes (maximum) is not much observing time to lose. It seems like a sufficient number of "ifs" have been built up in arriving at this worst-case scenario that an acceptable risk has been established.

Redder Bands

Until now, this note has assumed V-band guiding. Although it has been shown that satisfactory performance is achieved at V (0.55 μm), redder bands such as R (0.65 μm) or I (0.83 μm) should be considered. The photon flux corresponding to a given magnitude decreases with increasing wavelength (20th magnitude fluxes are 7100 photons/sec @ V, 6000 photons/sec @ R and 5500 photons/sec @ I), but the star counts at a given magnitude increase considerably. This reduces the limiting magnitude necessary to ensure finding a guide star. The limiting magnitudes necessary to keep a 98% probability of finding a guide star at the galactic pole are V = 20, R = 19.5 and I = 18.6.

CCD quantum efficiencies between V and R are roughly the same, but at I the efficiency drops almost in half. Full moon sky backgrounds are much fainter at redder bands, and the seeing also improves. Even assuming no improvement in background, seeing or atmospheric transparency, the models used previously show that the integration times necessary to reach the desired centroid accuracy with a limiting magnitude star drop considerably with increasing wavelength. R-band exposures need only 65% of the V-band integration time, and I-band exposures need roughly 50% of the V-band time.

The problem with I-band is that expensive, less durable mirror coatings would be required, and a commercial lens may not perform adequately. The R-band is probably optimal, and a commercial lens can be refocused to perform well at these wavelengths.

Technical Considerations

A CCD that meets the requirements of this design is currently manufactured by SITe (formerly Tektronix), which offers a 1024 x 1024 pixel device with 24 μm pixels and dark currents less than 1 e$^{!}$ @ ! 30/C. Photometrics, Princeton, and other companies offer turn-key cameras using this device, with acceptable read noises (see Appendix 3). All these packages offer subarray readouts, decreasing the readout time without increasing the readout noise.

The mirrors we require are not offered off-the-shelf but can be custom made to our specifications by companies such as International Scientific Products, at a cost far less than lenses performing the same function. Re-imaging lenses to capture the collimated beam and give the requisite f/2.5 imaging onto 24 μm pixels are commonly available from any major camera company like Nikon or Canon. For R-band guiding, these lenses have an “infrared” refocus dial.

Optical Design

All guider optical Zemax design files can be found in the *altair/c/zmx404/nirspec/guider* directory. The final end-to-end design is *gcam00.zmx*, which is in millimeters. The design expressed in meters is in *cdrgcam.zmx*, and tolerances were generated in *gcam00tl.zmx*.

The full optical prescription of the guider system is included in Appendix 4. Table 3 shows the optical and mechanical specifications for the guider mirrors. The substrates should not exceed the dimensions given in Table 3 or they will run into the dewar wall. The surfaces must meet the performace specifications out to within 3 mm of the edge.

TABLE 3. Guider Optical Prescription

Mirror	Radius (mm)	Major axis (mm)	Minor axis (mm)	Thickness[a] (mm)
flat	infinity	233.0	165.0	23.0
(flat hole)	-	83.2	58.8	-

sphere	1060.3	190.0	190.0	-

[a] Thickness refers to the physical thickness of the mirror substrate, not a distance between surfaces. No thickness is listed for the spherical mirror because no restrictions apply to it.

Note that the beam footprint at the flat is elliptical. The dimensions given for this mirror and its hole are for the major and minor axes of these ellipses. The hole must be an ellipse, but the mirror can be rectangular. The edge of the hole must be chamfered at 45E in the long axis, so that neither beam “sees” the substrate. It is preferable, but not necessary, to have the edge of this mirror that is closest to the dewar chamfered at 45E. The thickness of this mirror must not exceed 23 mm, or one tenth of its major axis, to allow sufficient room for the lens behind it. No thickness restrictions apply to the spherical mirror.

Optomechanical tolerances were generated by limiting the degradation of spot size, plate scale, and clearance through the hole in the flat mirror and entrance aperture of the commercial lens. Table 4 shows the tolerances that must be met to ensure that these constraints are preserved.

TABLE 4. Guider Optomechanical Tolerances

Tolerance	Units	flat	flat hole	sphere
axes (diam)	mm	± 2	± 0.5	± 2
radius	mm	-	-	+ 9 - 11
surface figure	$l_{632.8\text{nm}}$ rms	4	-	2
surface quality	-	60/40	-	60/40
surface roughness	Angstroms	150	-	150
thickness	mm	+ 0	-	-

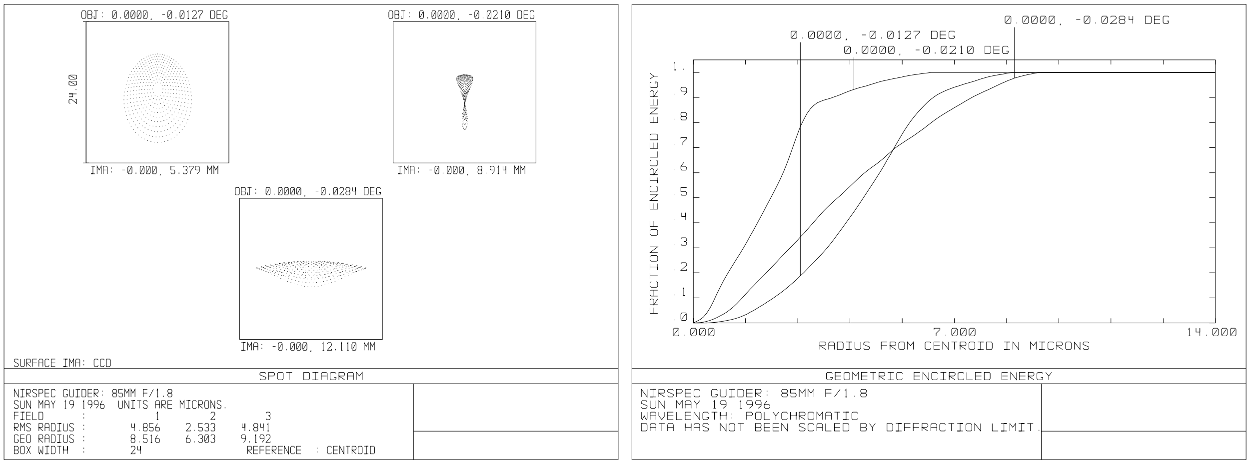
The tolerance on the hole dimensions are most critical at the lowermost position as viewed in Figure 1, where the collimated beam is at its closest point. A tighter tolerance than that listed above is desirable at that point, whereas the rest of the hole could be kept to a looser tolerance if necessary.

Spot diagrams and geometric encircled energy plots in Figure 2 are traced for three field points: inner, middle, and outer points on the guiding annulus. The end-to-end performance does not include aberrations from the final re-imaging lens, since its design is unavailable to us. By the same token, diffraction encircled energy could not be measured either. The ray-trace design simply uses a perfect “paraxial” lens with the correct focal length in place of the real lens. Because of this, the ray-trace is independent of wavelength. Nevertheless, the spots at all field points are substantially smaller than the size of one pixel. At visible wavelengths diffraction effects will be minimal, and the performance of commercial lenses are usually close to diffraction-limited.

Figure 2. Spot diagrams and geometric encircled energy plots for inner, middle, and outer field points in the guider annulus. Box size in spot diagrams is equal to one pixel. Rightmost edge of encircled energy plot represents the energy captured in one pixel.

Summary

The simple, fixed guider system appears to be able to satisfy all of the defined performance requirements. That is, it is easy to scan the field in search of a guide star since the whole field is imaged at once; it can hold a guide star all night; its field of view provides a low probability of not finding a suitable star; and in theory it can guide to acceptable accuracy anywhere in the sky except for a few minutes at the smallest zenith angles. Optical models show the performance to be more than satisfactory at all field points without the need for a focus mechanism, and all necessary components for this system can be acquired either commercially or custom-made.



APPENDIX 1. Guider Centroid Error with V=20 Star, 0.7" seeing @ full moon

Variables:

0.300	e	total system throughput [e/photon]
20.00	Vstar	V magnitude of guide star
0.70	FWHM	seeing [arcsec]
2.72	Ae	effective area used for centroiding [arcsec^2]
18.00	Vsky	V magnitude of sky (22 dark, 18 full moon)
1.00	D	dark current [e/sec/pix]
0.20	a	pixel size [arcsec]
25.00	R	readout noise [e/pixel]
7100.00	N20	photons/sec from V=20 star hitting Keck aperture at top of atmosphere

exp time [sec]	star counts	sky counts	dark current	readnoise^2	tot. noise^2	centroid error
0.5	1065	18274	34	42492	61865	0.0983
1	2130	36548	68	42492	81239	0.0563
1.5	3195	54823	102	42492	100612	0.0418
2	4260	73097	136	42492	119985	0.0342
2.5	5325	91371	170	42492	139358	0.0295
3	6390	109645	204	42492	158731	0.0262
3.5	7455	127919	238	42492	178105	0.0238
4	8520	146194	272	42492	197478	0.0219
4.5	9585	164468	306	42492	216851	0.0204
5	10650	182742	340	42492	236224	0.0192
5.5	11715	201016	374	42492	255597	0.0182
6	12780	219291	408	42492	274971	0.0173
6.5	13845	237565	442	42492	294344	0.0165
7	14910	255839	476	42492	313717	0.0158
7.5	15975	274113	510	42492	333090	0.0152
8	17040	292387	544	42492	352463	0.0147
8.5	18105	310662	578	42492	371837	0.0142
9	19170	328936	612	42492	391210	0.0137
9.5	20235	347210	646	42492	410583	0.0133
10	21300	365484	680	42492	429956	0.0130
10.5	22365	383758	714	42492	449330	0.0126
11	23430	402033	748	42492	468703	0.0123
11.5	24495	420307	782	42492	488076	0.0120
12	25560	438581	816	42492	507449	0.0117
12.5	26625	456855	850	42492	526822	0.0115
13	27690	475130	884	42492	546196	0.0112
13.5	28755	493404	918	42492	565569	0.0110
14	29820	511678	952	42492	584942	0.0108
14.5	30885	529952	986	42492	604315	0.0106
15	31950	548226	1020	42492	623688	0.0104
15.5	33015	566501	1054	42492	643062	0.0102
16	34080	584775	1088	42492	662435	0.0100
16.5	35145	603049	1122	42492	681808	0.0099
17	36210	621323	1156	42492	701181	0.0097
17.5	37275	639597	1190	42492	720554	0.0096
18	38340	657872	1224	42492	739928	0.0094
18.5	39405	676146	1258	42492	759301	0.0093
19	40470	694420	1292	42492	778674	0.0092
19.5	41535	712694	1326	42492	798047	0.0090
20	42600	730969	1360	42492	817420	0.0089

APPENDIX 2. Guide Star Speed (in field arcseconds/second).

CCD plate scale		0.2	arcsec/pixel		
dist from optical axis		74	mm	min=31mm	max= 74mm
t (min)	8	6	4	2	0
t (deg.)	2	1.5	1	0.5	0

Z	dP/dt	dP/dt	dP/dt	dP/dt	dP/dt
12	0.033	0.033	0.033	0.034	0.034
11	0.036	0.036	0.036	0.037	0.037
10	0.039	0.039	0.040	0.040	0.040
9	0.043	0.044	0.044	0.045	0.045
8	0.048	0.049	0.050	0.050	0.050
7	0.053	0.055	0.056	0.057	0.057
6	0.061	0.063	0.065	0.067	0.067
5	0.070	0.074	0.077	0.080	0.080
4	0.082	0.089	0.095	0.099	0.100
3	0.095	0.109	0.122	0.130	0.134
2	0.105	0.133	0.164	0.190	0.201
1	0.087	0.133	0.212	0.328	0.401
0.22	0.023	0.042	0.093	0.326	1.824
-0.22	-0.026	-0.045	-0.096	-0.329	-1.824
-1	-0.090	-0.136	-0.214	-0.329	-0.401
-2	-0.108	-0.135	-0.165	-0.190	-0.201
-3	-0.097	-0.110	-0.122	-0.131	-0.134
-4	-0.083	-0.090	-0.095	-0.099	-0.100
-5	-0.071	-0.075	-0.078	-0.080	-0.080
-6	-0.061	-0.064	-0.065	-0.067	-0.067
-7	-0.054	-0.055	-0.057	-0.057	-0.057
-8	-0.048	-0.049	-0.050	-0.050	-0.050
-9	-0.043	-0.044	-0.044	-0.045	-0.045
-10	-0.039	-0.040	-0.040	-0.040	-0.040
-11	-0.036	-0.036	-0.036	-0.037	-0.037
-12	-0.033	-0.033	-0.033	-0.034	-0.034

APPENDIX 4. Full Optical Prescription for the Guider Camera

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System/Prescription Data

File : G:\ZMX45\NIRSPEC\GUIDER\GCAM00.ZMX
Title: NIRSPEC Guider: 85mm f/1.8
Date : SAT MAY 25 1996

GENERAL LENS DATA:

Surfaces        :          15
Stop            :           2
System Aperture :Entrance Pupil Diameter
Ray aiming      : Off
Apodization     :Uniform, factor =     0.000000
Eff. Focal Len. :    -24229.7 (in air)
Eff. Focal Len. :    -24229.7 (in image space)
Total Track     :     19255.7
Image Space F/# :     2.42297
Working F/#     :      2.4737
Obj. Space N.A. :4.99999e-007
Stop Radius     :        5000
Parax. Ima. Hgt.:     12.0269
Parax. Mag.     :           0
Entr. Pup. Dia. :       10000
Entr. Pup. Pos. :       16650
Exit Pupil Dia. :     68.4762
Exit Pupil Pos. :    -165.958
Field Type      : Angle in degrees
Maximum Field   :     0.02844
Primary Wave    :    0.700000
Lens Units      : Millimeters
Angular Mag.    :    -146.036

Fields          : 5
Field Type: Angle in degrees
#        X-Value        Y-Value         Weight
1       0.000000      -0.012700       1.000000
2       0.000000      -0.021000       1.000000
3       0.000000      -0.028440       1.000000
4       0.000000       0.028440       1.000000
5       0.000000       0.012700       0.000000

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     : 1
Units: Microns
#          Value         Weight
1       0.700000       1.000000

SURFACE DATA SUMMARY:

Surf     Type       Radius    Thickness        Glass     Diameter       Conic
 OBJ STANDARD     Infinity     Infinity                         0           0
   1 STANDARD     Infinity        16650                     491.4           0
 STO STANDARD       -34974    -15394.99       MIRROR        10000   -1.003683
   3 STANDARD    -4737.916     17818.62       MIRROR     1309.857   -1.644326
   4 COORDBRK     --------            0                         0    --------
   5 STANDARD     Infinity            0                  222.9301           0
   6 STANDARD     Infinity            0       MIRROR     222.9301           0
   7 COORDBRK     --------    -490.8212                         0    --------
   8 STANDARD     1060.308     490.8212       MIRROR     179.1102           0
   9 COORDBRK     --------            0                         0    --------
  10 STANDARD     Infinity            0                      81.2           0
  11 COORDBRK     --------           74                         0    --------
  12 STANDARD     Infinity      11.4325                  42.42345           0
  13 STANDARD     Infinity       8.7325                      45.8           0
  14 PARAXIAL     --------     87.85641                  48.37912    --------
 IMA STANDARD     Infinity            0                  24.21961           0

SURFACE DATA DETAIL:
```

```
Surface OBJ     : STANDARD
Surface   1     : STANDARD
 Aperture       : Circular Obscuration
 Minimum Radius :             0
 Maximum Radius :       654.929
Surface STO     : STANDARD
 Aperture       : Circular Aperture
 Minimum Radius :       654.929
 Maximum Radius :        1e+010
Surface   3     : STANDARD
Surface   4     : COORDBRK
 Decenter X     :             0
 Decenter Y     :             0
 Tilt About X   :            45
 Tilt About Y   :             0
 Tilt About Z   :             0
Surface   5     : STANDARD
 Comment        : PICKOFF HOLE
 Aperture       : Elliptical Obscuration
 X Half Width   :          29.5
 Y Half Width   :          41.6
Surface   6     : STANDARD
 Comment        : PICKOFF FLAT
 Aperture       : Elliptical Aperture
 X Half Width   :          82.4
 Y Half Width   :         116.5
Surface   7     : COORDBRK
 Decenter X     :             0
 Decenter Y     :             0
 Tilt About X   :            45
 Tilt About Y   :             0
 Tilt About Z   :             0
Surface   8     : STANDARD
 Comment        : COLLIMATOR
 Aperture       : Circular Aperture
 Minimum Radius :             0
 Maximum Radius :            95
Surface   9     : COORDBRK
 Decenter X     :             0
 Decenter Y     :             0
 Tilt About X   :           -45
 Tilt About Y   :             0
 Tilt About Z   :             0
Surface  10     : STANDARD
 Comment        : PICKOFF HOLE
 Aperture       : Elliptical Aperture
 X Half Width   :          29.5
 Y Half Width   :          41.6
Surface  11     : COORDBRK
 Decenter X     :             0
 Decenter Y     :             0
 Tilt About X   :            45
 Tilt About Y   :             0
 Tilt About Z   :             0
Surface  12     : STANDARD
 Comment        : FRONT OF LENS
 Aperture       : Circular Aperture
 Minimum Radius :             0
 Maximum Radius :          35.5
Surface  13     : STANDARD
 Comment        : 1ST LENS ELEMENT
 Aperture       : Circular Aperture
 Minimum Radius :             0
 Maximum Radius :          23.6
Surface  14     : PARAXIAL
 Comment        : PRINCIPLE PLANE
 Focal length   :        84.815
Surface IMA     : STANDARD
 Comment        : CCD
 Aperture       : Rectangular Aperture
 X Half Width   :          12.3
 Y Half Width   :          12.3

SOLVE AND VARIABLE DATA:

Semi Diam   1      : Fixed
Semi Diam   2      : Fixed
Semi Diam   3      : Fixed
Thickness of   7   : Variable
Parameter  3 Surf   7: Pickup from 4 times 1.000000
```

```
Curvature of   8   : Variable
Thickness of   8   : Solve, pick up value from 7, scaled by -1.00000
Parameter  3 Surf  11: Pickup from 9 times -1.000000
Thickness of  14   : Variable

INDEX OF REFRACTION DATA:

Surf     Glass      0.700000
   0              1.00000000
   1              1.00000000
   2    MIRROR    1.00000000
   3    MIRROR    1.00000000
   4              1.00000000
   5              1.00000000
   6    MIRROR    1.00000000
   7              1.00000000
   8    MIRROR    1.00000000
   9              1.00000000
  10              1.00000000
  11              1.00000000
  12              1.00000000
  13              1.00000000
  14              1.00000000
  15              1.00000000

F/# DATA:
             Wavelength:        0.700000
 #              Field        Tan       Sag
 1  0.0000, -0.0127 deg:    2.4719    2.4738
 2  0.0000, -0.0210 deg:    2.4686    2.4738
 3  0.0000, -0.0284 deg:    2.4641    2.4737
 4   0.0000, 0.0284 deg:    2.4641    2.4737
 5   0.0000, 0.0127 deg:    2.4719    2.4738

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  16650.000000  0.000000  0.000000  1.000000
  3      0.000000      0.000000   1255.015000  0.000000  0.000000  1.000000
  4      0.000000      0.000000  19073.633360  0.000000 -0.707107  0.707107
  5      0.000000      0.000000  19073.633360  0.000000 -0.707107  0.707107
  6      0.000000      0.000000  19073.633360  0.000000 -0.707107  0.707107
  7      0.000000      0.000000  19073.633360  0.000000 -1.000000 -0.000000
  8      0.000000    490.821158  19073.633360  0.000000 -1.000000 -0.000000
  9      0.000000      0.000000  19073.633360  0.000000 -0.707107  0.707107
 10      0.000000      0.000000  19073.633360  0.000000 -0.707107  0.707107
 11      0.000000      0.000000  19073.633360  0.000000 -1.000000 -0.000000
 12      0.000000    -74.000000  19073.633360  0.000000 -1.000000 -0.000000
 13      0.000000    -85.432500  19073.633360  0.000000 -1.000000 -0.000000
 14      0.000000    -94.165000  19073.633360  0.000000 -1.000000 -0.000000
 15      0.000000   -182.021409  19073.633360  0.000000 -1.000000 -0.000000

ELEMENT VOLUME DATA:

Units are cubic cm.
Values are only accurate for plane and spherical surfaces.
```