FOREOPTICS AND SLIT VIEWER OPTICAL DESIGN

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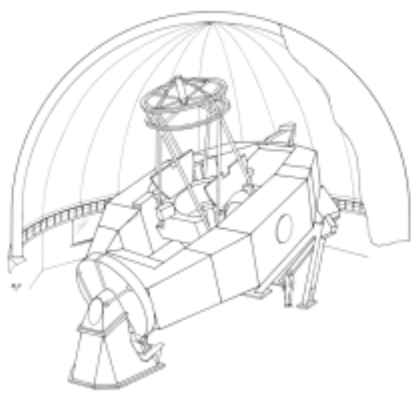

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Revision History

Revision No.	Author & Date	Approval & Date	Description
Revision 1	John Rayner 1/12/13		Preliminary Release.

Contents

1 INTRODUCTION

This document explains how the foreoptics and slit viewer optical design is derived and implemented. The design requirements are derived from the science case and the design decisions are discussed.

2 DESIGN

2.1 Requirements

The top-level requirements (**TR_#**) flow down from the science derived requirements (see Science Requirements Document) and are the starting point for the FPRD and optical alignment plan:

Table 2.1. Fpreoptics and slit viewer optical design requirements

Requirement Number	Requirement Name
SR_2	Sensitivity
SR_8	Slit orientation
SR_14	Observing efficiency
TR_1	Throughput
TR_7	Image rotator
TR_8	Cold Stop and Pupil Viewer
TR_12	Image Quality at the Slit
TR_14	Image Quality at the Slit Viewer Detector
TR_16	Position at the Slit Viewer Detector

2.2 Layout

2.2.1 Foreoptics

The fundamental reason for having foreoptics (i.e. pre-slit optics) in iSHELL is to place the entrance pupil on a cold stop prior to the slit. As explained in the Spectrograph Optical Design document (section 4.1) this avoids the diffractive blurring effects of placing the cold stop following the slit and is optimum for minimizing scattered light and thermal background. This is achieved with a collimator and camera arrangement. To minimize aberrations in the spectrograph collimators one-to-one reimaging in the foreoptics feeds the slow f/38.3 beam from the telescope into the spectrograph.

The layout of the fore-optics and slit viewer is shown in Figure 2.1. The f/38.3 beam from the telescope enters the cryostat through a CaF_2 entrance window and comes to a focus at the telescope focal plane (TFP), which is 42″ in diameter. Immediately inside the window is a baffle tube (not shown). A mirror then folds the beam from vertical to horizontal. The design allows this mirror to be replaced by a dichroic that transmits the optical beam out of the bottom of the cryostat through a CaF_2 exit window, while the infrared beam is reflected. There are no immediate plans to use the optical beam but this design retains the option of using a CCD guider of the type that has proved useful for SpeX (the MORIS CCD camera).

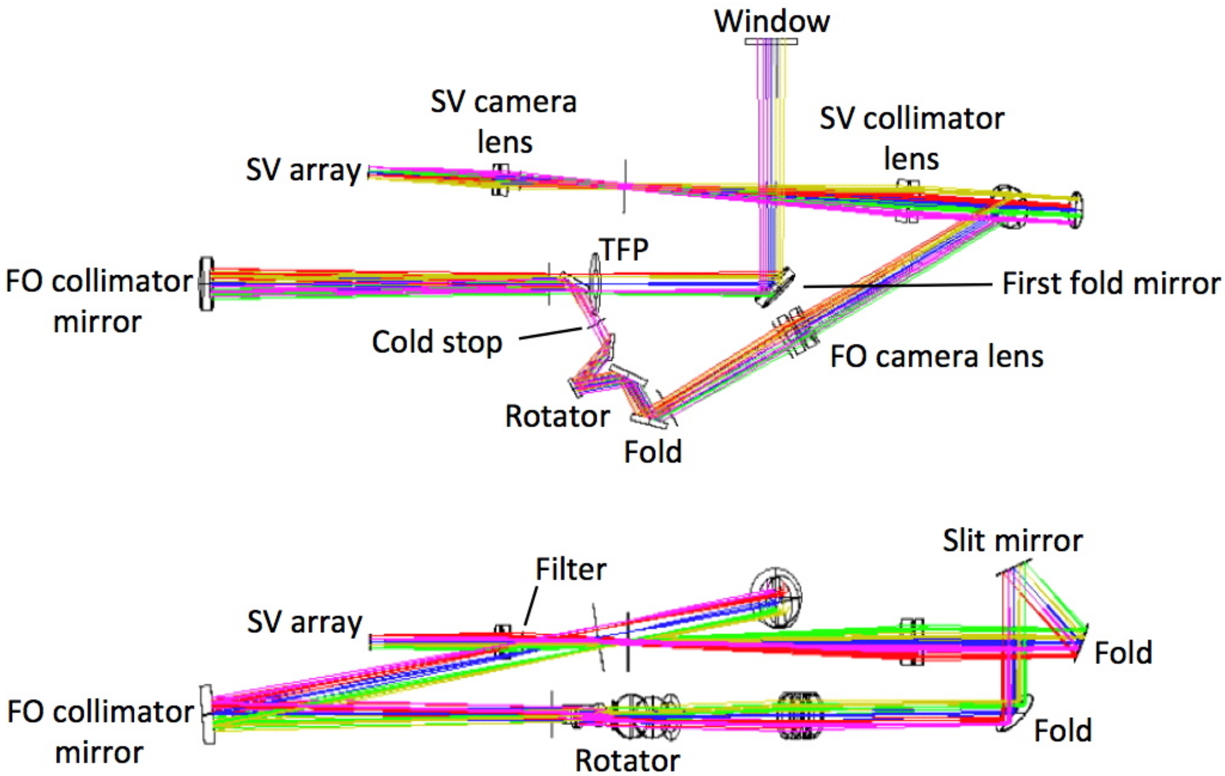

Figure 2.1. Raytrace of the foreoptics and slit viewer. For scale the distance from the first fold mirror to the foreoptics collimator mirror is 556 mm. Light enters the spectrograph through a slot in the slit mirror.

The TFP is re-imaged onto the slit wheel by a collimator-camera system. A spherical collimator mirror of focal length 381 mm gives an entrance pupil diameter of 10.00 mm. This is a compromise between available space and the need for accurate photometry. A smaller stop requires a shorter focal length but is more sensitive to lateral position and therefore vignetting. A 5-degree tilt of the collimator is required to clear the incoming beam but does not introduce significant aberrations. The cold stop is also the best place to baffle to minimize off-axis scattered light and thermal flux from the telescope, which is not baffled.

Together with the optical performance requirements another important requirement is to rotate the plane of the sky on the slit. This is done with a k-mirror image rotator located just behind the cold stop to keep it manageably small. A BaF_2 –LiF achromatic doublet lens images the beam exiting the rotator onto the slit wheel.

2.2.2 Slit viewer

One disadvantage of imaging at f/38.3 onto the slit is the relatively large spatial size of the field of view (1.80″ mm^{-1}). A practical limit is about 25 mm in diameter, which, allowing for a tilt of 22.5 degrees to direct the reflected field into the slit viewer, gives a field of 42″ in diameter. A refractive collimator-camera re-images the slit field onto a Raytheon 512x512 InSb array with an image scale of 0.10″ per pixel, which is a good image scale for guiding. The collimator and camera lenses are both BaF_2 –LiF achromatic doublets. A filter wheel containing about 15 positions allows a selection of 19.05 mm diameter filters to be used for object acquisition, guiding, and scientific imaging (see Table 2.2).

Table 2.2. Filters (tbc) in the slit viewer filter wheel.

Position #	***Filter***	***Notes***
1	Blank	
2	Y	1.00-1.10 μm
3	J_{MK}	1.164-1.326 μm
4	H_{MK}	1.487-1.783 μm
5	K_{MK}	2.027-2.363 μm
6	L'_{MK}	3.424-4.124 μm
7	M'_{MK}	4.564-4.803 μm
8	J+H	Notch
9	H+K	Notch
10	Cont K	2.26 μm 1.5%
11	Cont K + ND 2.0	2.26 μm 1.5%
12	3.454 μm	0.5%
13	3.953 μm	0.5%
14	PV lens + nb$L$	Pupil diameter 325 pixels, spatial resolution 3.6 pixels (33 mm on primary)
15	TBD	

2.2.3 Pupil viewer

A ZnS lens sandwiched together with a narrow-band L filter in the filter wheel can be used to image the telescope pupil. The pupil viewer (PV) provides a means to align the cryostat on the MIM by examining the image of the telescope secondary mirror conjugated at the cold stop. The diameter of the re-imaged pupil on the slit viewer array is 325 pixels and the spatial resolution is 3.6 pixels (about 1% of the pupil). The resolution is diffraction limited by the aperture of the foreoptics lenses.

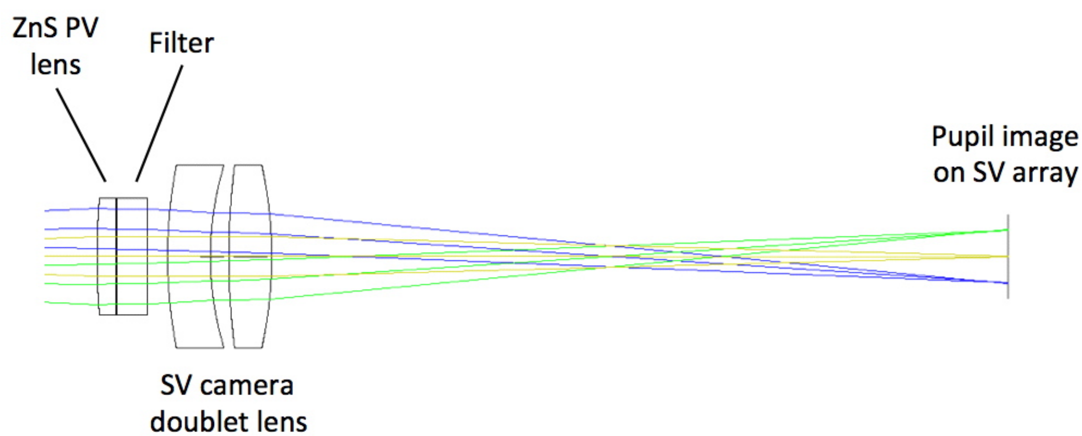

Figure 2.2. Pupil viewer lens sandwiched with *nbL* filter in filter wheel. The filter is 19.05 mm diameter.

2.3 Optimization and Nominal Performance

2.3.1 Cold stop

A spherical collimator mirror of focal length 381 mm gives an achromatic entrance pupil diameter of 10.00 mm. It is tilted by 5 degrees to avoid colliding with the incoming beam. The image quality at the cold stop is about 0.1 mm (see Figure 2.3) and meets the image quality requirement (TR_8).

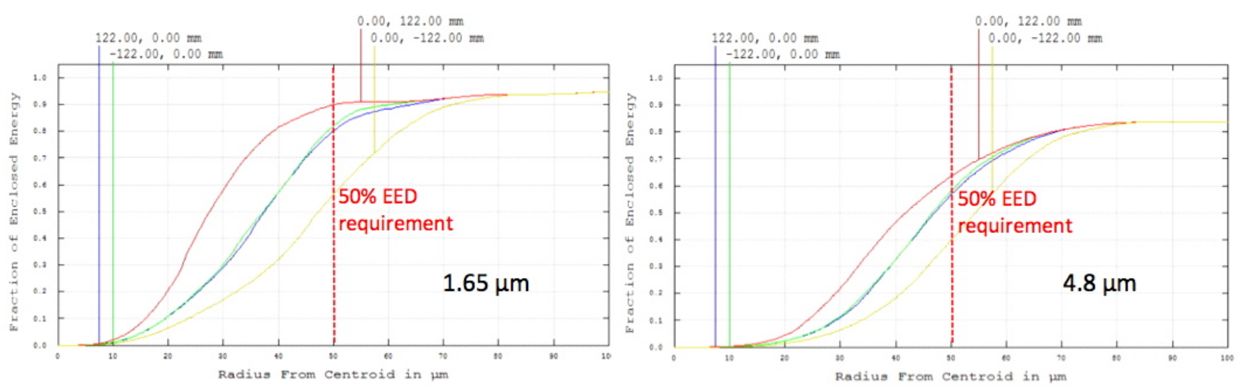

Figure 2.3. Encircled energy of optical spots at cold stop including diffraction. Fifty percent full width is about 0.1 mm at 1.65 µm (*left*) and 4.8 µm (*right*).

2.3.2 Image quality at slit

The TFP is re-imaged at one-to-one magnification onto the slit plane by a collimator-camera system consisting of the spherical collimating mirror and camera lens. For the camera lens the low-index materials BaF_2 and LiF form a good achromatic match across 1-5 µm. All the lens surfaces are spherical.

Higher index materials are not required to meet the image quality requirement. By placing the stop at the front focus of the camera the f/38.3 beam at the slit is telecentric and so any slight changes in telescope focus do not change the image scale.

Figure 2.4 shows the through-focus spot diagram at the slit plane for all wavelengths (1.1 µm, 1.25 µm, 1.65 µm, 2.2 µm, 3.8 µm, 4.8 µm, and 5.3 µm) and the indicated field positions. The geometrical spot sizes are small compared to the 2.2 µm Airy disk drawn (204 µm diameter).

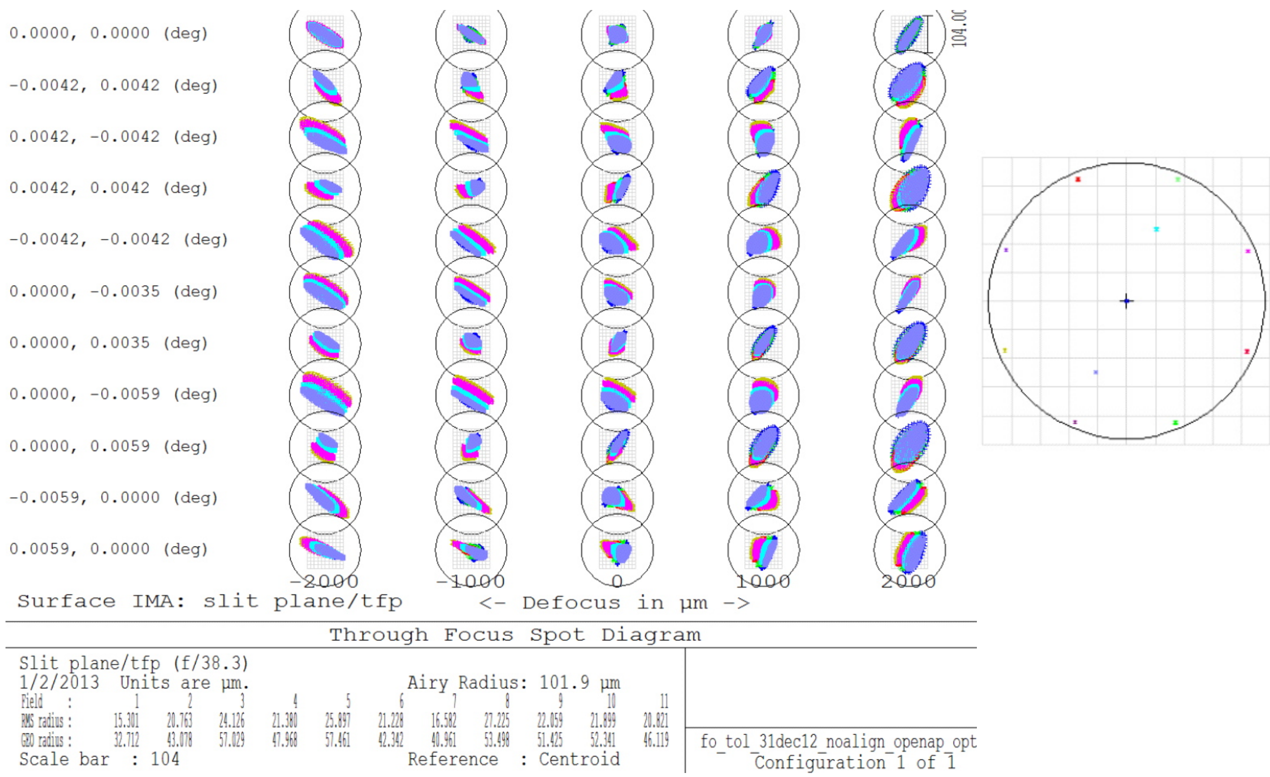

Figure 2.4. Through-focus spot diagram at all wavelengths and the indicated field positions. The location of the fields in the 25 mm diameter FOV are shown in the inset (right). The 2.2 µm Airy disk is shown.

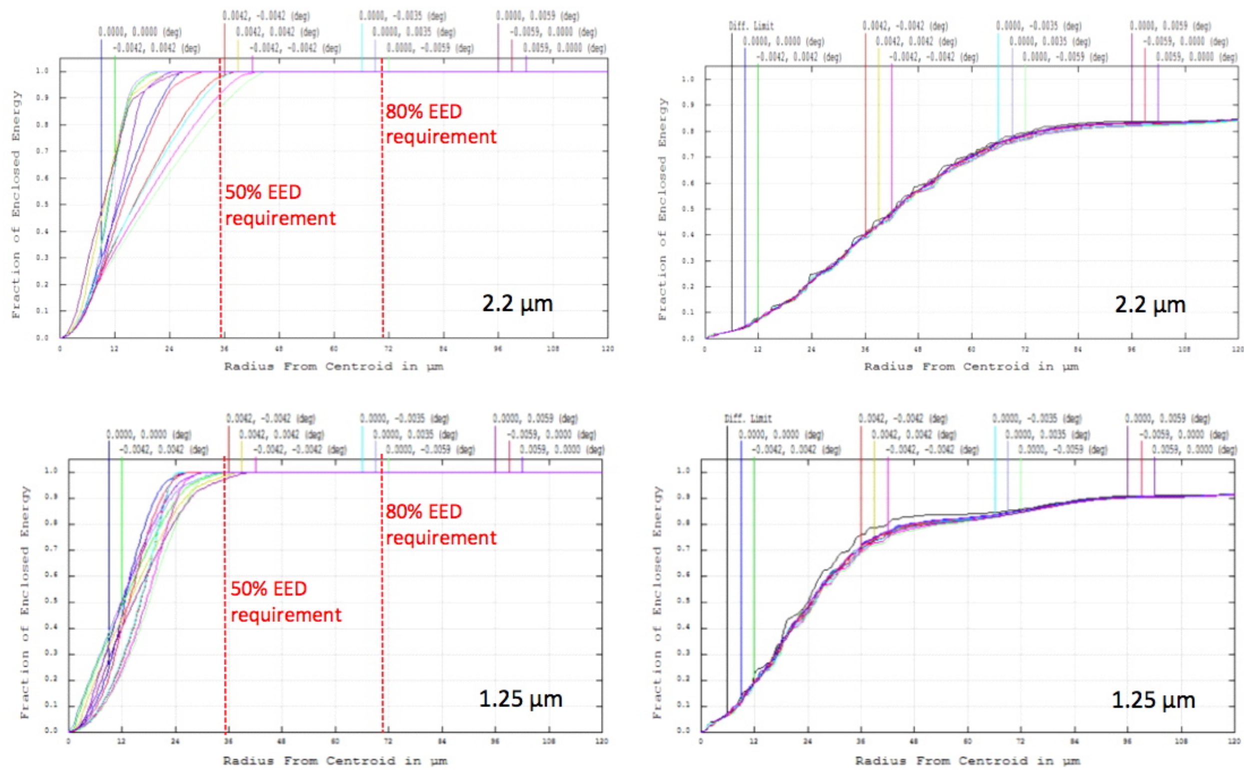

Figure 2.5. Geometric (*left*) and diffraction (*right*) encircled energy diagrams for the foreoptics at the slit plane. The broadening of the image profile due to geometric effects in the nominal optical design is insignificant compared to telescope diffraction (*right*). For comparison the smallest slit width is 0.375″ (208 μm) and the best seeing is typically about 0.4″ (222 μm) FWHM in the *K* band.

Figure 2.5 shows the geometric and diffraction (including geometric errors) encircled energy plots. The nominal design easily meets in the image quality requirement at the slit (TR_12: 50% EED ≤ 70 μm and 80% EED ≤ 140 μm).

2.3.3 Image quality at the slit viewer

The slit plane is re-imaged at 1:0.49 magnification onto the slit viewer array by a refractive collimator-camera system optimized for 1-5 μm and with a final image scale of 0.10″ per pixel (27 μm). The collimator forms a 6.7 mm diameter image of the pupil. However, the filter wheel is placed about 100 mm behind the pupil so that a lens in the filter wheel can image the pupil onto the slit viewer array. At 15.6 mm diameter the beam at the filter wheel is still small enough to use the same diameter filters as used in the SpeX slit viewer (19.05 mm diameter).

Figure 2.6 shows the through-focus spot diagram at the slit viewer array for all wavelengths (1.1 μm, 1.25 μm, 1.65 μm, 2.2 μm, 3.8 μm, 4.8 μm, and 5.3 μm). The five field positions are the on-axis position and four points on the circumference of the 42″-diameter field of view. The geometrical spot sizes are small compared to the 2.2 μm Airy disk drawn (100 μm diameter).

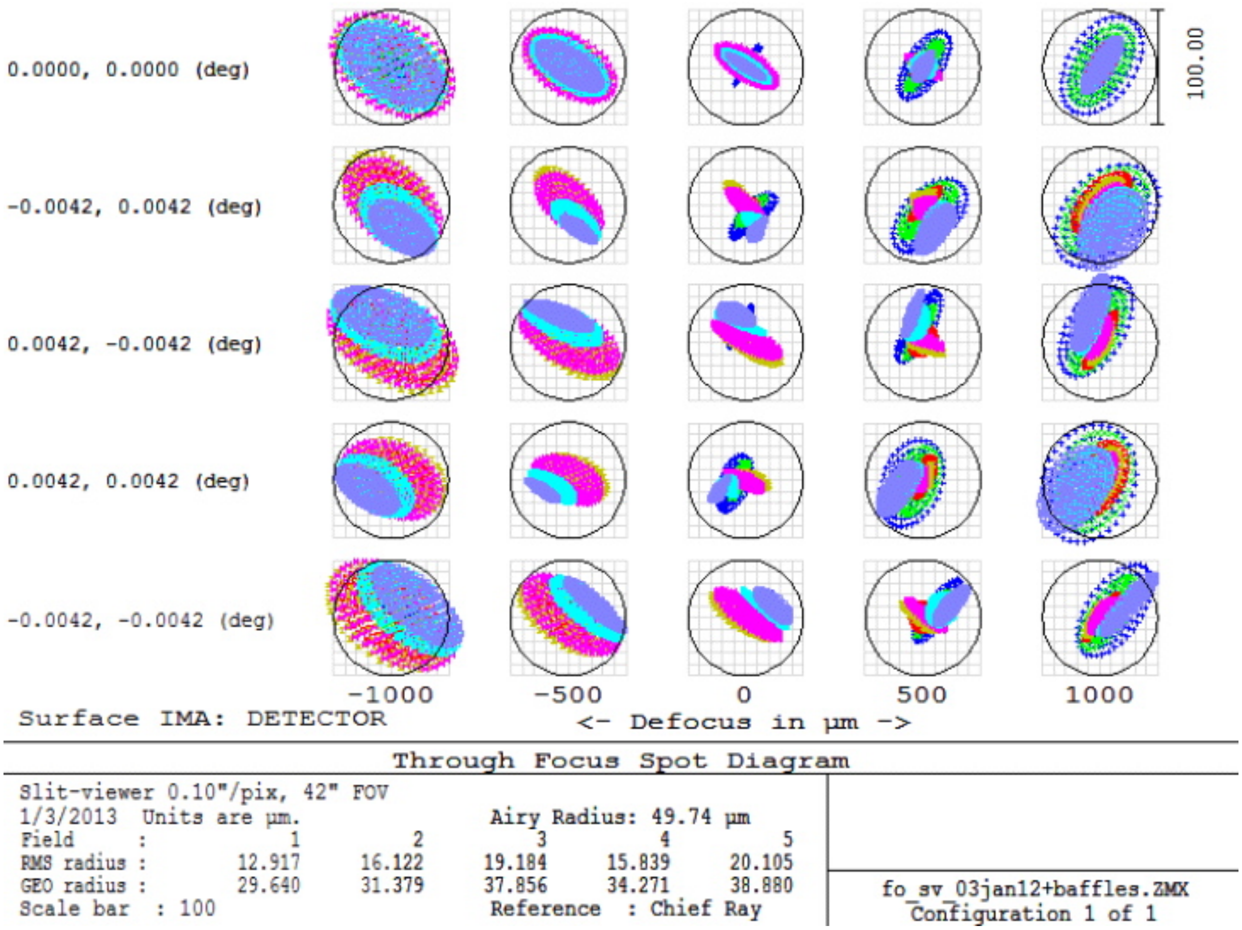

Figure 2.6. Through-focus spot diagram at all wavelengths and the indicated field positions. The five field positions are the on-axis position and four points on the circumference of the 42″-diameter field of view. The 2.2 µm Airy disk is shown.

Figure 2.7 shows the geometric and diffraction (including geometric errors) encircled energy plots. The nominal design easily meets in the image quality requirement at the slit viewer array (TR_14: geometric 50% EED ≤ 48 µm and 80% EED ≤ 97 µm).

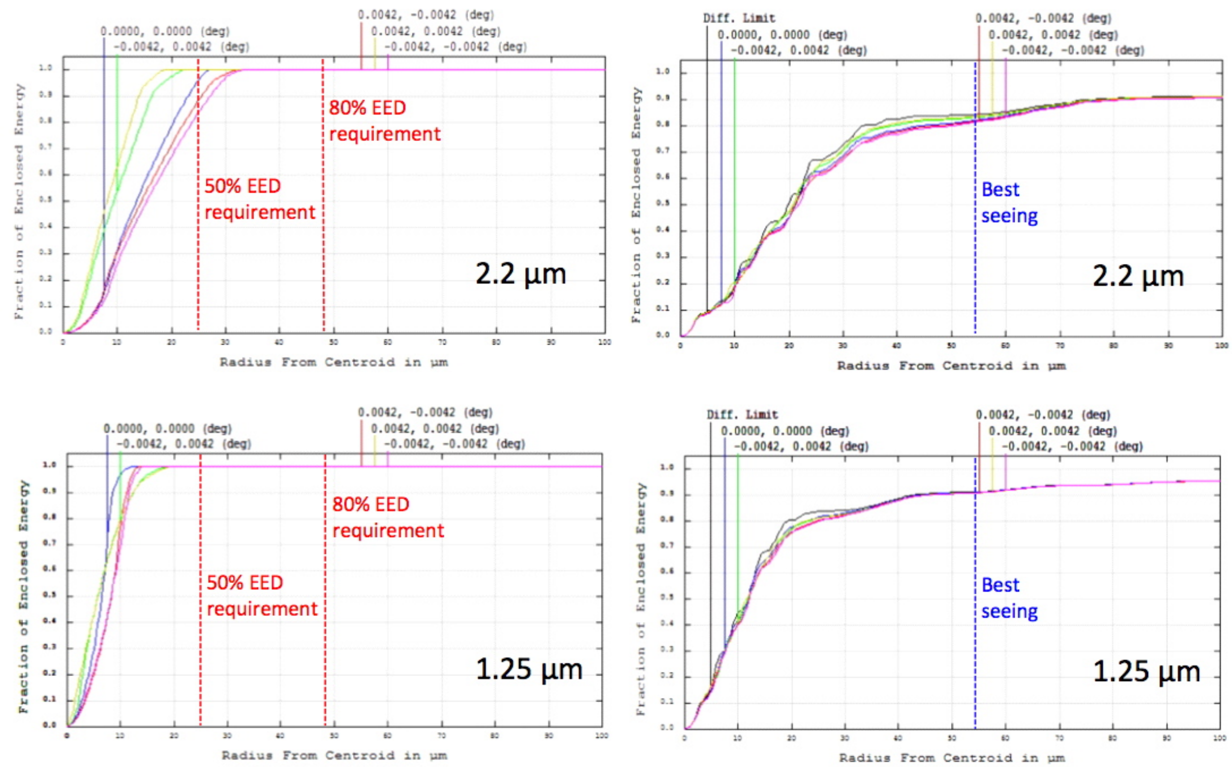

Figure 2.7. Geometric (*left*) and diffraction (*right*) encircled energy diagrams for at the slit viewer array. The broadening of the image profile due to geometric effects in the nominal optical design is insignificant compared to telescope diffraction (*right*). For comparison the best seeing is about 0.4″ (108 µm) FWHM in the *K* band.

3 TOLERANCING OF THE FOREOPTICS AND SLIT VIEWER

Due to the requirement for one percent and better photometry with the slit viewer the foreoptics are very sensitive to flexure and alignment affecting the entrance pupil projection onto the cold stop. In contrast image quality is relatively insensitive to standard fabrication and alignment tolerances. Tolerancing of the foreoptics is split into two major assemblies: the window to the slit (foreoptics) and the slit to the slit viewer array (slit viewer). As with the spectrograph analysis the low-frequency spatial errors affecting the core of the image profile are analyzed using Zemax while the mid-frequency and high-frequency (roughness) spatial errors affecting the wider wings of the image profile are analyzed using a wavefront error method (surface irregularity). The Zemax tolerance analysis is detailed in two separate documents (Image Quality Analysis at the Slit and Image Quality Analysis at the Slit Viewer Detector). The analysis shows that the image quality and flexure requirements listed in Table 2.1 are met.

3.1 Surface irregularity

This analysis follows the method used for the spectrograph optics (see Spectrograph Optical Design document).

The total wavefront error due to irregularity, σ_T, is given by

$$\sigma_T^2 = \sum_1^l \left[\sigma_l \left(\frac{FP_l}{D_l}\right)^{\frac{1}{2}} \frac{\lambda_t}{\lambda_u} (n-1)_l \right]^2 + \sum_1^m \left[2\sigma_m \left(\frac{FP_m}{D_m}\right)^{\frac{1}{2}} \frac{\lambda_t}{\lambda_u} \right]^2 \quad (1)$$

In the first term of the summation $\boldsymbol{\sigma_l}$ is the RMS wavefront error in waves over the diameter $\boldsymbol{D_l}$ of the l^{th} lens surface (factor of *(n-1)* for surface refraction) measured at the wavelength it is tested λ_t and used at wavelength λ_u, n is the refractive index of the lens medium, and $\boldsymbol{FP_l}$ is the diameter of the bean footprint at the l^{th} element. In the second term of the summation $\boldsymbol{\sigma_m}$ is the RMS wavefront error in waves over the diameter $\boldsymbol{D_m}$ of the m^{th} mirror surface (factor of *2* for surface reflection) measured at the wavelength it is tested λ_t and used at wavelength λ_u, and $\boldsymbol{FP_m}$ is the diameter of the bean footprint at the m^{th} element.

Using the vendor specifications for irregularity given in Table 3.1 we calculate the wavefront error (scaled for beam footprint) for each surface from Equation 1 and list the results in Table 3.2.

Table 3.1. Vendor supplied RMS surface irregularity (σ)

Surface	***Surface σ (waves)***	***Note***
Flat mirrors (FS substrate)	1/10	Measured at 0.63 μm, typical off-the-shelf
Spherical mirror	1/8	Measured at 0.63 μm, typical off-the-shelf
CaF_2	1/4	Measured at 0.63 μm (from OSI)
BaF_2	1/4	Measured at 0.63 μm (from OSI)
LiF	1/2	Measured at 0.63 μm (from OSI)
ZnS	1/4	Flat filter substrate measured at 0.63 μm

Table 3.2. Beam footprint RMS wavefront errors σ per surface

SURFACE	***(1)APERTURE SIZE (MM) D_M***	***(2) BEAM FOOTPRINT (MM) FP_M***	***DIAM. (2)/(1)***	***RMS WFE σ @1.65μm (waves)***	***NOTES***
Foreoptics					
Window, front	50	11 ϕ	0.22	0.012	
Window, back	50	11 ϕ	0.22	0.012	
Fold 1	45	7	0.16	0.024	λ/10 at 0.63μm
Collimator	50	10	0.20	0.027	
Fold 2	30	20	0.67	0.039	λ/10 at 0.63μm
Rotator 1	25	17	0.68	0.040	λ/10 at 0.63μm
Rotator 2	20	11	0.55	0.036	λ/10 at 0.63μm
Rotator 3	38	17	0.45	0.032	λ/10 at 0.63μm
Fold 3	36	14	0.39	0.030	λ/10 at 0.63μm
BaF_2 lens, front	40	10	0.25	0.013	
BaF_2 lens, back	40	10	0.25	0.013	
LiF lens, front	40	10	0.25	0.021	

LiF lens, back	40	10	0.25	0.021	
Fold 4	45	4	0.09	0.014	λ/10 at 0.63μm
Slit viewer					
Slit mirror	38	~0 (point)	0.00	0.000	λ/10 at 0.63μm
Fold 5	35	3.2	0.09	0.014	λ/10 at 0.63μm
BaF_2 lens, front	40	6.4	0.16	0.011	
BaF_2 lens, back	40	6.4	0.16	0.011	
LiF lens, front	40	6.4	0.16	0.017	
LiF lens, back	40	6.4	0.16	0.017	
Filter, front	19.05	6.6	0.35	0.043	λ/4 at 0.63μm
Filter, back	19.05	6.6	0.35	0.043	λ/4 at 0.63μm
LiF lens, front	30	6.6	0.22	0.020	
LiF lens, back	30	6.6	0.22	0.020	
BaF_2 lens, front	30	6.5	0.22	0.013	
BaF_2 lens, back	30	6.5	0.22	0.013	

The wavefront error from different elements of the foreoptics and slit viewer are given in Tables 3.3 and 3.4 and the resulting total wavefront error estimated. The Strehl ration, S, of the foreoptics and slit viewer are calculated using the Mahajan approximation

$$S \approx \exp-\left(2\pi\sigma_T\right)^2 \qquad (2)$$

Table 3.3. Total wavefront error for the foreoptics

UNIT	***RMS WFE σ @ 1.65μm (waves)***	***Note***
Flat mirrors	0.084	λ/10 at 0.63 μm, typical off-the-shelf
Flat mirrors	0.059	λ/20 at 0.63 μm
Lenses and window	0.039	Custom OSI
Collimating mirror	0.027	Custom OSI
Total foreoptics	**0.097**	**Strehl=0.69 at 1.65 μm, λ/10 flats at 0.63 μm**
	0.076	**Strehl=0.80 at 1.65 μm, λ/20 flats at 0.63 μm**

Table 3.4. Total wavefront error for the slit viewer optics

UNIT	***RMS WFE σ @ 1.65μm (waves)***	***Note***
Flat mirrors	0.014	λ/10 at 0.63 μm, typical off-the-shelf
Flat mirrors	0.010	λ/20 at 0.63 μm
Lenses	0.034	Custom OSI
Filter	0.061	Custom
Total slit viewer	**0.0710**	**Strehl=0.82 at 1.65 μm, λ/10 flats at 0.63 μm**
	0.0705	**Strehl=0.82 at 1.65 μm, λ/20 flats at 0.63 μm**

To meet the image quality requirement for Strehl ratio (S>0.08, TR_12 and TR_14) the flat mirrors need to be λ/20 or better since there are so many of them (9).

4 STRAY LIGHT EFFECTS AND MITIGATION

We define stray light as being detected on the detector array at an unintended location. There are three main sources of stray light in the foreoptics and slit viewer:

1. Off-axis stray light from the telescope and sky
2. Ghost reflections from lenses
3. General surface scatter

4.1 Off-axis stray light from the telescope and sky

Narrow-angle off-axis stray light from the telescope and sky is controlled by forming an image of the telescope entrance pupil on a cold stop in the foreoptics. However, wide-angle off-axis stray light and thermal flux can still enter the instrument at the entrance window and once inside can scatter off surfaces and past the cold stop. This is controlled by a series of low reflection (black) cold baffle tubes that force off-axis light to undergo several high incidence reflections so that it is absorbed. Having baffle tubes arranged in series significantly reduces stray light (e.g. if a baffle tube absorbs 10% of the stray light entering it a series of three baffle tubes will reduce stray light by a factor of 1000).

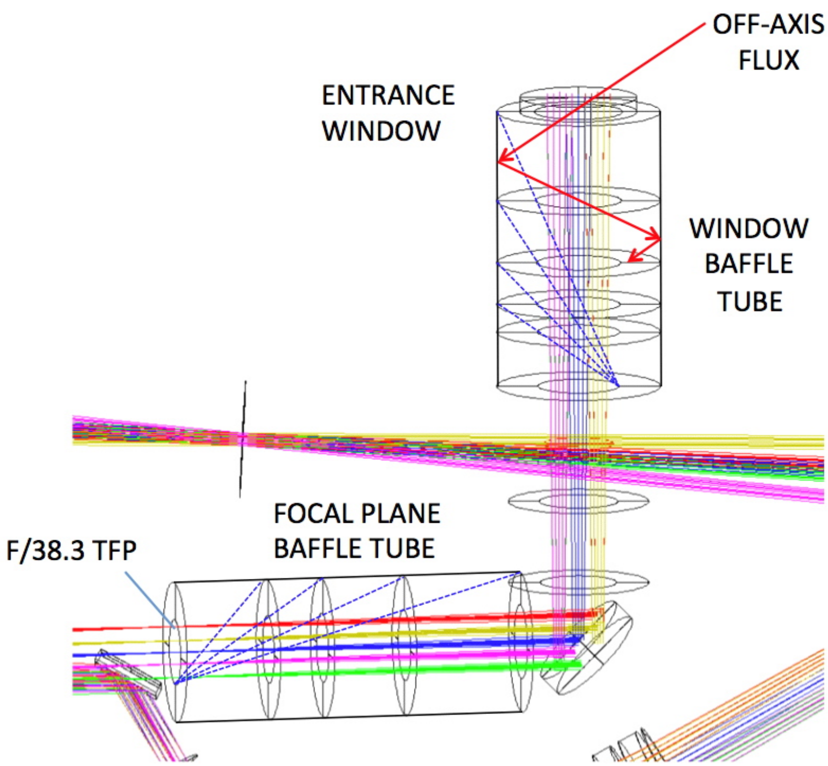

Figure 4.1. Baffle tubes behind the entrance window and in front of the TFP absorb most of the off-axis light and thermal flux entering the window. The baffles are placed to prevent the exit aperture of the baffle tube seeing the side of the tube (grazing incidence). The dashed blue lines define the positioning of the baffles.

A series of baffles are designed into the foreoptics. The window baffle and focal plane baffle tubes are illustrated in Figure 4.1. A further baffle tube is located between the slit viewer detector and cold stop (see Figure 4.2). Single baffles are also placed at convenient locations along the optical train. The final baffle locations are dependent on details of the mechanical design (location of walls and partitions TBD).

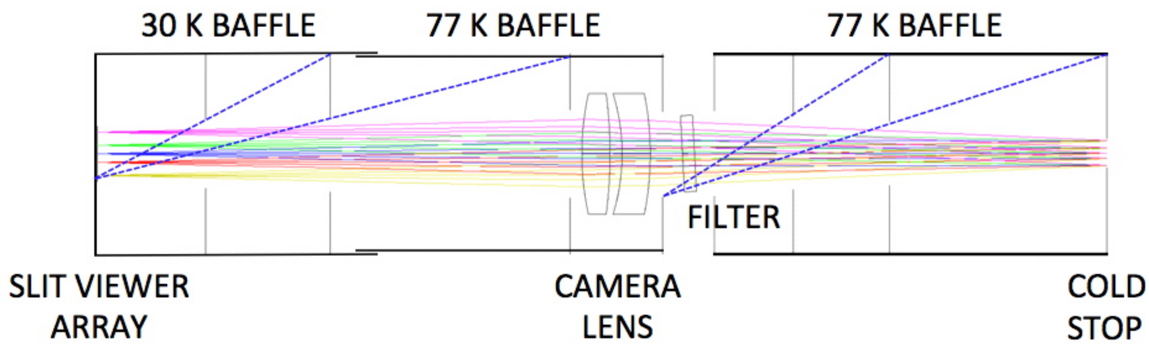

Figure 4.2. Slit viewer baffling. The baffle immediately in front of the array is cooled to the same temperature of the array (30 K) and also serves the function of keeping the thermal background from the LN_2 cooled enclosure below 0.01 e/s by limiting the solid angle viewed by the array.

4.2 Ghost reflection from lenses

Ghost image analysis was done with the non-sequential raytrace package in ZEMAX. The BaF_2-LiF doublet lenses are low refractive index materials. This in combination with BBAR coats keeps the reflection per surface to about 2% and less across the 1-5 μm range. Ghosts at the slit plane and at the slit viewer array are of very low intensity (10^{-4}-10^{-5} of a point source). See Figures 4.3 and 4.4.

4.3 General scatter

Stray light from surface scatter (i.e. wide angle scatter) arises from mid-frequency and high-frequency (roughness) spatial errors of optical surfaces. The analysis of section 3.1 shows that the specified surface irregularity meets the image quality requirement.

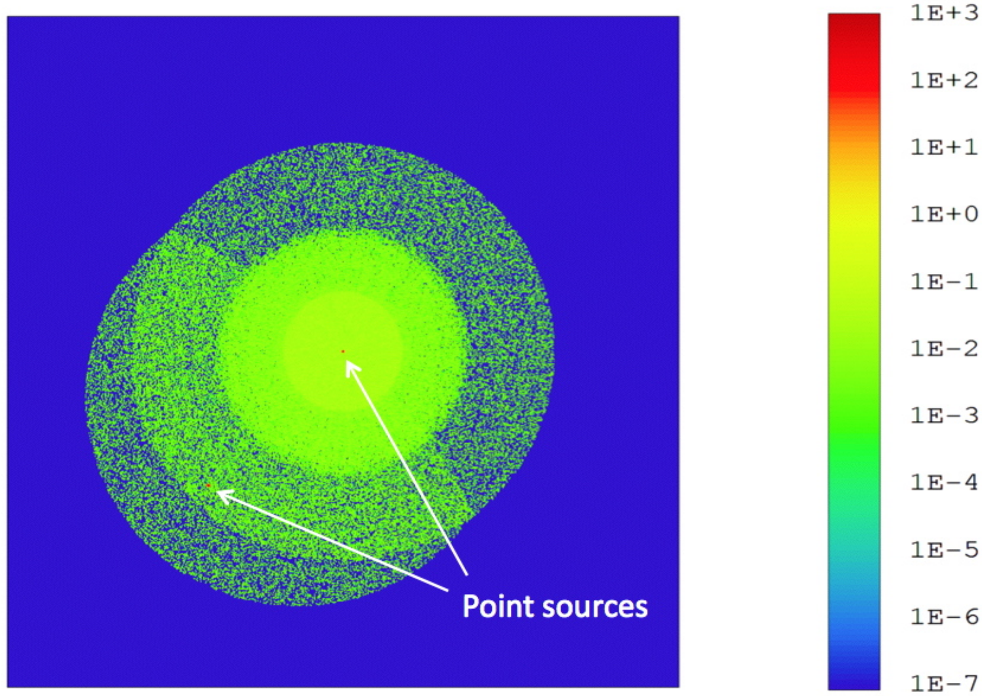

Figure 4.3. Ghosts at the slit plane from the foreoptics camera doublet. The two point sources are separated by 12.5″. The maximum ghost intensity is about 10^{-4}.

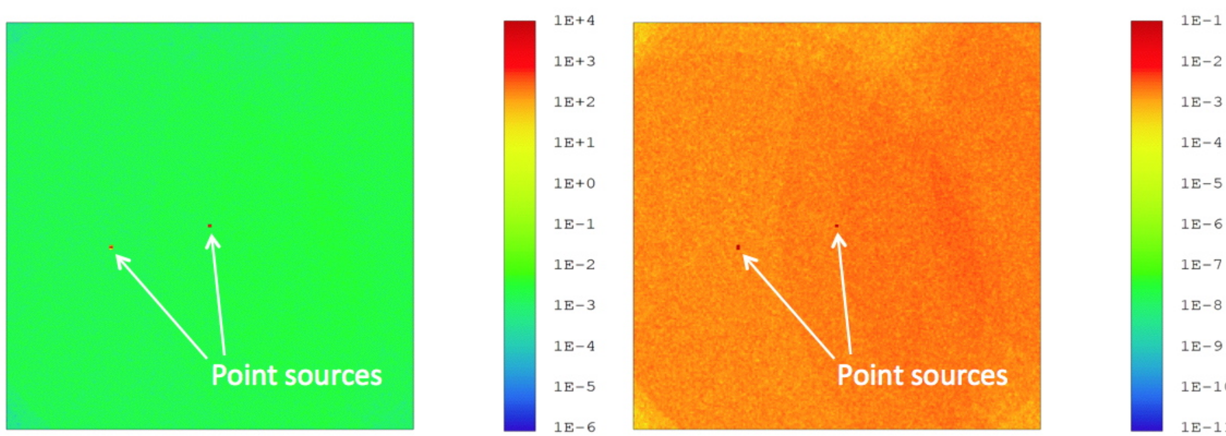

Figure 4.4. Narcissus ghosts at the slit viewer array from the slit viewer lenses. The right and left panels show different stretches of the same image. The two point sources are separated by 12.5″. The maximum ghost intensity is about 10^{-5}. Ghosts from filters are avoided by tilting the filters by three degrees.

5 FOREOPTICS AND SLIT VIEWER THROUGHPUT

The throughput of the spectrograph is estimated in Table 5.1. Throughput as a function of wavelength will be refined when spectral estimates become available.

Table 5.1. Foreoptics and Slit Viewer throughput estimate.

Element	***Transmission***	***Notes***
Foreoptics		
CaF_2 window	0.98^2	BBAR coat est.
Fold mirror 1	0.98	Fused silica substrate, protected-silver
Collimating mirror	0.98	Fused silica substrate, protected-silver
Fold mirror 2	0.98	Fused silica substrate, protected-silver
Cold stop	0.95	Undersized to mask telescope
Rotator mirror 1	0.98	Fused silica substrate, protected-silver
Rotator mirror 1	0.98	Fused silica substrate, protected-silver
Rotator mirror 1	0.98	Fused silica substrate, protected-silver
Fold mirror 3	0.98	Fused silica substrate, protected-silver
Lens 1 (BaF_2)	0.98^2	BBAR coat est.
Lens 2 (LiF)	0.98^2	BBAR coat est.
Fold mirror 4	0.98	Fused silica substrate, protected-silver
Total Foreoptics	**0.71**	@ ~1.65 μm
Slit viewer		
Slit mirror	0.98	Gold-coated CaF_2 (same SpeX)
Fold mirror 5	0.98	Fused silica substrate, protected-silver
Lens 3 (BaF_2)	0.98^2	BBAR coat est.
Lens 4 (LiF)	0.98^2	BBAR coat est.
Cold stop	1.00	Oversized
Filter	0.80	Typical
Lens 5 (LiF)	0.98^2	BBAR coat est.
Lens 6 (BaF_2)	0.98^2	BBAR coat est.
Aladdin 2 array	0.75	Eng. array from SpeX est.
Total Slit Viewer	**0.49**	@ ~1.65 μm
Total FO+SV	**0.35**	@ ~1.65 μm (cf. SpeX about 0.25)

The predicted throughput is higher than SpeX. SpeX uses three BaF_2-LiF-ZnS triplets instead of three BaF_2-LiF doublet lenses and most of the difference is due to the 0.95 transmission per ZnS BBAR-coated surface.

6 OPTICAL ELEMENT SPECIFICATIONS

6.1 Foreoptics, slit viewer, and pupil lenses

The specifications are given in Tables 6.1, 6.2, 6.3, and 6.4 (CC means concave, CX means convex). The following documentation must be included with the fabricated lenses:

1. Report on actual linear dimensions of each finished element (diameter, center thickness, edge thickness) to ±0.01mm.
2. Documentation of the measurement of each optical surface in the form of a fringe image against the measured test plate or Zygo surface map.
3. All surfaces should be completely polished including outside diameter and bevels.

Table 6.1. Foreoptics camera lens specifications.

Parameter	*Lens*		*Tolerance/note*
LENS#	1	2	
WORKING TEMP	77K	77K	±2 K
MATERIAL	BaF_2	LiF	
R_1/mm (3 fringe fit to test plate)	296.19 CX	128.62 CX	±0.1%
R_2/mm	245.04 CX	96.40 CC	±0.1%
IRREG: >1.0 line/mm (figure)	<0.50 fr. RMS	<1.00 fr. RMS	At 0.63 μm, over CA.
IRREG: ~0.1 line/mm	<0.16 fr. RMS	<0.33 fr. RMS	At 0.63 μm, over CA.
IRREG: roughness	<16 nm RMS	<16 nm RMS	Assumes irreg. $\propto$ scale$^{-0.5}$
CENTER THICKNESS/mm	10.03	8.04	±0.05mm
RUNOUT/mm	0.00	0.00	±0.03mm
DIAMETER/mm	40.12	40.19	+0.00/-0.02mm
CLEAR APER (CA.)/mm	31	31	
SURFACE (scratch/dig)	60/40	60/40	
BEVEL	See drawing	See drawing	On drawing
COATING (1.1-5.4 μm)	BBAR < 2%	BBAR < 2%	Reflection per surface
QUANTITY	1	1	

Table 6.2. Slit viewer collimator lens specifications.

Parameter	*Lens*		*Tolerance/note*
LENS#	3	4	
WORKING TEMP	77K	77K	±2 K
MATERIAL	BaF_2	LiF	
R_1/mm (3 fringe fit to test plate)	146.18 CX	139.35 CC	±0.1%
R_2/mm	246.17 CX	236.41 CX	±0.1%
IRREG: >1.0 line/mm (figure)	<0.50 fr. RMS	<1.00 fr. RMS	At 0.63 μm, over CA.
IRREG: ~0.1 line/mm	<0.16 fr. RMS	<0.33 fr. RMS	At 0.63 μm, over CA.
IRREG: roughness	<16 nm RMS	<16 nm RMS	Assumes irreg. $\propto$ scale$^{-0.5}$
CENTER THICKNESS/mm	10.03	10.05	±0.05mm
RUNOUT/mm	0.00	0.00	±0.03mm
DIAMETER/mm	40.12	40.19	+0.00/-0.02mm
CLEAR APER (CA.)/mm	33	32	
SURFACE (scratch/dig)	60/40	60/40	
BEVEL	See drawing	See drawing	On drawing
COATING (1.1-5.4 μm)	BBAR < 2%	BBAR < 2%	Reflection per surface
QUANTITY	1	1	

Table 6.3. Slit viewer camera lens specifications.

Parameter	*Lens*		*Tolerance/note*
LENS#	5	6	
WORKING TEMP	77K	77K	±2 K
MATERIAL	LiF	BaF_2	
R_1/mm (3 fringe fit to test plate)	77.88 CX	119.05 CX	±0.1%
R_2/mm	51.62 CC	69.41 CX	±0.1%
IRREG: >1.0 line/mm (figure)	<1.00fr. RMS	<0.50 fr. RMS	At 0.63 μm, over CA.
IRREG: ~0.1 line/mm	<0.33 fr. RMS	<0.16 fr. RMS	At 0.63 μm, over CA.
IRREG: roughness	<16 nm RMS	<16 nm RMS	Assumes irreg. $\propto$ scale$^{-0.5}$
CENTER THICKNESS/mm	7.03	7.02	±0.05mm
RUNOUT/mm	0.00	0.00	±0.03mm
DIAMETER/mm	30.14	30.09	+0.00/-0.02mm
CLEAR APER (CA.)/mm	18	18	
SURFACE (scratch/dig)	60/40	60/40	
BEVEL	See drawing	See drawing	On drawing
COATING (1.1-5.4 μm)	BBAR < 2%	BBAR < 2%	Reflection per surface
QUANTITY	1	1	

Table 6.4. Pupil viewer lens specifications.

Parameter	*Lens*	*Tolerance/note*
LENS#	7	
WORKING TEMP	77K	±2 K
MATERIAL	Cleartran (ZnS)	
R_1/mm (3 fringe fit to test plate)	121.97 CX	±0.1%
R_2/mm	Flat	±0.2 fr. at 0.63 μm
IRREG: >1.0 line/mm (figure)	<0.50 fr. RMS	At 0.63 μm, over CA.
IRREG: ~0.1 line/mm	<0.16 fr. RMS	At 0.63 μm, over CA.
IRREG: roughness	<16 nm RMS	Assumes irreg. $\propto$ scale$^{-0.5}$
CENTER THICKNESS/mm	15.02	±0.05mm
RUNOUT/mm	0.00	±0.1mm
DIAMETER/mm	19.07	+0.00/-0.02mm
CLEAR APER (CA.)/mm	15.6	
SURFACE (scratch/dig)	60/40	
BEVEL	See drawing	On drawing
COATING (1.1-5.4 μm)	BBAR < 4%	Reflection per surface
QUANTITY	1	

6.2 Foreoptics collimating mirror

The specifications are given in Table 6.5. The following documentation must be included with the fabricated mirror:

1. Report on actual linear dimensions of each finished element (diameter, center thickness, edge thickness) to ±0.01mm.
2. Documentation of the measurement of the optical surface in the form a Zygo surface map.

Table 6.5. Foreoptics collimating mirror specifications.

Parameter	*Spectrum mirror*	*Tolerance/Note*
WORKING TEMP	77K	±2 K
SUBSTRATE	Fused silica	
SHAPE	Spherical	
R_1/mm (3 fringe fit to test plate)	762.0 CC	±0.1%
R_2/mm	Flat	±0.2 fr. at 0.63 μm
PARALLELISM	0.5 arc-min	
IRREG: >1.0 line/mm (figure)	<0.25 fr. RMS	At 0.63 μm, over CA.
IRREG: ~0.1 line/mm	<0.08 fr. RMS	At 0.63 μm, over CA.
IRREG: roughness	<10 nm RMS	Assumes irreg. $\propto$ scale$^{-0.5}$
CENTER THICKNESS/mm	8.0	±0.1mm, (≈diam./6)
RUNOUT/mm	0.00	±0.05mm
DIAMETER/mm	50.0	+0.00/-0.02mm
CLEAR APER (CA.)/mm	35	
SURFACE (scratch/dig)	60/40	
BEVEL	See drawing	On drawing
COATING	Protected silver	
QUANTITY	1	

6.3 Foreoptics and slit viewer flat fold mirrors

The specifications are given in Table 6.6. The following documentation must be included with the fabricated mirror:

3. Report on actual linear dimensions of each finished element (diameter, center thickness, edge thickness) to ±0.01mm.
4. Documentation of the measurement of the optical surface in the form a Zygo surface map.

Table 6.6. Flat fold mirror specifications.

Parameter	*Fold 1*	*Fold 2*	*Fold 3*	*Tolerance/Note*
WORKING TEMP	77K	77K	77K	±2 K
SUBSTRATE	Fused silica	Fused silica	Fused silica	
SHAPE	Flat, ±0.2 fr.	Flat, ±0.2 fr.	Flat, ±0.2 fr.	At 0.63 μm
PARALLELISM	0.5 arc-min	0.5 arc-min	0.5 arc-min	
IRREG: >1.0 line/mm (figure)	<0.05 waves RMS <0.25 waves pk-v	<0.05 waves RMS <0.25 waves pk-v	<0.05 waves RMS <0.25 waves pk-v	At 0.63 μm, over CA.
IRREG: ~0.1 line/mm	<0.02 waves RMS	<0.02 waves RMS	<0.02 waves RMS	At 0.63 μm, over CA.
IRREG: roughness	<5 nm RMS	<5 nm RMS	<5 nm RMS	Assume irreg $\propto$ scale$^{-0.5}$
SURFACE (scratch/dig)	60/40	60/40	60/40	
DIAMETER/mm	45.0	30.0x16.0 rect.	36.0	+0.00/-0.02mm
CENTER THICKNESS/mm	10.0	10.0	10.0	±0.1mm
CLEAR APER. (CA.)/mm	37	37	29	
COATING	Protected silver	Protected silver	Protected silver	
QUANTITY	1	1	1	

Table 6.6. Flat fold mirror specifications (cont.).

Parameter	*Fold 4*	*Fold 5*	*Tolerance/Note*
WORKING TEMP	77K	77K	±2 K
SUBSTRATE	Fused silica	Fused silica	
SHAPE	Flat, ±0.2 fr.	Flat, ±0.2 fr.	At 0.63 μm
PARALLELISM	0.5 arc-min	0.5 arc-min	
IRREG: >1.0 line/mm (figure)	<0.05 waves RMS <0.25 waves pk-v	<0.05 waves RMS <0.25 waves pk-v	At 0.63 μm, over CA.
IRREG: ~0.1 line/mm	<0.02 waves RMS	<0.02 waves RMS	At 0.63 μm, over CA.
IRREG: roughness	<5 nm RMS	<5 nm RMS	Assumes irreg. $\propto$ scale$^{-0.5}$
SURFACE (scratch/dig)	60/40	60/40	
DIAMETER/mm	45.0	35.0	+0.00/-0.02mm
CENTER THICKNESS/mm	10.0	10.0	±0.10mm
CLEAR APER. (CA.)/mm	34	37	
COATING	Protected silver	Protected silver	
QUANTITY	1	1	

6.4 Rotator flat mirrors

The specifications are given in Table 6.7. The following documentation must be included with the fabricated mirrors:

1. Report on actual linear dimensions of each finished element (diameter, center thickness, edge thickness) to ±0.01mm.
2. Documentation of the measurement of each optical surface in the form a Zygo surface map.

Table 6.7. Rotator flat mirror specifications.

Parameter	*Fold 1*	*Fold 2*	*Fold 3*	*Tolerance/Note*
WORKING TEMP	77K	77K	77K	±2 K
SUBSTRATE	Fused silica	Fused silica	Fused silica	
SHAPE	Flat, ±0.2 fr.	Flat, ±0.2 fr.	Flat, ±0.2 fr.	At 0.63 μm
PARALLELISM	0.5 arc-min	0.5 arc-min	0.5 arc-min	
IRREG: >1.0 line/mm (figure)	<0.05 waves RMS <0.25 waves pk-v	<0.05 waves RMS <0.25 waves pk-v	<0.05 waves RMS <0.25 waves pk-v	At 0.63 μm, over CA.
IRREG: ~0.1 line/mm	<0.02 waves RMS	<0.02 waves RMS	<0.02 waves RMS	At 0.63 μm, over CA.
IRREG: roughness	<5 nm RMS	<5 nm RMS	<5 nm RMS	Assume irreg $\propto$ scale$^{-0.5}$
SURFACE (scratch/dig)	60/40	60/40	60/40	
DIAMETER/mm	25.0	20.0	38.0	+0.00/-0.02mm
CENTER THICKNESS/mm	6.0	6.0	6.0	±0.1mm
CLEAR APER. (CA.)/mm	21	16	29	
COATING	Protected silver	Protected silver	Protected silver	
QUANTITY	1	1	1	

6.5 Cryostat window

The specifications are given in Table 6.8. The following documentation must be included with the fabricated mirrors:

1. Report on actual linear dimensions of each finished element (diameter, center thickness, edge thickness) to ±0.01mm.
2. Documentation of the measurement of each optical surface in the form a Zygo surface map.

Table 6.8. Cryostat entrance window specifications.

Parameter	*Fold 1*	*Tolerance/Note*
WORKING TEMP	275 K	±2 K
SUBSTRATE	Calcium fluoride	
SHAPE	Flat, ±0.2 fr.	At 0.63 μm
PARALLELISM	0.5 arc-min	
IRREG: >1.0 line/mm (figure)	<0.25 waves RMS <1.25 waves pk-v	At 0.63 μm, over CA.
IRREG: ~0.1 line/mm	<0.08 waves RMS	At 0.63 μm, over CA.
IRREG: roughness	<16 nm RMS	Assume irreg $\propto$ scale$^{-0.5}$
SURFACE (scratch/dig)	60/40	
DIAMETER/mm	50.0	+0.00/-0.02mm
CENTER THICKNESS/mm	6.35	±0.10mm
CLEAR APER. (CA.)/mm	27	
COATING (1.1-5.4 μm)	BBAR < 2%	Reflection per surface
QUANTITY	3	

6.6 Slit mirrors

Assumes substrate-type slit (TBC)

The specifications are given in Table 6.9. The following documentation must be included with the fabricated mirrors:

1. Report on actual linear dimensions of each finished element (diameter, center thickness, edge thickness) to ±0.01mm.
2. Documentation of the measurement of each optical surface in the form a Zygo surface map.

Table 6.8. Slit miror specifications.

Parameter	*Slit mirror*	*Tolerance/Note*
WORKING TEMP	77 K	±2 K
SUBSTRATE	Calcium fluoride	
SHAPE	Flat, ±0.2 fr.	At 0.63 μm
PARALLELISM	0.5 arc-min	
IRREG: >1.0 line/mm (figure)	<0.25 waves RMS <1.25 waves pk-v	At 0.63 μm, over CA.
IRREG: ~0.1 line/mm	<0.08 waves RMS	At 0.63 μm, over CA.
IRREG: roughness	<16 nm RMS	Assume irreg ∝ scale$^{-0.5}$
SURFACE (scratch/dig)	60/40	
DIAMETER/mm	38.10	+0.00/-0.02mm
CENTER THICKNESS/mm	5.00	±0.10mm
CLEAR APER. (CA.)/mm	27	
SUBSTRATE COATING (1.1-5.4 μm)	BBAR < 2%	Reflection per surface
FRONTSIDE MIRROR	Gold	Lithographically applied
BACKSIDE COAT	Low reflection (TBD)	Lithographically applied
SLIT HEIGHT/mm	16.700	±0.002 mm (TBC)
SLIT WIDTH/mm	0.226 (0.375″)	±0.002 mm (TBC)
(slit is tilted 22.5 deg.)	0.452 (0.750″)	±0.002 mm (TBC)
	0.904 (1.500″)	±0.002 mm (TBC)
	2.412 (4.000″)	±0.002 mm (TBC)
	None (mirror)	
QUANTITY	One of each	