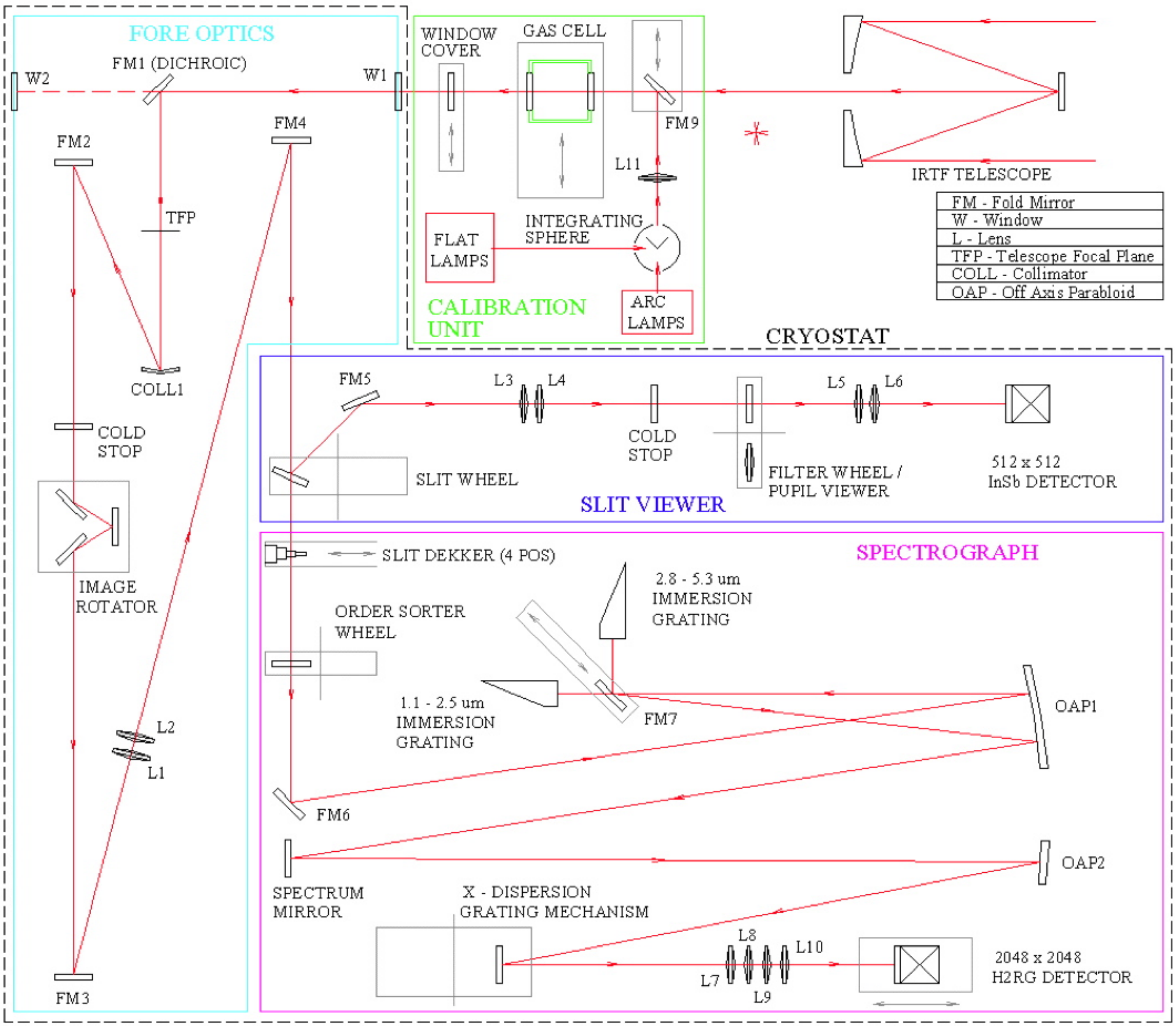
Optical Design

- Instrument concept
- Foreoptics and slit viewer
- Spectrograph
- Alignment plan



FORE OPTICS
W2
FM1 (DICHROIC)
W1
WINDOW COVER
GAS CELL
FM9
L11
IRTF TELESCOPE
FM2
FM4
TFP
COLL1
COLD STOP
IMAGE ROTATOR
L2
L1
FM3
FLAT LAMPS
INTEGRATING SPHERE
ARC LAMPS
CALIBRATION UNIT
FM - Fold Mirror
W - Window
L - Lens
TFP - Telescope Focal Plane
COLL - Collimator
OAP - Off Axis Paraboloid
CRYOSTAT
FM5
L3
L4
COLD STOP
L5
L6
FILTER WHEEL / PUPIL VIEWER
512 x 512 InSb DETECTOR
SLIT WHEEL
SLIT VIEWER
SLIT DEKKER (4 POS)
SPECTROGRAPH
2.8 - 5.3 um IMMERSION GRATING
ORDER SORTER WHEEL
1.1 - 2.5 um IMMERSION GRATING
FM7
OAP1
FM6
SPECTRUM MIRROR
OAP2
X - DISPERSION GRATING MECHANISM
L7
L8
L9
L10
2048 x 2048 H2RG DETECTOR

iSHELL Design Summary

Resolving Power	70,000 (0.375″ slit, 3 pixel sampling)
Slit width	0.375″, 0.75″, 1.5″, 4.0″
Slit length	5″, 10″,15″, 25″
Silicon immersion gratings	13.2 lines/mm, R3 (71.6°) for *LL′M* 22.2 lines/mm, R3 (71.6°) for *JHK*
XD gratings	11 first-order tilt-table gratings (*JHKLL′M* bands)
Collimated beam	22 mm diameter
Spectrograph coll. focal length	838 mm (diamond-turned OAP)
Spectrograph cam. focal length	212 mm (BaF_2-ZnS-LiF)
Spectrograph detector	Teledyne H2RG, 2Kx2K, 18 µm pixel, 0.8-5.3 µm
Slit viewer detector	Aladdin 2 InSb, 512x 512, 27 µm pixel, 0.8-5.5 µm
Slit viewer field of view	42″ diameter, 0.10″/pixel
Optics temperature	76 K
Cold mechanisms (9)	K mirror, slit wheel, slit dekker, order sorter wheel, XD mechanism (2), slit viewer filter wheel, grating selection mirror, spectrograph focus
Calibration unit	Illumination optics, integrating sphere, arc lamps, flat-field lamps, $^{13}CH_4$ gas cell

List of cross dispersers and spectral formats

Exp. name (Mode)	Wavelength coverage (μm)	Orders Covered	XD (line/mm)	Blaze wavel. (μm)	Blaze angle (deg.)	Order sorter (μm)	Slit length (arcsec)	XD tilt (degrees)	XD size (mm)	Custom grating?
J	1.15-1.35	279-237	800	1.25	29.9	1.05-1.45	5.0	39.4	40x40	Yes
H	1.50-1.80	211-176	530	1.67	25.7	1.40-1.90	5.0	35.2	40x40	Yes
K	1.97-2.52	160-125	290	2.19	18.5	1.80-2.60	5.0	28.0	40x40	Yes
J1	1.15-1.26	280-255	1200	1.2	46.0	1.05-1.45	10.0	56.0	55x40	No
J2	1.25-1.35	255-236	1200	1.2	46.0	1.05-1.45	15.0	61.5	55x40	-
H1	1.50-1.66	211-191	847	1.67	45.0	1.40-1.90	10.0	51.6	50x40	Yes
H2	1.60-1.75	198-181	847	1.67	45.0	1.40-1.90	15.0	55.0	50x40	-
H3	1.68-1.83	188-173	847	1.67	45.0	1.40-1.90	15.0	57.1	50x40	-
K1	1.84-2.03	171-156	720	1.90	43.1	1.80-2.60	15.0	54.1	50x40	No
K2	2.02-2.18	156-144	720	1.90	43.1	1.80-2.60	15.0	58.9	50x40	-
K3	2.12-2.34	148-135	600	2.16	40.4	1.80-2.60	15.0	51.6	50x40	No
K4	2.32-2.52	135-125	600	2.16	40.4	1.80-2.60	15.0	56.4	50x40	-
L1	2.80-3.10	184-167	450	3.14	45.0	2.70-4.20	15.0	51.3	50x40	Yes
L2	3.02-3.30	171-157	450	3.14	45.0	2.70-4.20	15.0	55.0	50x40	-
L3	3.14-3.42	164-151	450	3.14	45.0	2.70-4.20	15.0	57.3	50x40	-
L4	3.28-3.67	157-141	360	3.70	42.0	2.70-4.20	15.0	48.5	50x40	No
L5	3.65-4.01	141-129	360	3.70	42.0	2.70-4.20	15.0	53.5	50x40	-
L6	3.84-4.18	134-124	360	3.70	42.0	2.70-4.20	25.0	56.2	50x40	-
M1	4.55-5.27 s	113-98	210	5.0	31.7	4.50-5.50	15.0	40.4	40x40	No
M2	4.55-5.27 l	113-98	210	5.0	31.7	4.50-5.50	15.0	40.4	40x40	No

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H2	1.60-1.75	198-181	847	1.67	45.0	1.40-1.90	15.0	55.0	50x40	-
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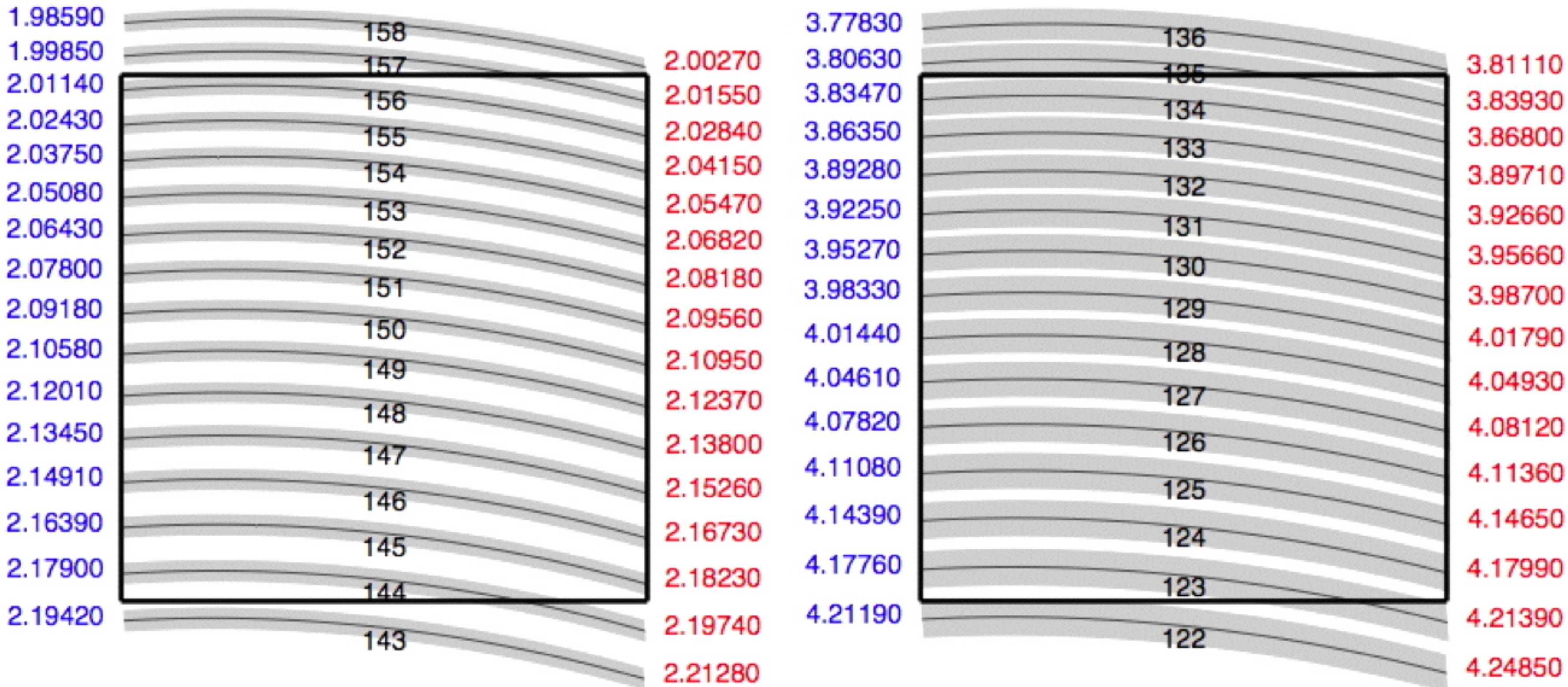
L3	3.14-3.42	164-151	450	3.14	45.0	2.70-4.20	15.0	57.3	50x40	-
L4	3.28-3.67	157-141	360	3.70	42.0	2.70-4.20	15.0	48.5	50x40	No
L5	3.65-4.01	141-129	360	3.70	42.0	2.70-4.20	15.0	53.5	50x40	-
L6	3.84-4.18	134-124	360	3.70	42.0	2.70-4.20	25.0	56.2	50x40	-
M1	4.55-5.27 s	113-98	210	5.0	31.7	4.50-5.50	15.0	40.4	40x40	No
M2	4.55-5.27 l	113-98	210	5.0	31.7	4.50-5.50	15.0	40.4	40x40	No

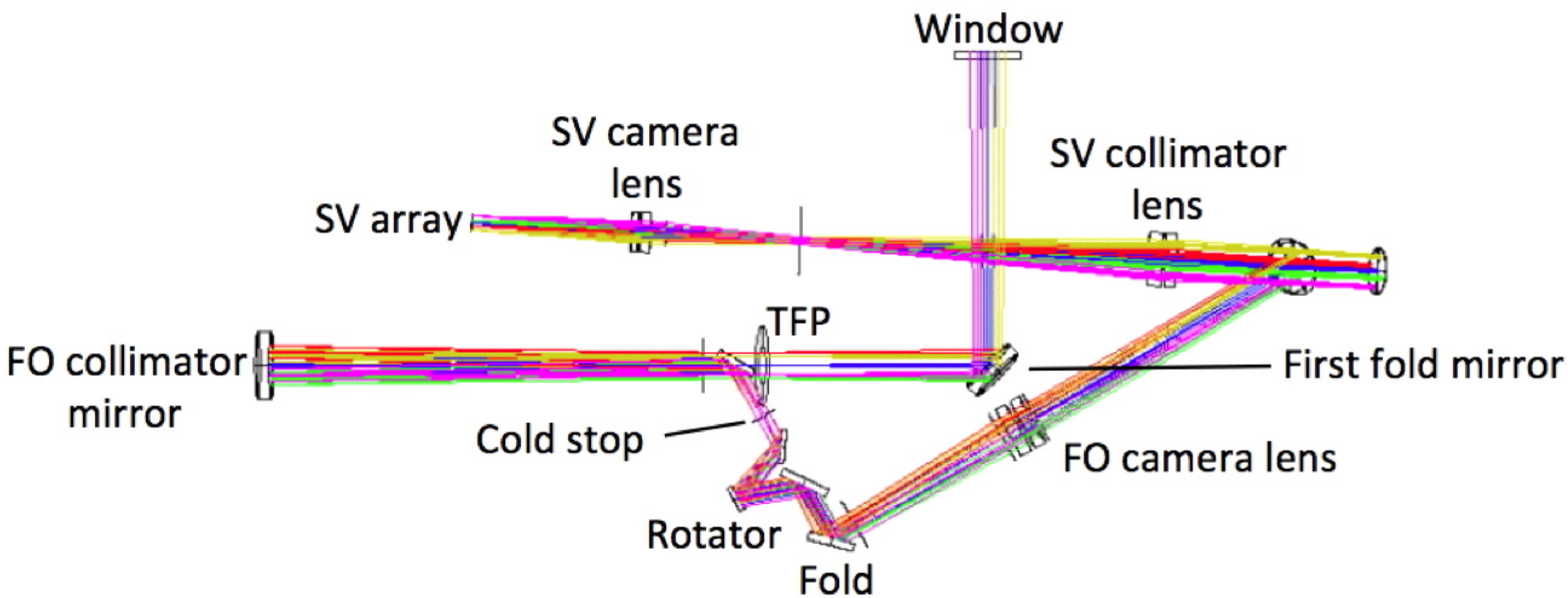
Example spectral formats

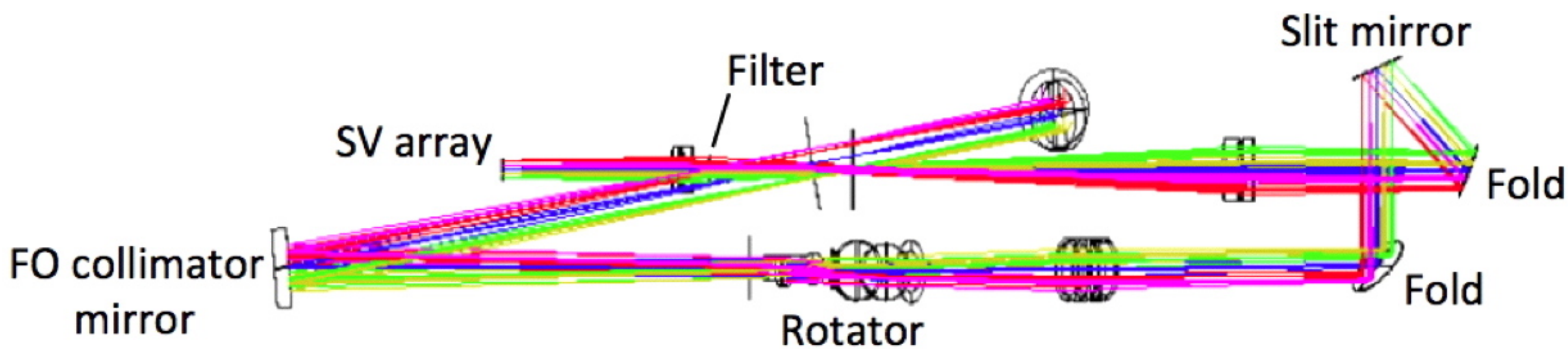


K2 – 15” slit

L6 – 25” slit

Foreoptics and Slit Viewer





Foreoptics and slit viewer optical design requirements

Requirement Number	*Requirement Name*
SR_2	Sensitivity
SR_8	Slit orientation
SR_14	Observing efficiency
SR_16	Absolute flux
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

Image quality analysis

- Low-frequency spatial errors affecting the core of the image profile are analyzed using Zemax encircled energy diameter (EED)
- 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)

Cold stop

- Essential/optimal requirement is for 2%/1% photometry (SR_16)
- Pupil 10.1 mm diameter formed by tilted (5 degree) spherical mirror
- Cold stop mask is undersized to mask telescope for 0.95 throughput (9.9 mm diameter)

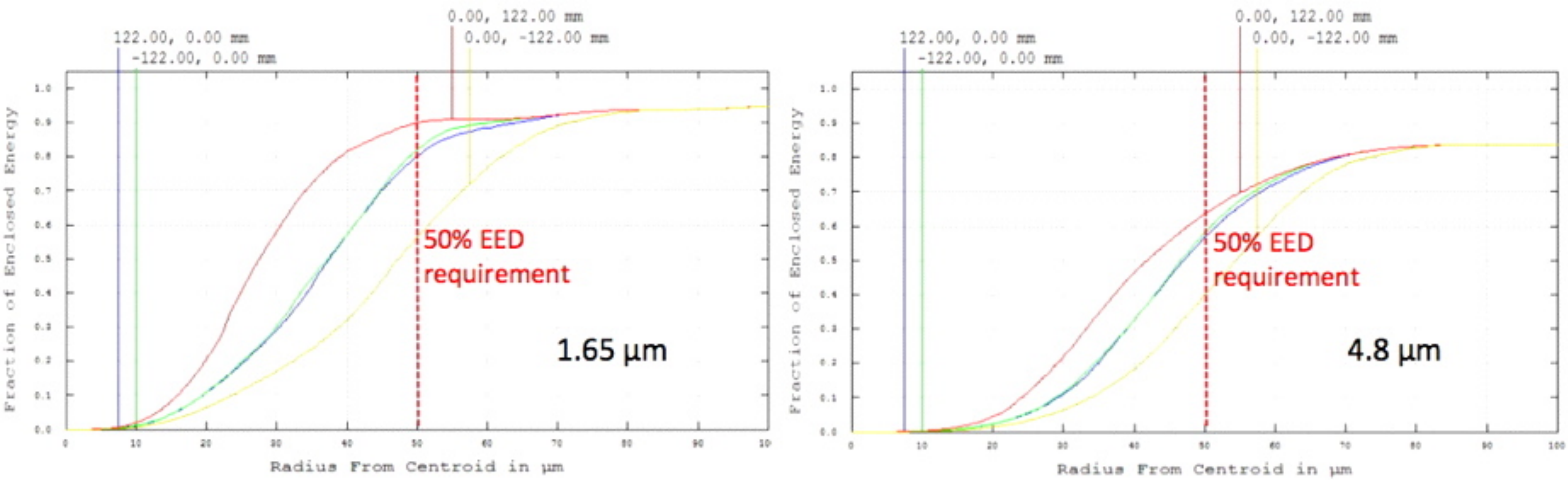
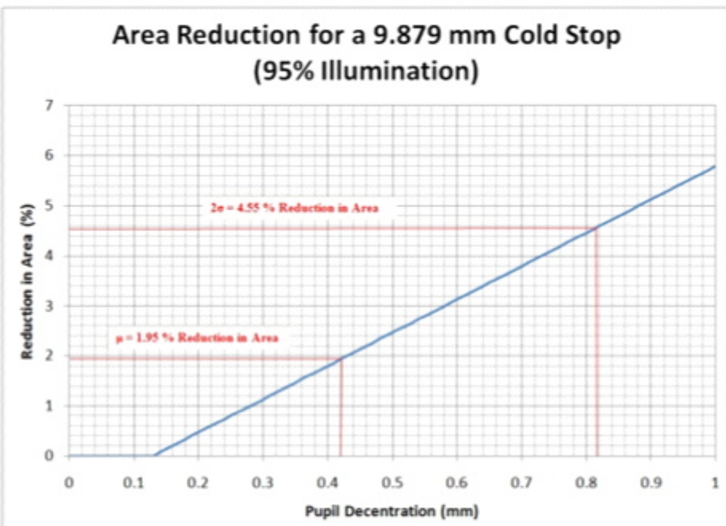


Image quality at cold stop

- Tolerancing adds a few percent to the EED

Cold stop: flexure analysis

- Monte Carlo analysis includes instrument and telescope secondary (entrance pupil)
- Tolerances based on semi-precision fabrication and flexure requirements
- Align stop at zenith using pupil viewer and then move



- Predicted decentration is 0.42 mm and throughput change of 2% (1 σ)
- Analysis implies that for good photometry stop should be recentered following repointing of telescope
- Plan is to use hexapod and lookup table

- Further analysis is needed to establish accuracy of photometry once pupil is recentered and over typical movements between object and standard stars

Pupil viewer

- Used to align cryostat on MIM by imaging secondary (conjugated with cold stop) at about 3.6 μm (thermal)
- Diameter of re-imaged pupil is 325 pixels with a spatial resolution 3.6 pixels (1% of pupil)
- Resolution is diffraction limited by diameter of foreoptics

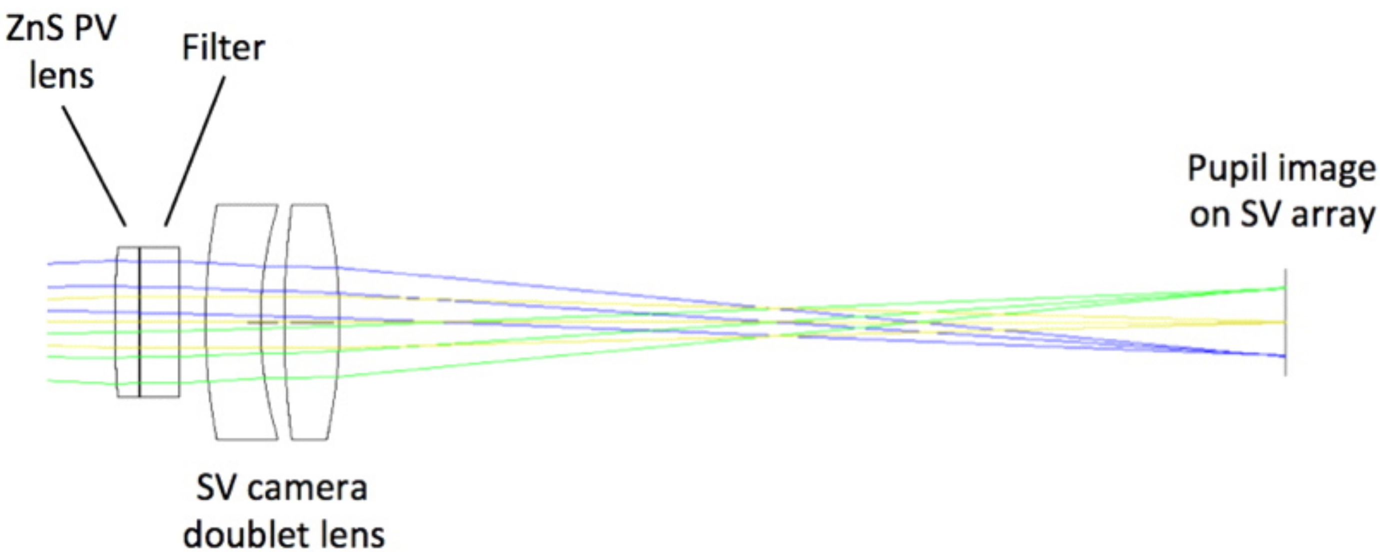
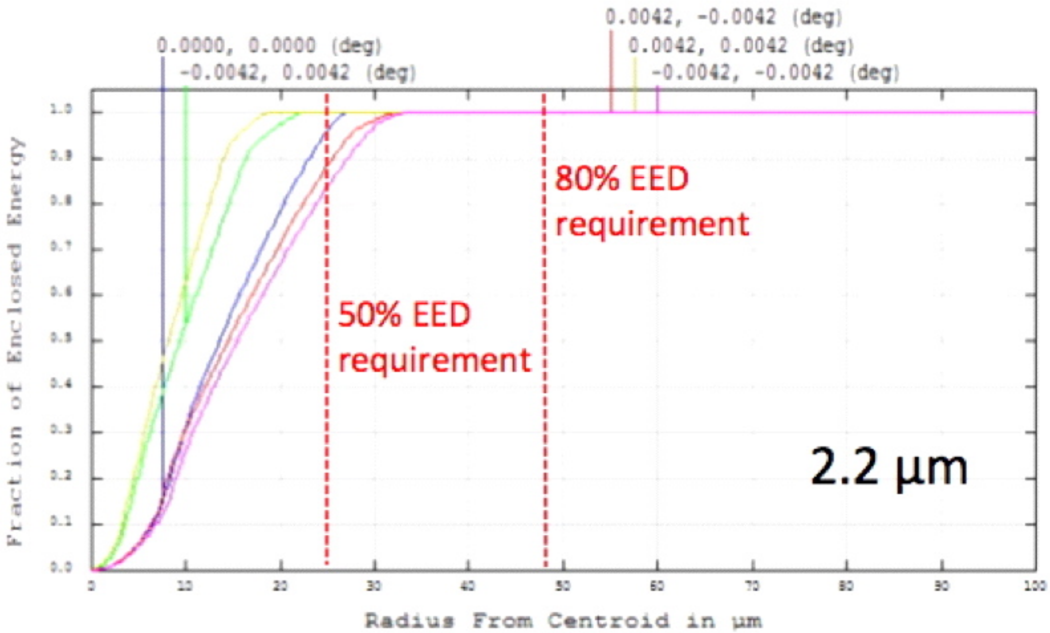
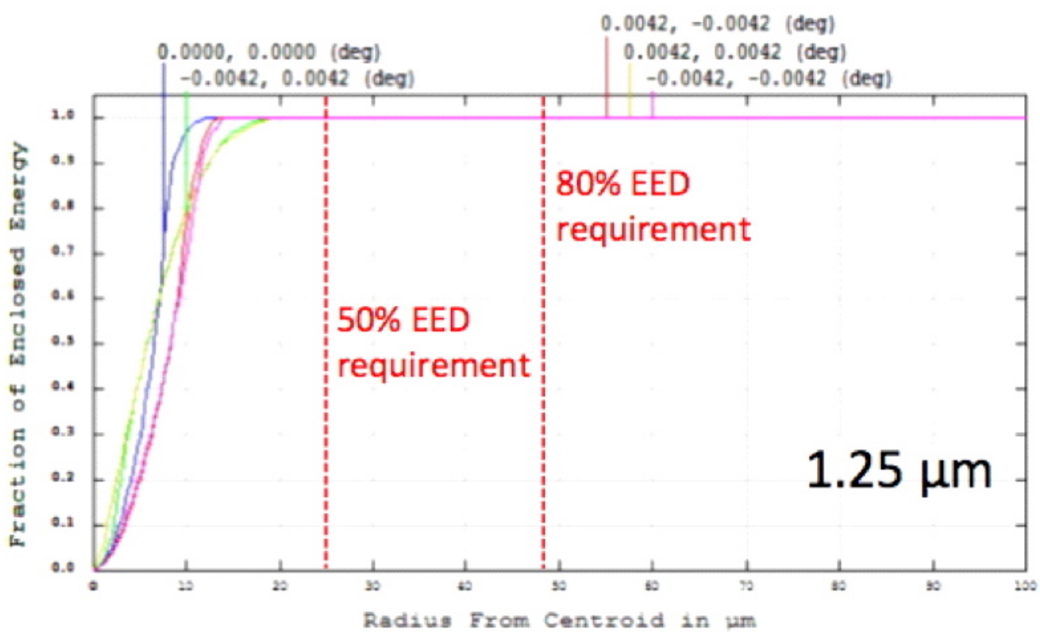


Image quality at slit

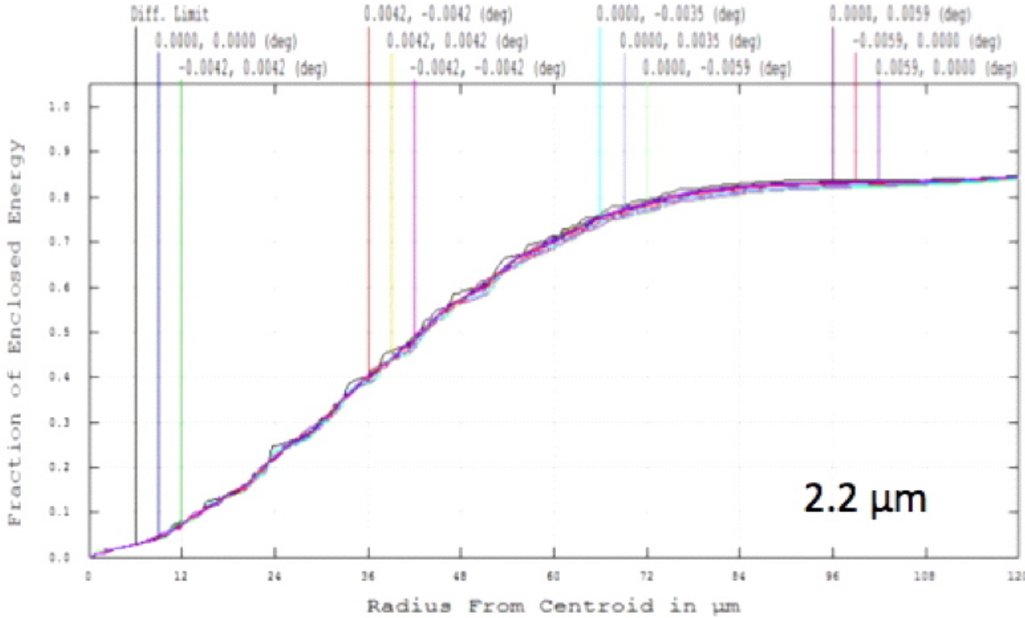


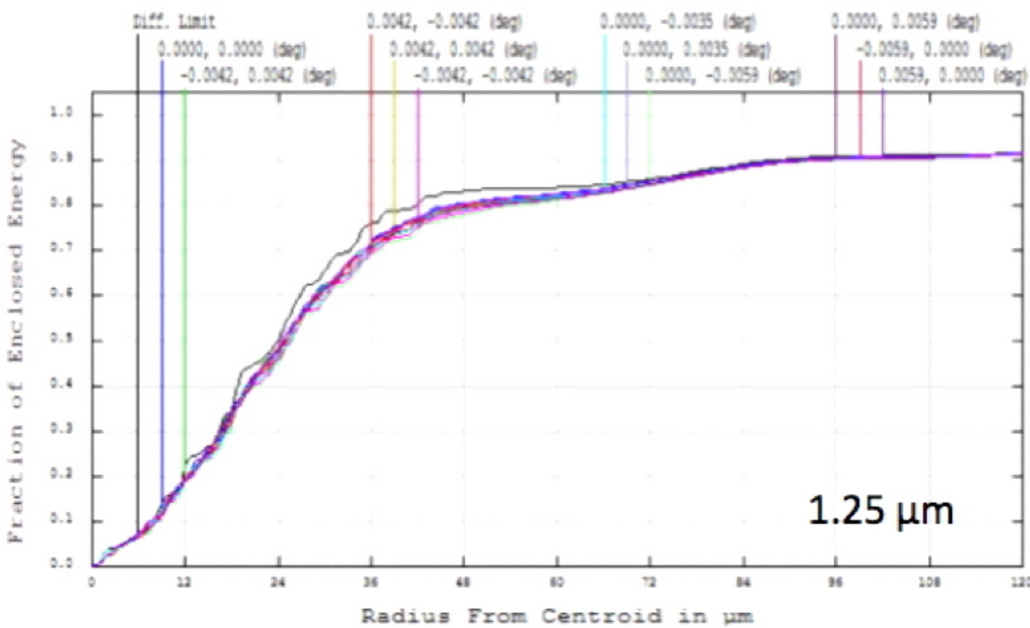


Geometric EED

Alignment and fabrication tolerances add about 5-10 μm to EED

Image quality at slit

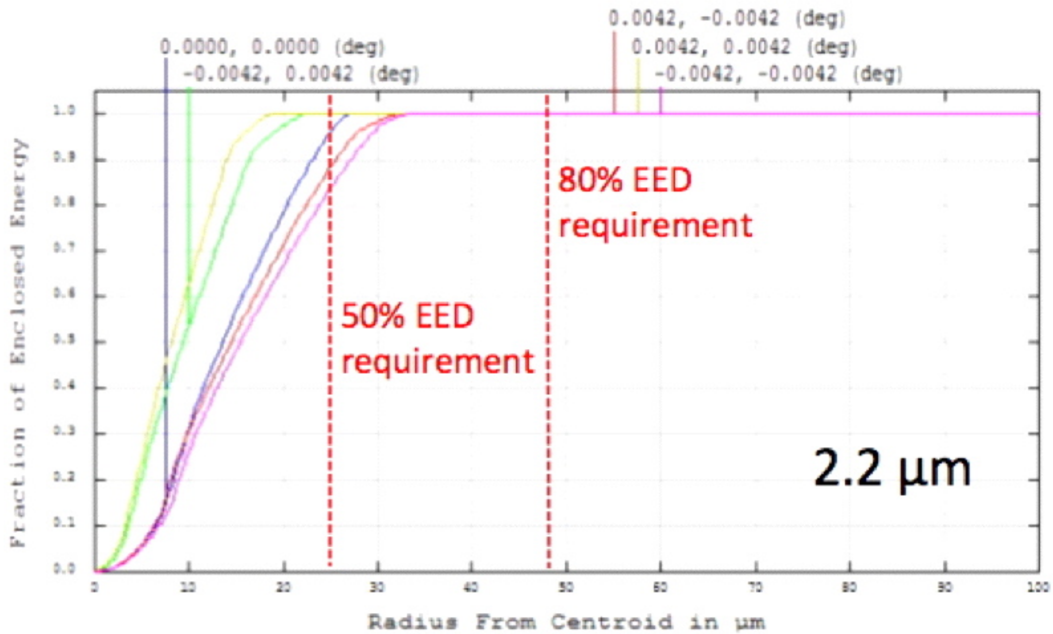


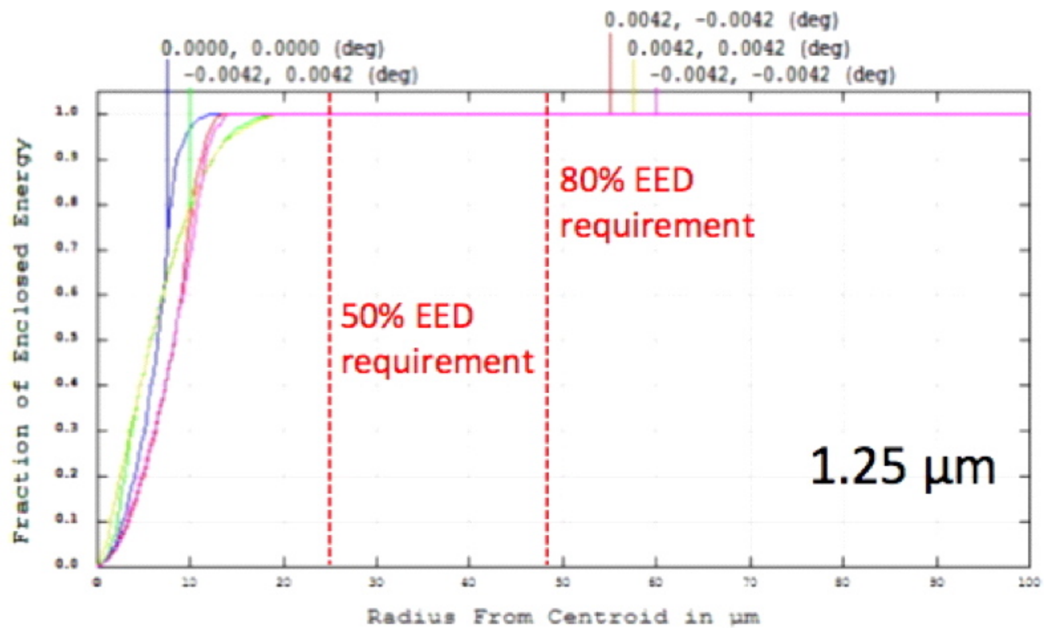


Diffraction EED

Geometric aberrations do not add significantly to EED

Image quality at slit viewer





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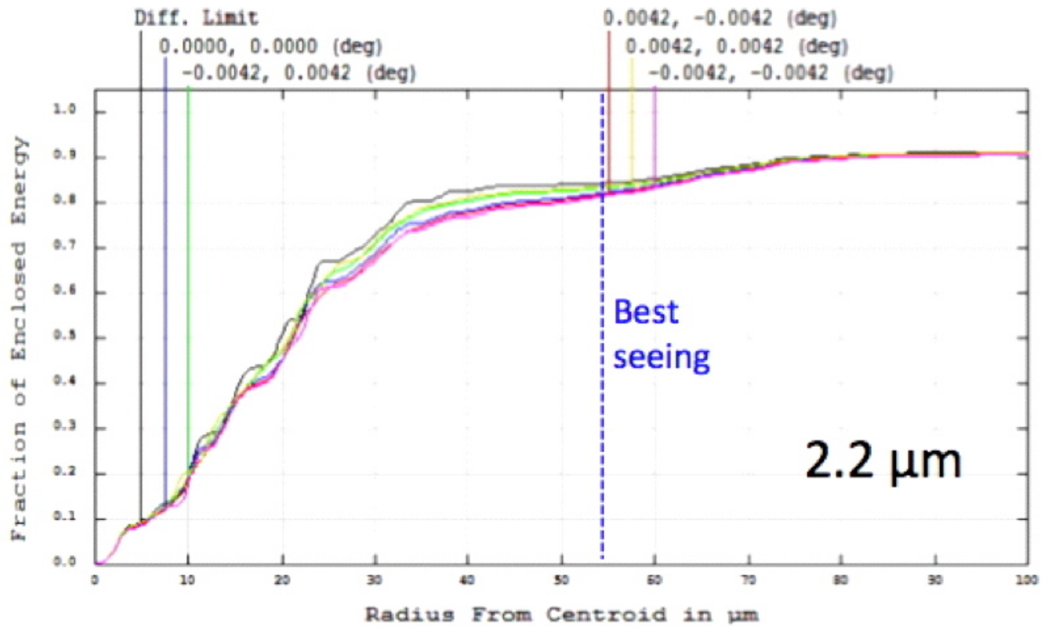
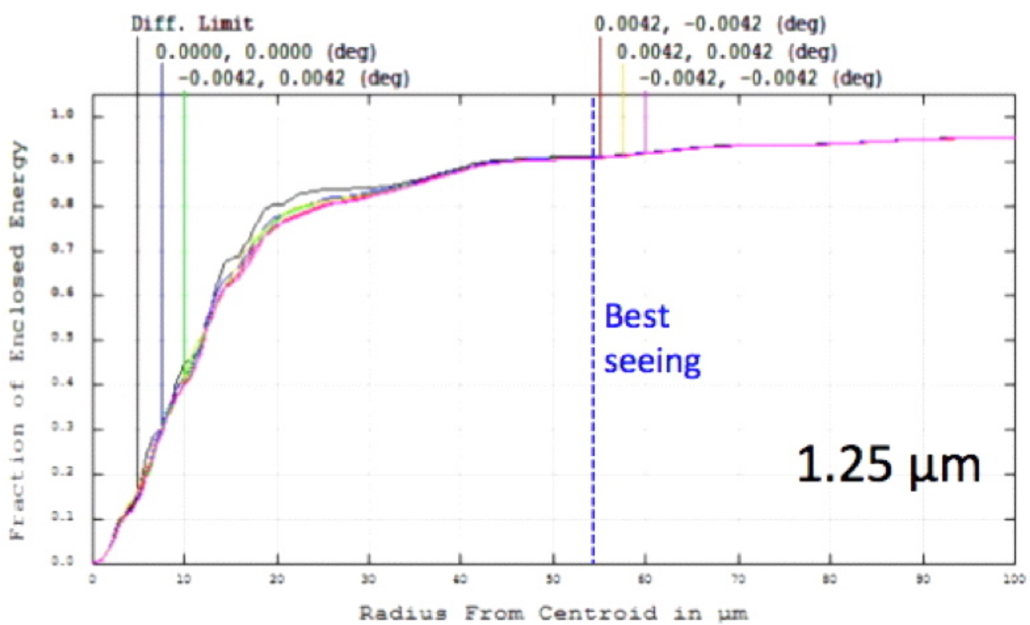




Diffraction EED

Geometric aberrations do not add significantly to EED

Surface irregularity (*Ftaclas*)

The total WFE due to irregularity, σ_T, is given by

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

lens mirror

Where σ is the RMS WFE in waves over diameter *D* and FP is the size of the beam footprint; λ_t and λ_u are the test and used wavelengths respectively

From Power Spectral Density (PSD) for typical materials $WFE \propto (scale)^{-1/2}$

Surface irregularity

Total WFE for 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**

Total WFE for slit viewer

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**

Requirements TR_12 and TR_14: diffraction-limited optics Stehl ≥ 0.8

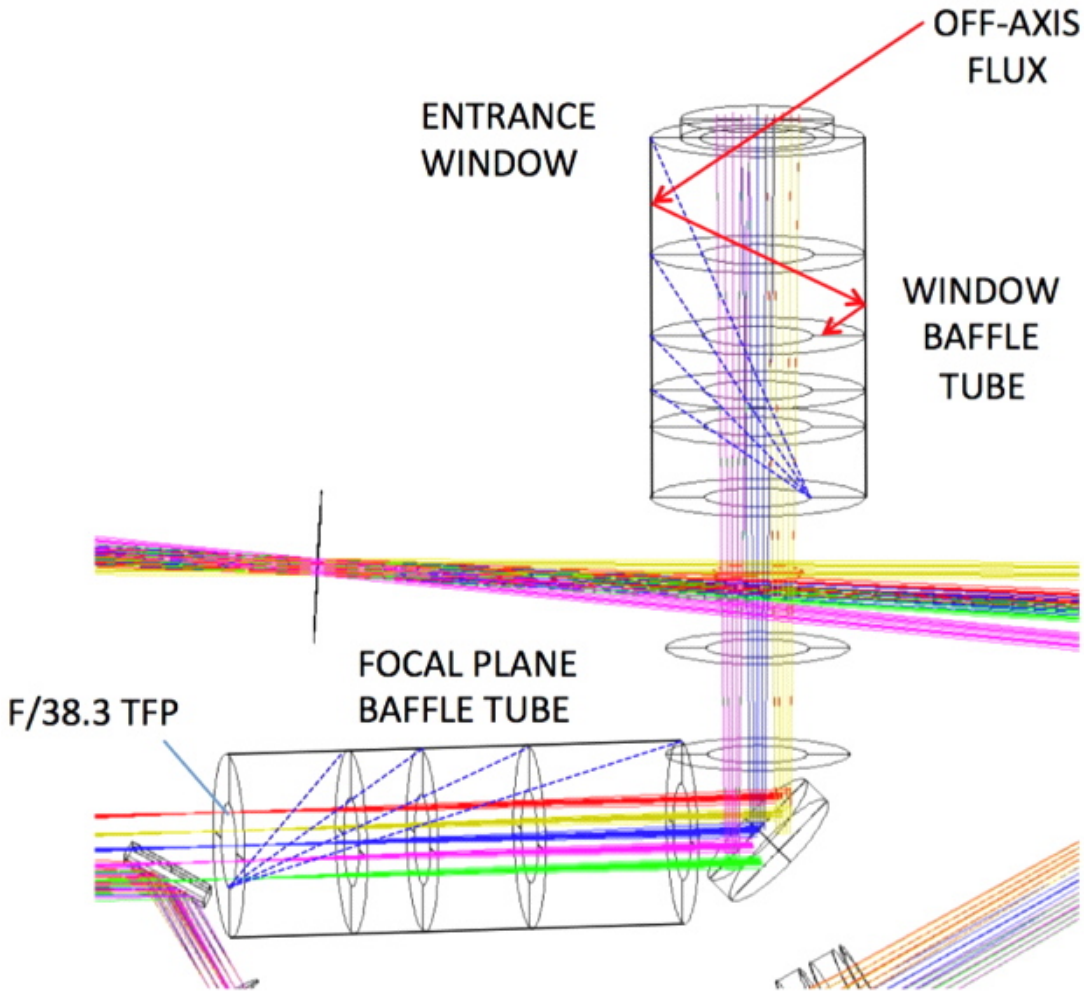
Stray light effects and mitigation

1. Off-axis stray light from telescope and sky
   - cold stop and baffle tubes

2. Ghost reflections from lenses and filters
   - tilt filters, BBAR coat lenses, ‘optimize’ lens radii
   (non-sequential analysis in Zemax)

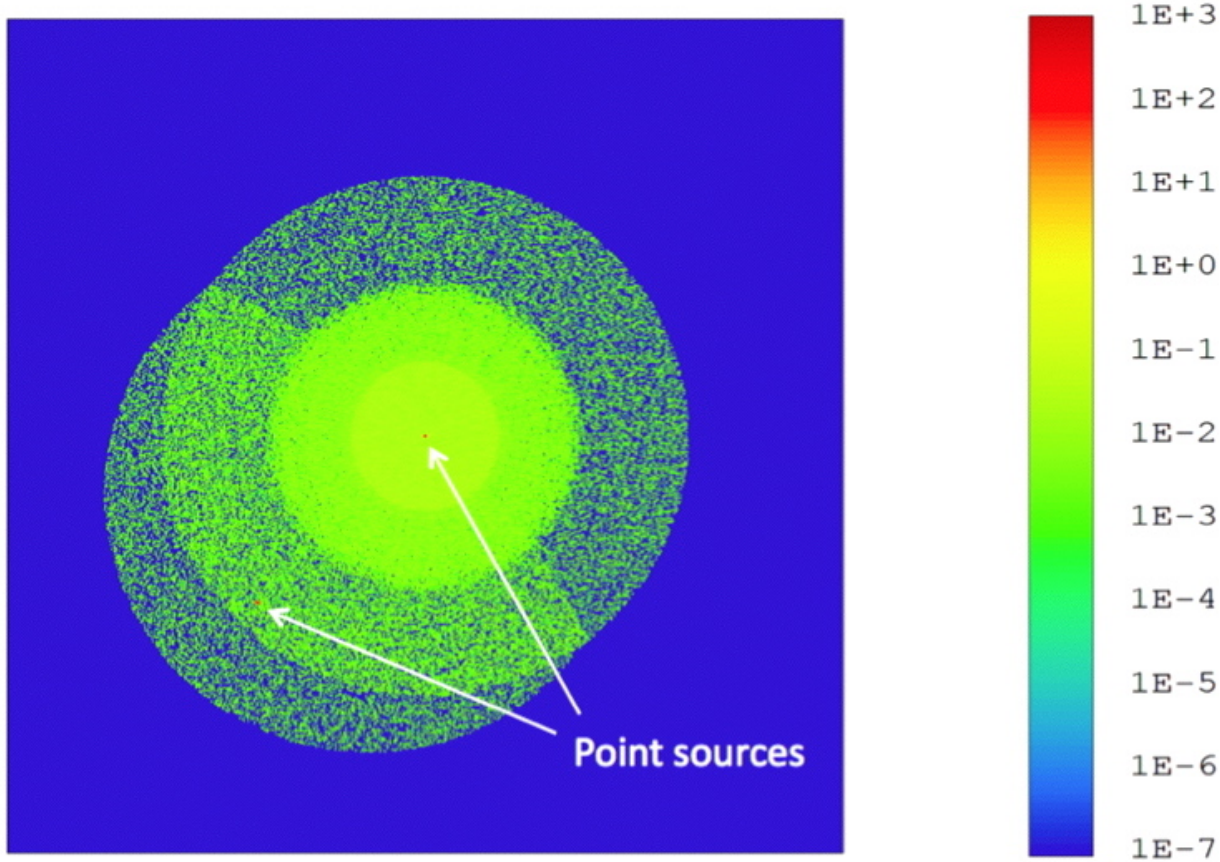
3. General surface scatter
   - minimize mid-scale errors and roughness
   (WFE analysis)

Stray light effects and mitigation



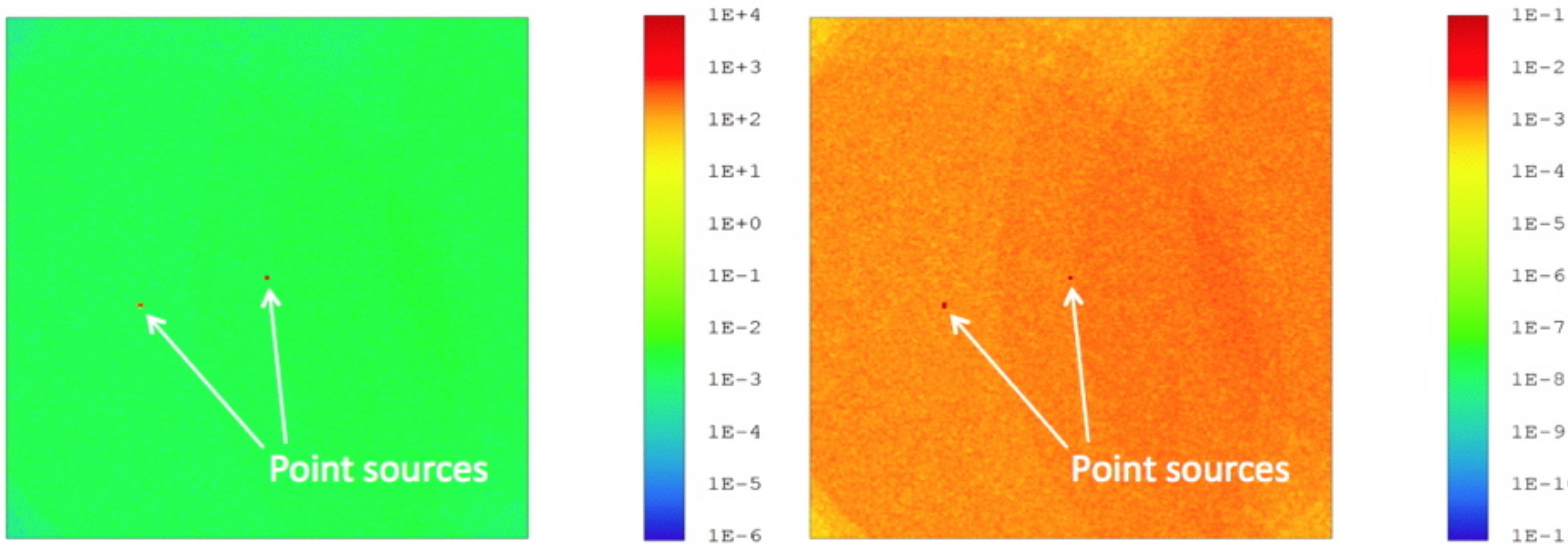
Foreoptics baffle tubes

Stray light effects and mitigation



Ghosts at slit plane – max ghost intensity 10^{-4}

Stray light effects and mitigation



Ghosts at slit viewer array – max ghost intensity 10^{-5}

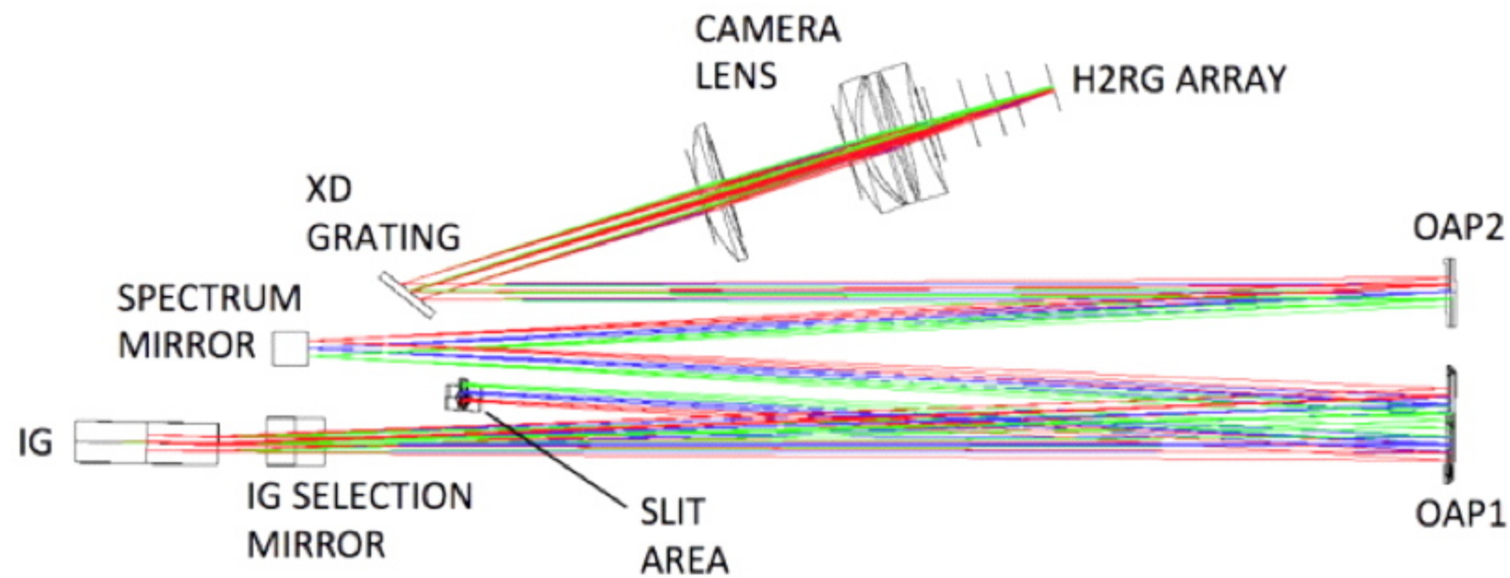
Throughput of the foreoptics and slit viewer

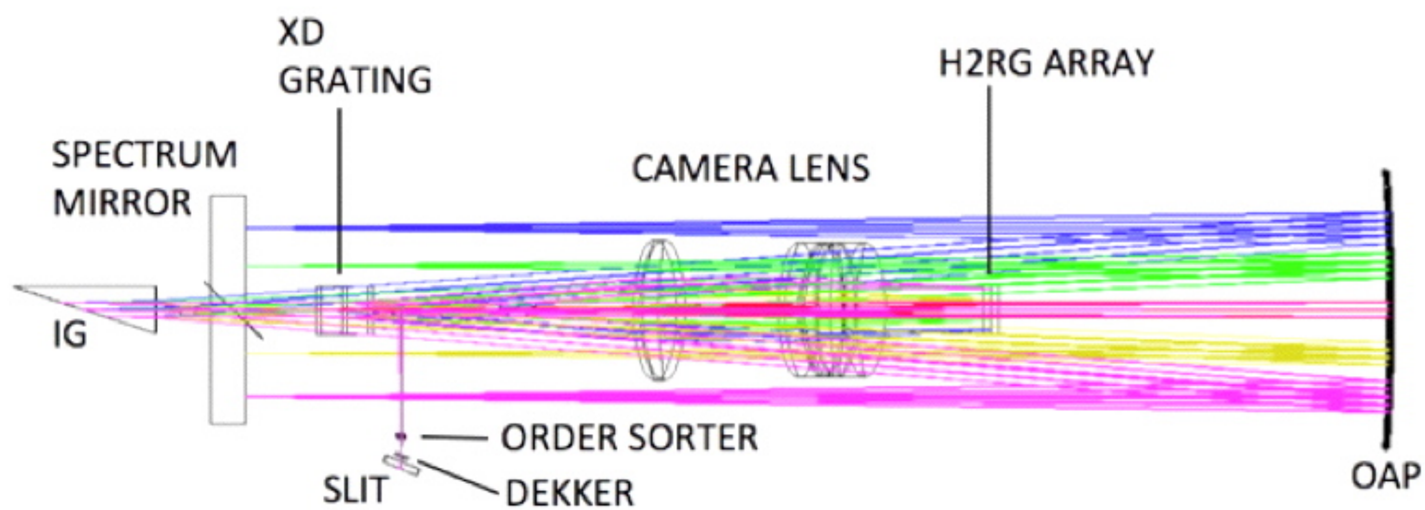
Element	*Transmission*	*Notes*
Foreoptics		
CaF_2 window	0.98^2	BBAR coat est.
Fold mirror 1	0.98	Fused silica substrate, protected-silver
Collimating mirror	0.98	Fused silica substrate, protected-silver
Fold mirror 2	0.98	Fused silica substrate, protected-silver
Cold stop	0.95	Undersized to mask telescope
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)

Example optical specification: foreoptics camera lens

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	

Spectrograph





Spectrograph optical design requirements

Requirement Number	Requirement Name
SR_1	Resolving power
SR_2	Sensitivity
SR_3	Continuous wavelength range
SR_4	Simultaneous wavelength range
SR_5	Slit width
SR_6	Sampling
SR_7	Slit length
SR_9	S/N limit (includes stray light)
SR_10	Wavelength measurement
SR_11	Radial velocity precision
SR_12	Spectral response function
TR_1	Throughput
TR_5	Pixel-field-of-view
TR_10	Image quality at the spectrograph detector
TR_11	Image stability at the spectrograph detector
TR_17	Position of the spectrograph detector
TR_18	Stray light at the spectrograph detector

Spectrograph design features

- White pupil layout, disperser at first pupil, cross cross disperser at second pupil
- Pseudo-Littrow orientation (γ =1.028 degrees)
  - tilts slit image for better sampling along slit
  - avoids potential 'picket fence' narcissus ghost
- Use silicon immersion gratings (SIGs) to minimize collimated beam diameter (22 mm) and iSHELL size
- Use two SIGs for more efficient use of array format
  - long λ SIG – FSR matched to array span at 4.15 μm (optimum for Science Case)
  - short λ SIG – FSR matched to array span at 2.50 μm
  - but overfills the array at 5 μm
- Use slow (f/38.3) OAPs with small off-axis angles (3 degrees) to minimize aberrations in the spectrograph

Optimization of OAPs

Two options for OAP design

1. Use two OAPs – optimization decenters optical axes by 26.4 mm to minimize astigmatism
2. Use single asphere to simplify mount but requires more specialized testing since more than one wave departure from a parabola (computer generated hologram)

Corning NetOptix recommends option 1 (cheaper)

Diamond-machined Al OAPs

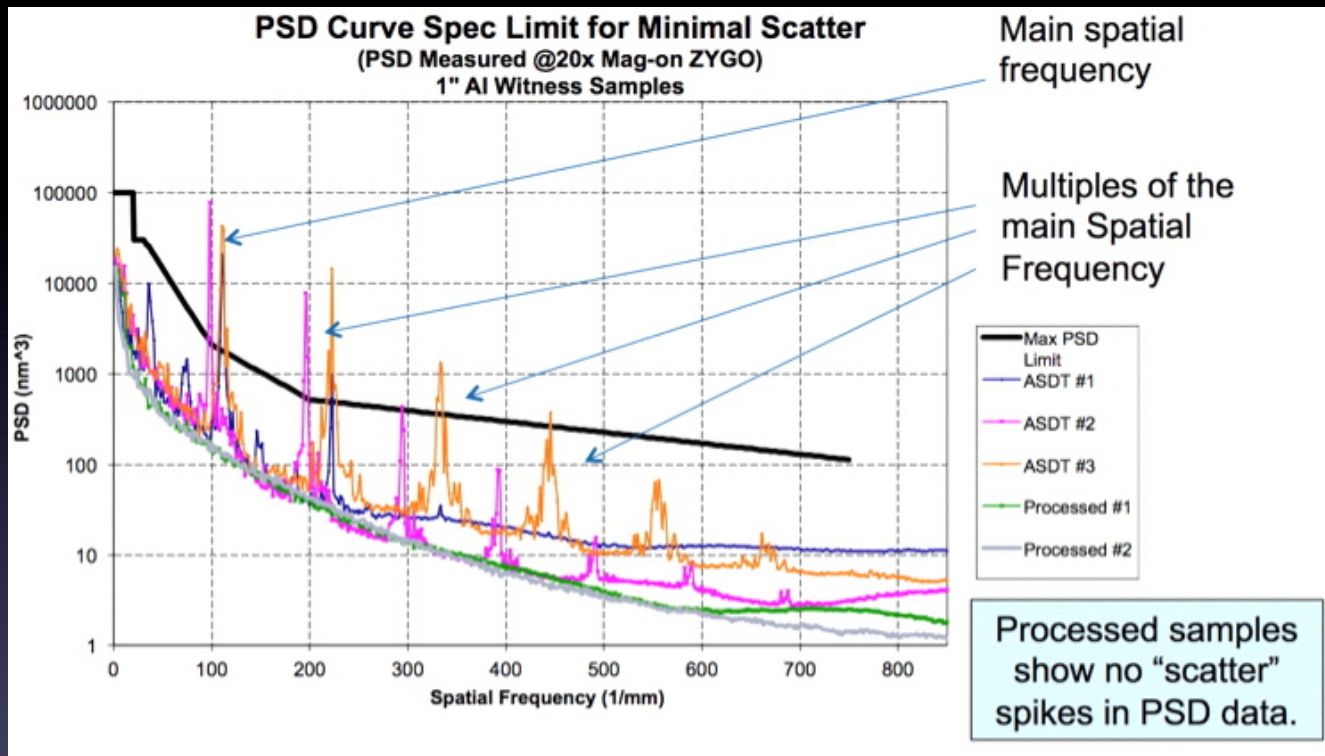
Three options for OAP fabrication

1. Corning NetOptix about $200k using LEC technique to minimize diamond turning ‘grooves’
2. Use standard diamond-turning procedure on RSP aluminum material to minimize grooves. Risky?
3. Use standard diamond-turning procedure on standard material and since grooves have minimal effect on scattered light (e.g. Durham Precision Optics about $30k)

OAPs to be co-aligned and co-mounted by vendor

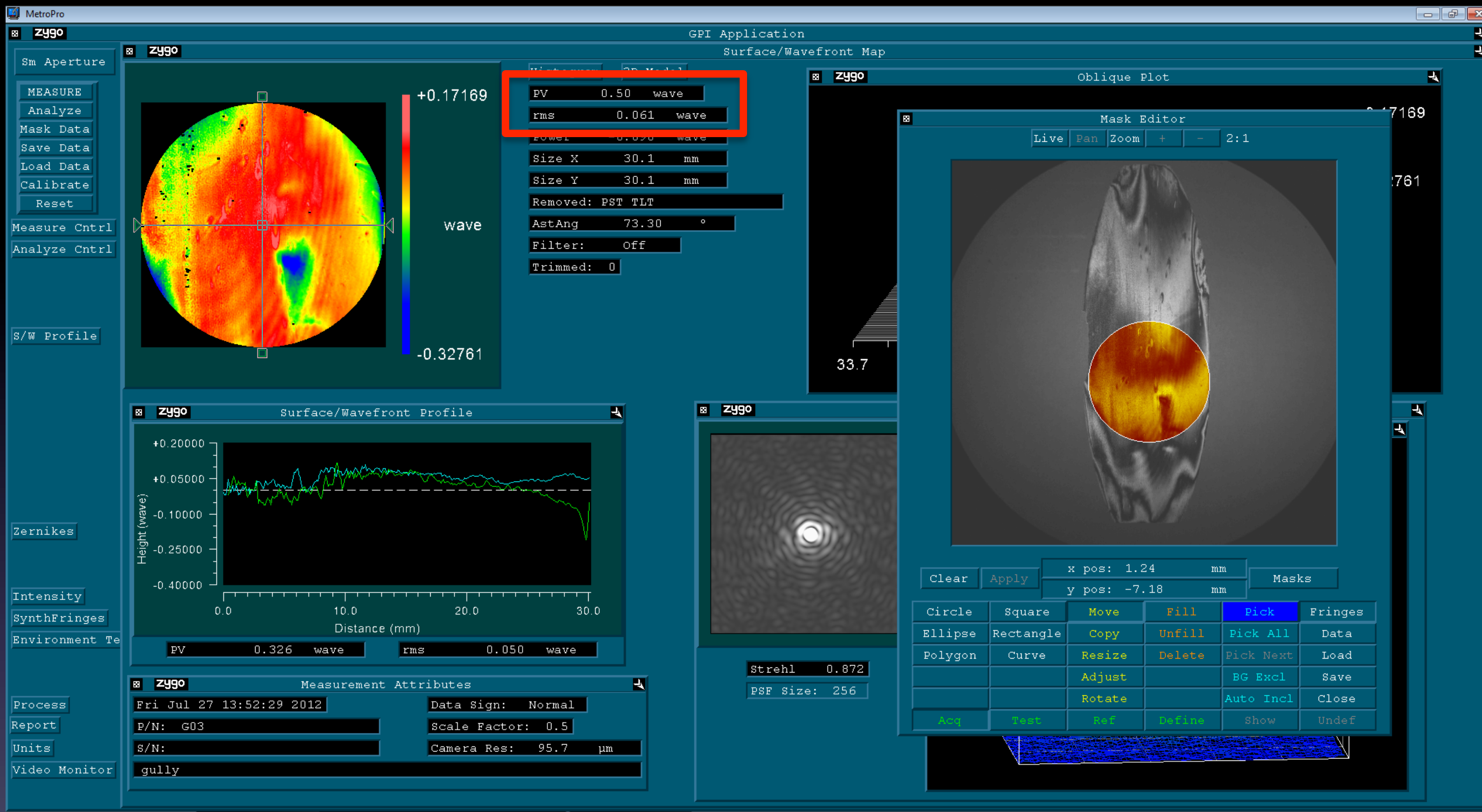
Diamond-machined Al OAPs

Power Spectral Density (PSD)



- Typical PSD from diamond-machined mirror from Corning standard and LEC process
- Amount of scatter is proportional to area under curve
- Scatter due to periodicity is therefore small

LM grating successfully fabricated



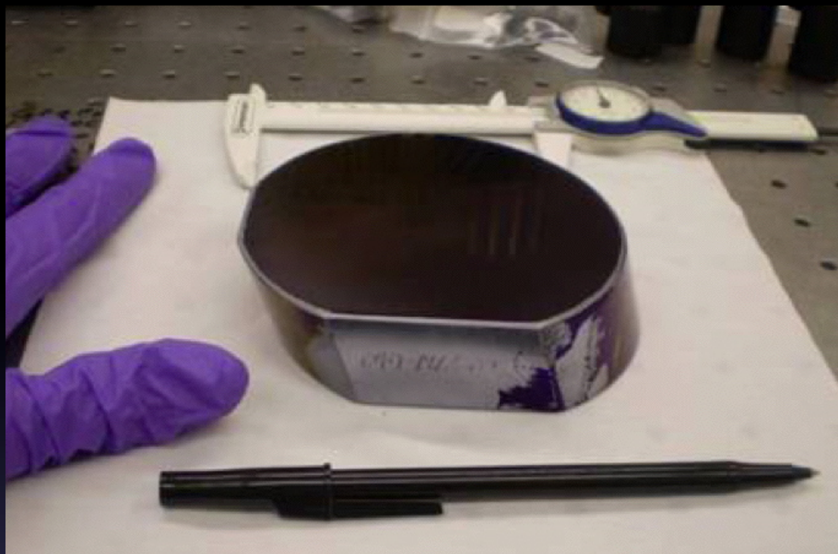
- Fabricated by contact lithography process at UT
- Meets spec., surface 0.061 waves RMS at 2.1 μm
- Grating will serve as backup since UT ‘can do better’

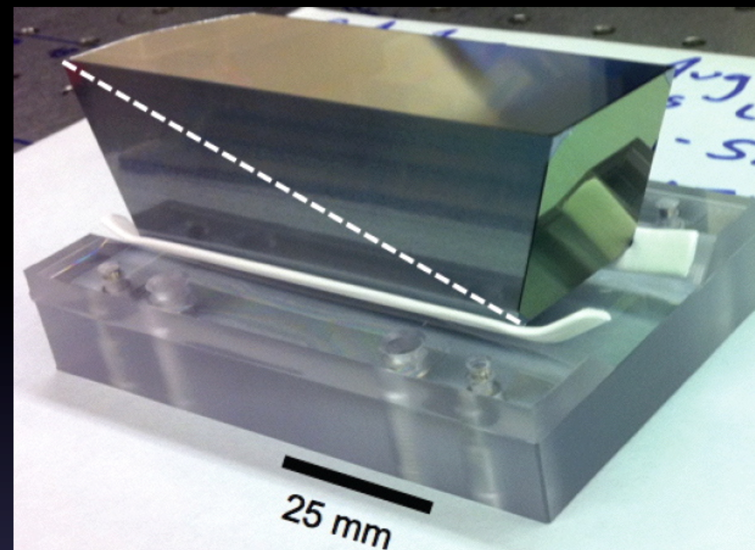
Immersion Grating Update

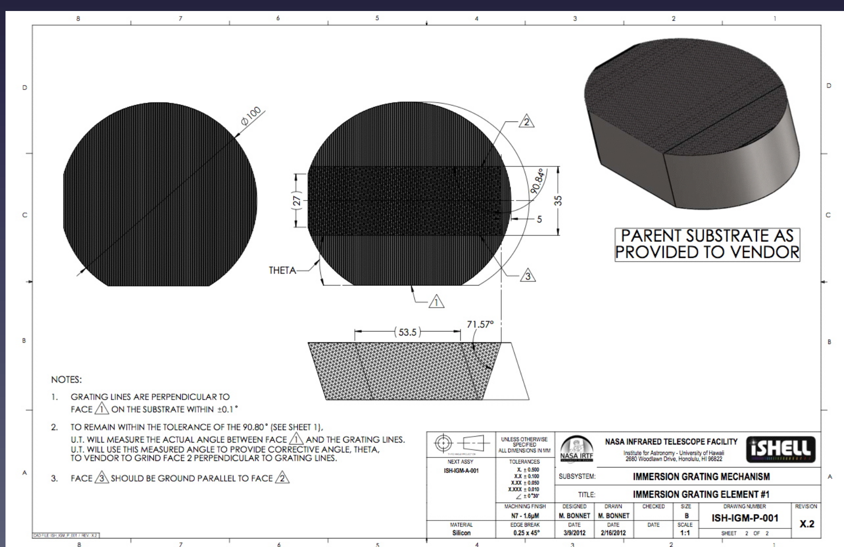
Schedule has slipped in an effort to better understand the sources of the dominant errors:

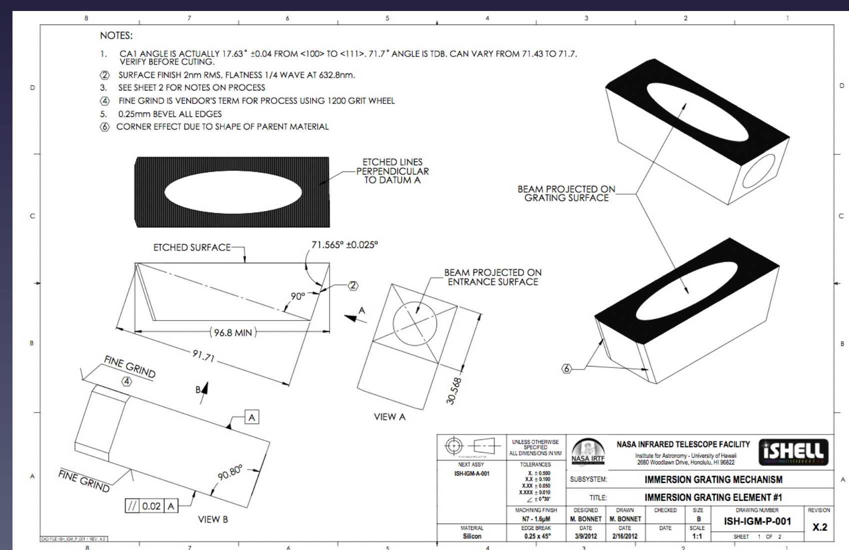
- Using new light meter to improve UV beam uniformity (contact lithography)
- Purchased own Zygo
- Plasma etch specialist now employed (Cindy Brooks)
- Plan to pattern *LM* grating (contact lithography) and *JHK* grating (e-beam lithography) by mid-2013

Next step: cut substrate to shape









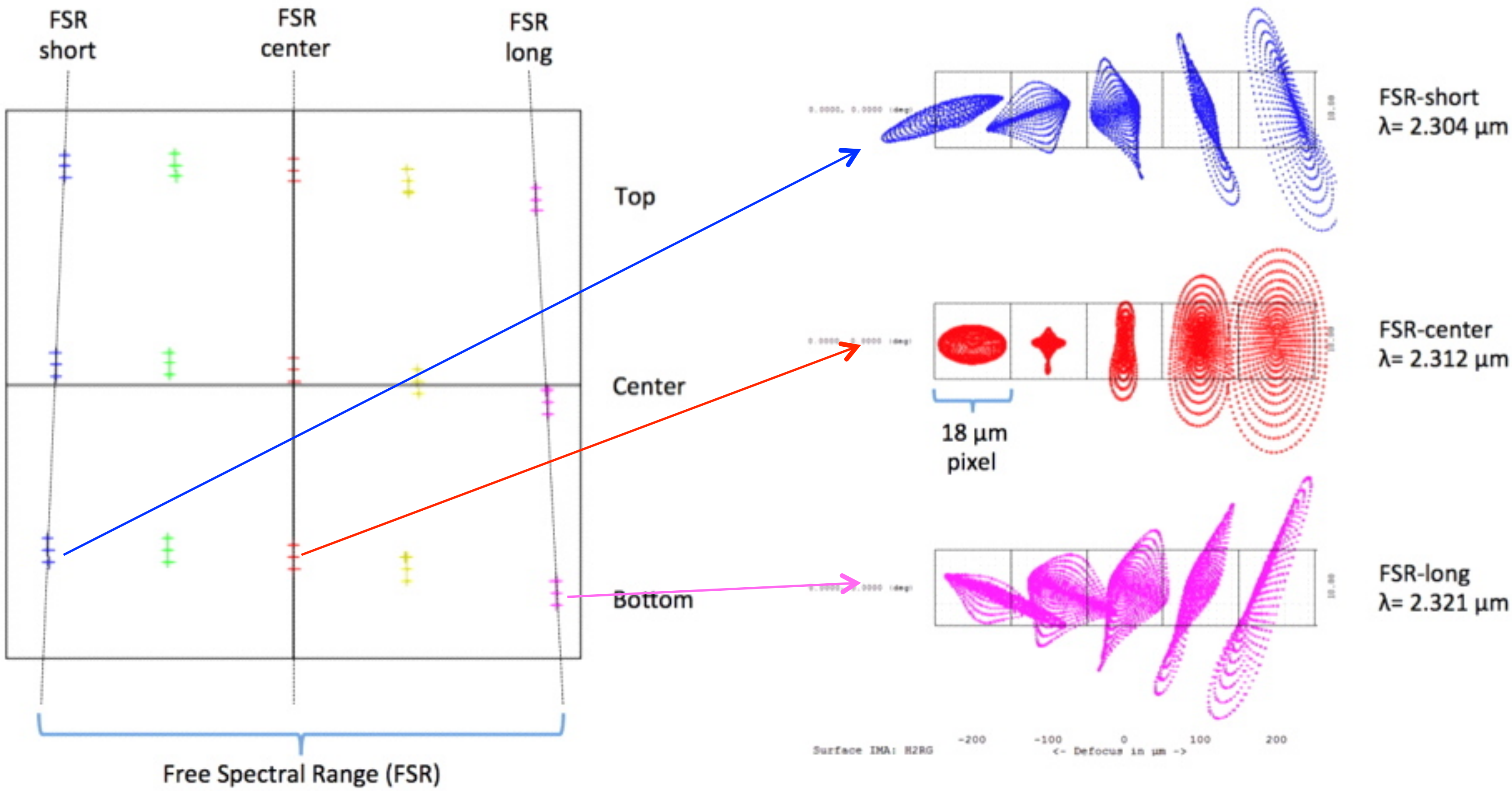
Spectrograph Camera

Two options for camera design

1. Three-mirror anastigmat preliminary design from SSG ($500k)
   - high transmission and achromatic
   - no ghosting and minimal scatter
   - some distortion
2. Optimized BaF_2-ZnS-LiF lens meets requirements ($80k OSI)
   - all spherical surfaces
   - BBAR coats to minimize ghosting
   - slightly chromatic requiring focus stage (about 2 mm)

Choose option 2 (cheaper)

Optimize lens design for x-EED (dispersion direction) making use of slight astigmatism in collimator



Toleranced lens design meets the image quality requirement (TR_10)

Table 2.6 Encircled energy widths in each of the spectral modes. Nominal design and 90th percentile Monte Carlo trial (see section 3)

Mode/ Config.	Position	Focus (mm)	50% x-EE (microns)			80% x-EE (microns)		
			FSR short	FSR center	FSR long	FSR short	FSR center	FSR long
Req.			<24.7	<24.7	<24.7	<49.3	<49.3	<49.3
J1/1	Top	-1.677	10.1 9.1	10.8 11.8	6.6 9.3	19.0 17.3	20.0 21.4	13.0 17.8
J1/3	Center	-1.677	10.0 10.0	7.0 7.0	8.8 7.2	14.1 16.9	12.3 12.0	15.5 12.6
J1/5	Bottom	-1.677	7.4 11.3	4.8 5.8	7.6 6.9	12.1 17.3	8.2 9.6	12.0 10.5
J2/6	Top	-1.322	8.1 7.0	9.0 10.0	4.6 7.2	16.0 13.7	17.1 18.6	9.4 14.3
J2/7	Center	-1.322	6.0 8.0	4.8 4.5	6.8 5.8	10.8 14.0	9.2 8.8	12.6 10.0
J2/8	Bottom	-1.322	6.0 10.1	2.8 3.6	6.6 5.8	9.4 15.0	5.0 6.4	9.1 8.3
H1/9	Top	-0.727	7.2 5.8	8.8 9.7	4.6 6.6	14.1 11.6	16.5 18.0	7.7 12.7
H1/10	Center	-0.727	6.0 8.5	4.3 4.1	7.6 6.0	10.1 13.8	7.8 7.2	12.8 9.5
H1/11	Bottom	-0.737	6.0 10.0	2.2 2.9	6.6 5.8	9.2 15.3	4.0 5.0	9.2 8.2
H2/12	Top	-0.646	5.8 4.6	6.0 8.5	2.4 4.7	12.0 9.8	15.2 16.1	5.2 9.8
H2/15	Center	-0.646	7.8 10.6	6.0 5.8	8.8 7.2	13.2 18.0	12.0 10.3	15.8 12.2
H2/16	Bottom	-0.646	7.0 11.6	1.9 3.6	7.6 6.8	10.0 16.2	3.5 5.0	10.0 10.8
H3/17	Top	-0.512	4.3 3.4	6.3 7.3	1.6 4.1	9.6 6.6	12.7 14.0	3.1 8.8
H3/18	Center	-0.512	5.4 8.1	3.4 3.2	6.8 6.2	9.4 13.8	6.8 6.1	12.0 8.9
H3/19	Bottom	-0.512	5.8 10.3	1.4 2.1	6.4 5.8	8.1 14.3	2.6 3.3	9.6 10.1
K1/20	Top	-0.311	4.3 3.5	7.0 8.1	1.6 4.2	9.5 6.6	13.8 15.4	3.1 8.8
K1/21	Center	-0.311	6.6 9.8	3.9 3.6	7.9 6.8	4.1 16.1	7.2 6.8	13.4 8.9
K1/22	Bottom	-0.311	6.0 10.6	1.2 1.7	7.2 6.5	8.3 15.1	2.5 2.9	10.7 10.8

Surface irregularity

Total WFE for spectrograph

UNIT	*RMS WFE σ @ 1.65μm (waves)*	*Note*
SIG	0.100 (0.050)	Assume best expected performance
OAPs	0.035	Two OAPs and spectrum mirror
Lenses	0.061	Three lenses
XD grating	0.044	Assume λ/10 at 0.63 μm
Fold mirror	0.020	Assume λ/10 at 0.63 μm
(SIG selection mirror)	0.048	Assume λ/10 at 0.63 μm
OS filters	0.020	Assume λ/4 at 0.63 μm
Total spectrograph	**0.141 (0.112)**	**λ/7.1 at 1.65 μm, Strehl=0.46 (λ/8.9 at 1.65 μm, Strehl=0.61)**

A Strehl of 0.5 results in a stray light background at the array of at most about 0.2% of the spectral continuum (order of magnitude less than lens ghosts)

Stray light effects and mitigation

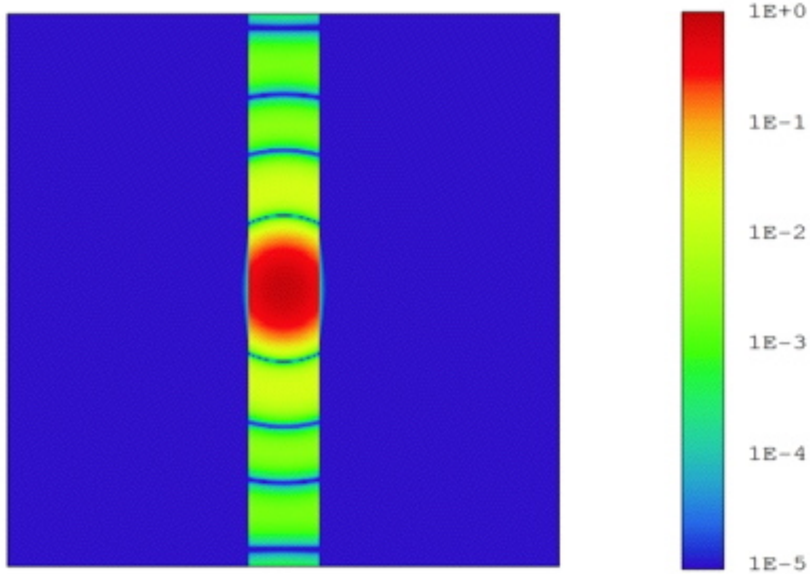
1. Diffraction from apertures in spectrograph
   - slit aperture – form cold stop in foreoptics
   - SIG entrance/exit aperture – maximize aperture

2. Grating ghosts – optimize fabrication
   - periodic grating errors
   - general scatter

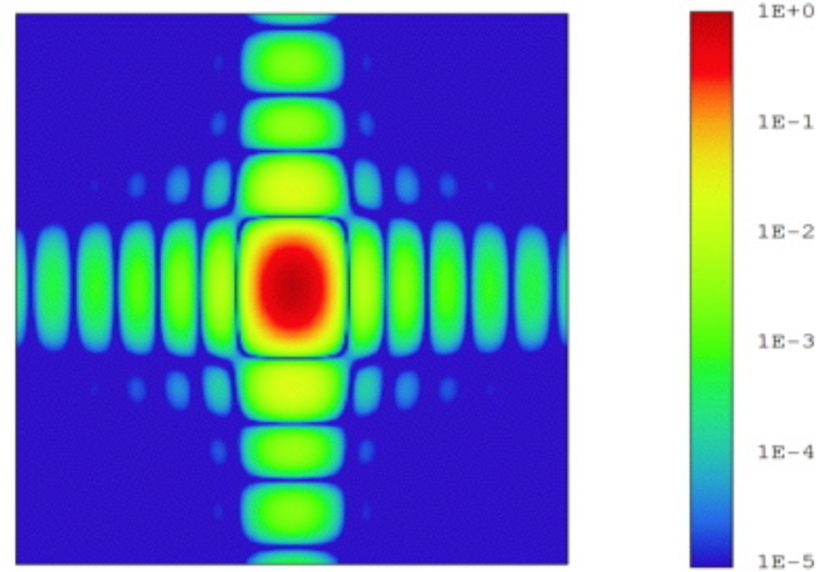
3. Ghost reflections
   - Slit substrate – backside slit
   - SIG – wedge entrance/exit aperture
   - Lens surfaces – BBAR coat, ‘optimize’ lens radii

4. General surface scatter
   - surface irregularity – minimize mid-scale errors and roughness

Image of slit and point-source in slit at 4.8 μm



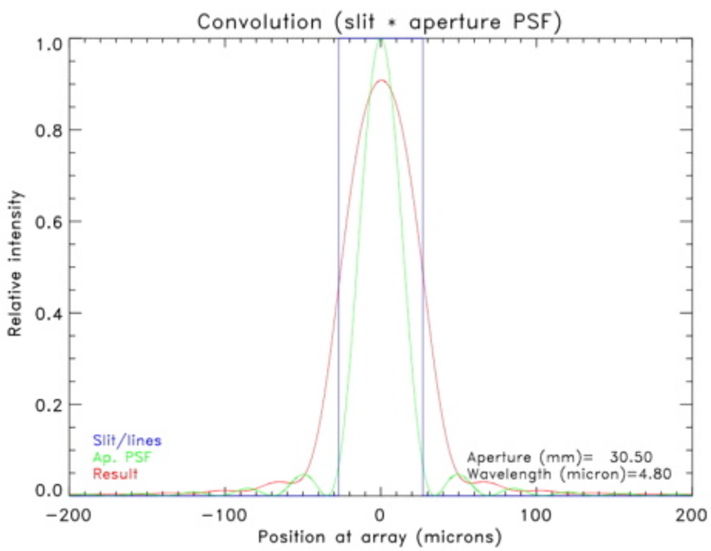
No diffraction
(large aperture)

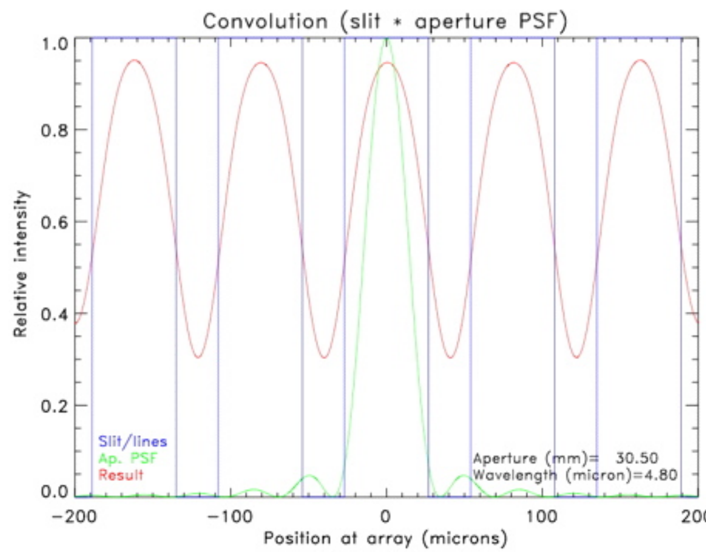


Diffraction from
SIG aperture

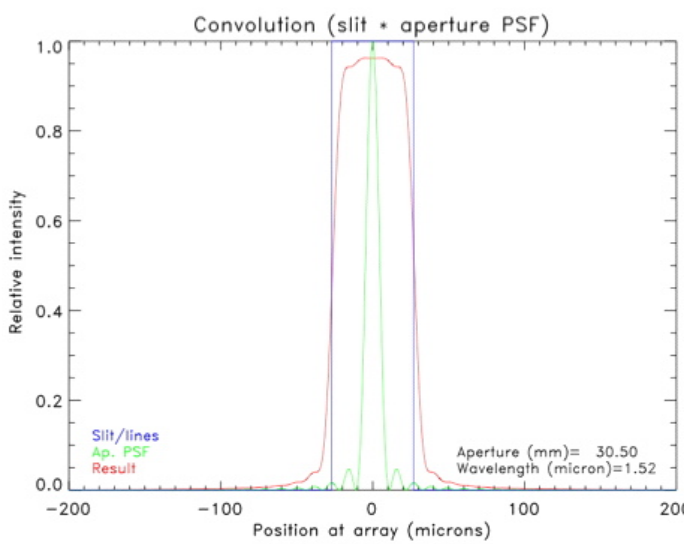
Reduction of contrast due to aperture of SIG

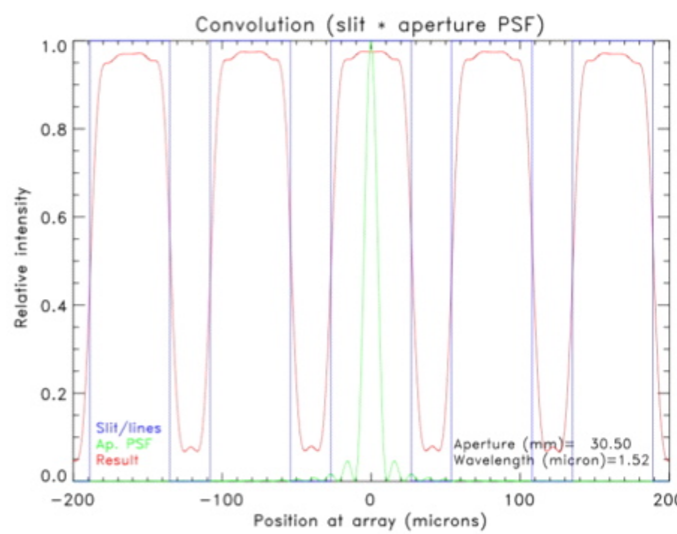
4.80 μm



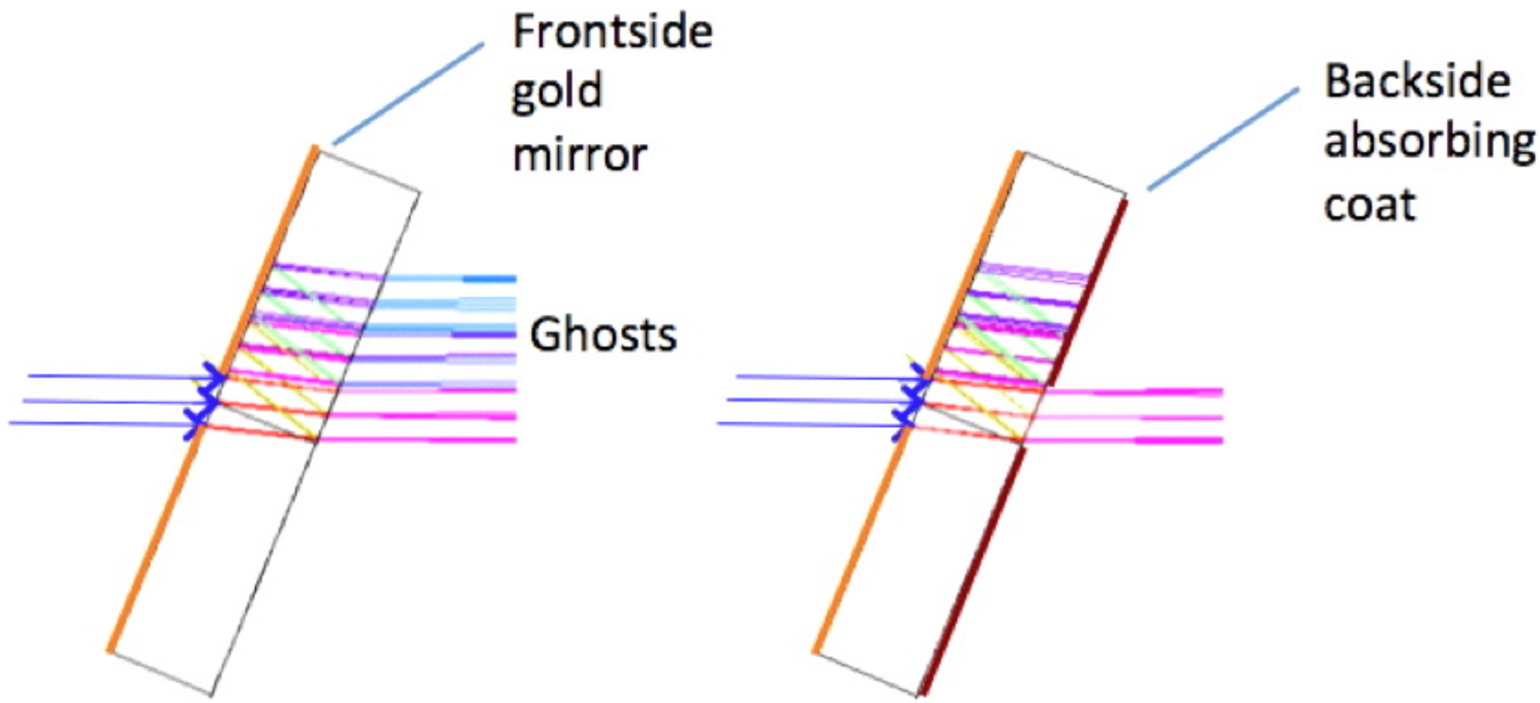


1.65 μm

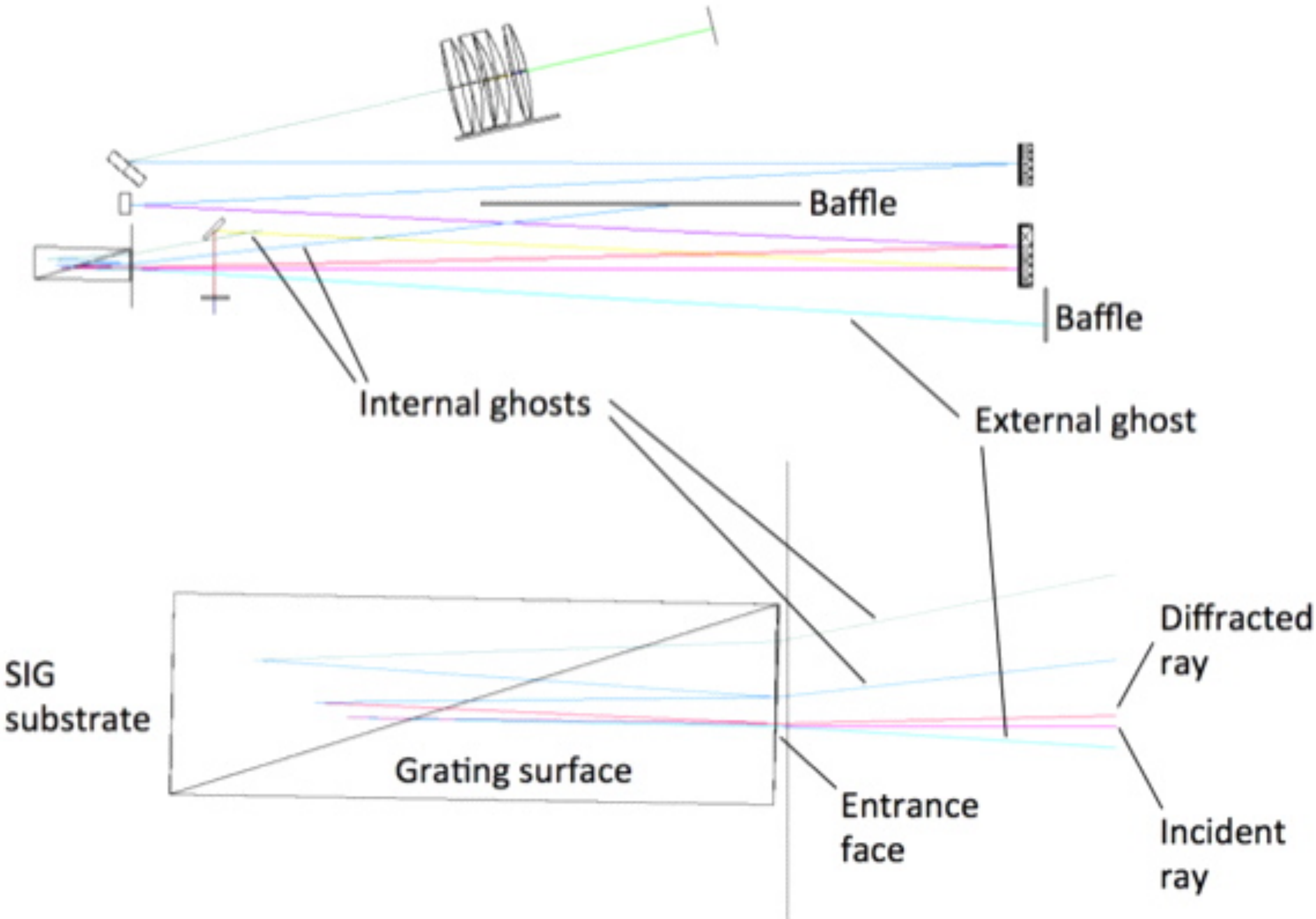




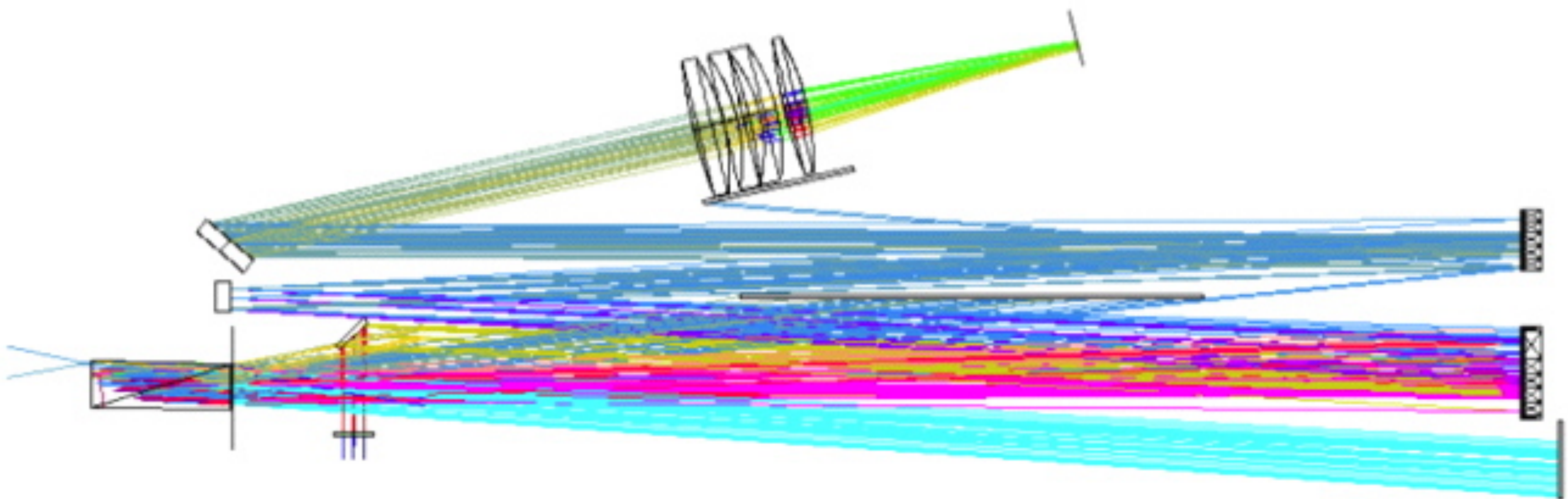
Ghosts from CaF_2 slit substrate



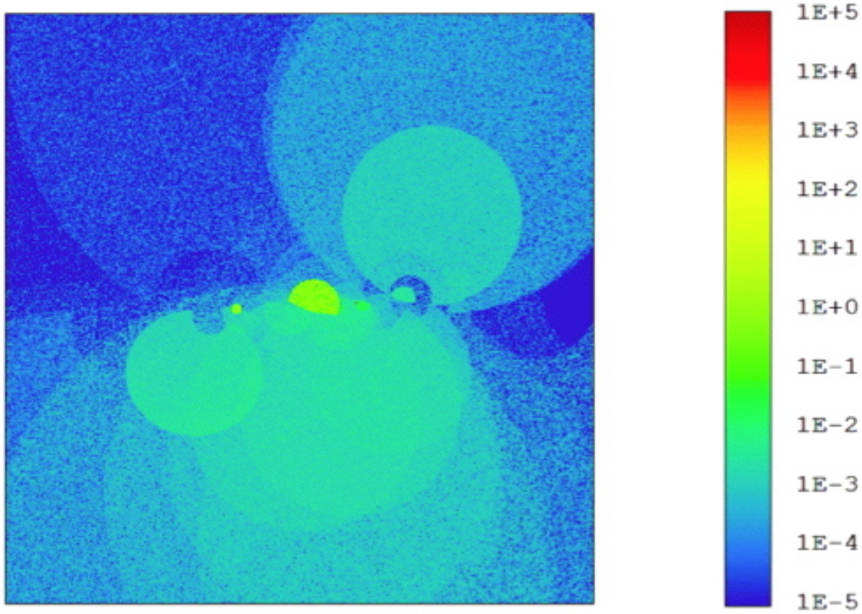
Ghosts from immersion grating



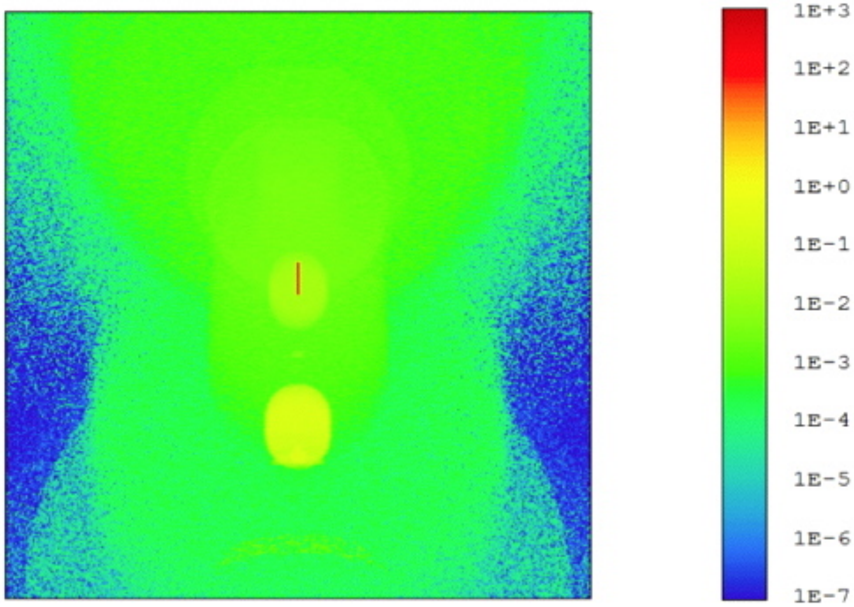
Ghosts from immersion grating



Ghosts from camera triplet lens



Point source
average ghost 10^{-7}



Flux along slit
average ghost 10^{-6}

Scaling for XD spectrum spread across array, estimated ghost is ~1%.
Marginally meets scattered light requirement TR_18

Throughput of spectrograph

Element	*Transmission*	*Notes*
Slit substrate (CaF_2)	0.98^2	BBAR coat est.
Order sorting filter	0.80	Peak of profile
Fold mirror	0.98	Fused silica substrate, protected-silver
OAP 1	0.98	Gold-coated aluminum
SIG	0.75	Peak measured at *H* and *K*
OAP 1	0.98	Gold-coated aluminum
Spectrum mirror	0.98	Fused silica substrate, protected-silver
OAP 2	0.98	Gold-coated aluminum
XD grating	0.70	Mix of custom and off-the-shelf gratings
Lens 1 (BaF_2)	0.98^2	BBAR coat est.
Lens 2 (ZnS)	0.96^2	BBAR coat est.
Lens 3 (LiF)	0.98^2	BBAR coat est.
H2RG QE	0.80	Measured SpeX science grade device
Total	0.25	At blaze peak

System throughput (telescope x foreoptics x spectrograph)=0.95 x 0.71 x 0.25=0.17 (at blaze peak and not including seeing losses at slit)

Example optical specification: spectrograph camera lens

Parameter	*Lens*			*Tolerance/note*
LENS#	1	2	3	
WORKING TEMP	77K	77K	77K	±2 K
MATERIAL	BaF_2	Cleartran (ZnS)	LiF	
R_1/mm (3 fringe fit to test plate)	153.27 CX	215.52 CX	196.67 CC	±0.1%
R_2/mm	1610.74 CC	1868.88 CC	304.07 CC	±0.1%
IRREG: >1.0 line/mm (figure)	<0.50 fr. RMS	<0.50 fr. RMS	<1.00 fr. RMS	At 0.63 μm, over CA.
IRREG: ~0.1 line/mm	<0.16 fr. RMS	<0.16 fr. RMS	<0.33 fr. RMS	At 0.63 μm, over CA.
IRREG: roughness	<16 nm RMS	<16 nm RMS	<16 nm RMS	Assumes irreg. $\propto$ scale$^{-0.5}$
CENTER THICKNESS/mm	15.05	15.02	7.03	±0.05mm
RUNOUT/mm	0.00	0.00	0.00	±0.03mm
DIAMETER/mm	104.32	100.11	94.45	+0.00/-0.02mm
CLEAR APER (CA.)/mm	84	84	75	
SURFACE (scratch/dig)	60/40	60/40	60/40	
BEVEL	See drawing	See drawing	See drawing	On drawing
COATING (1.1-5.4 μm)	BBAR < 2%	BBAR < 4%	BBAR < 2%	Reflection per surface
QUANTITY	1	1	1	

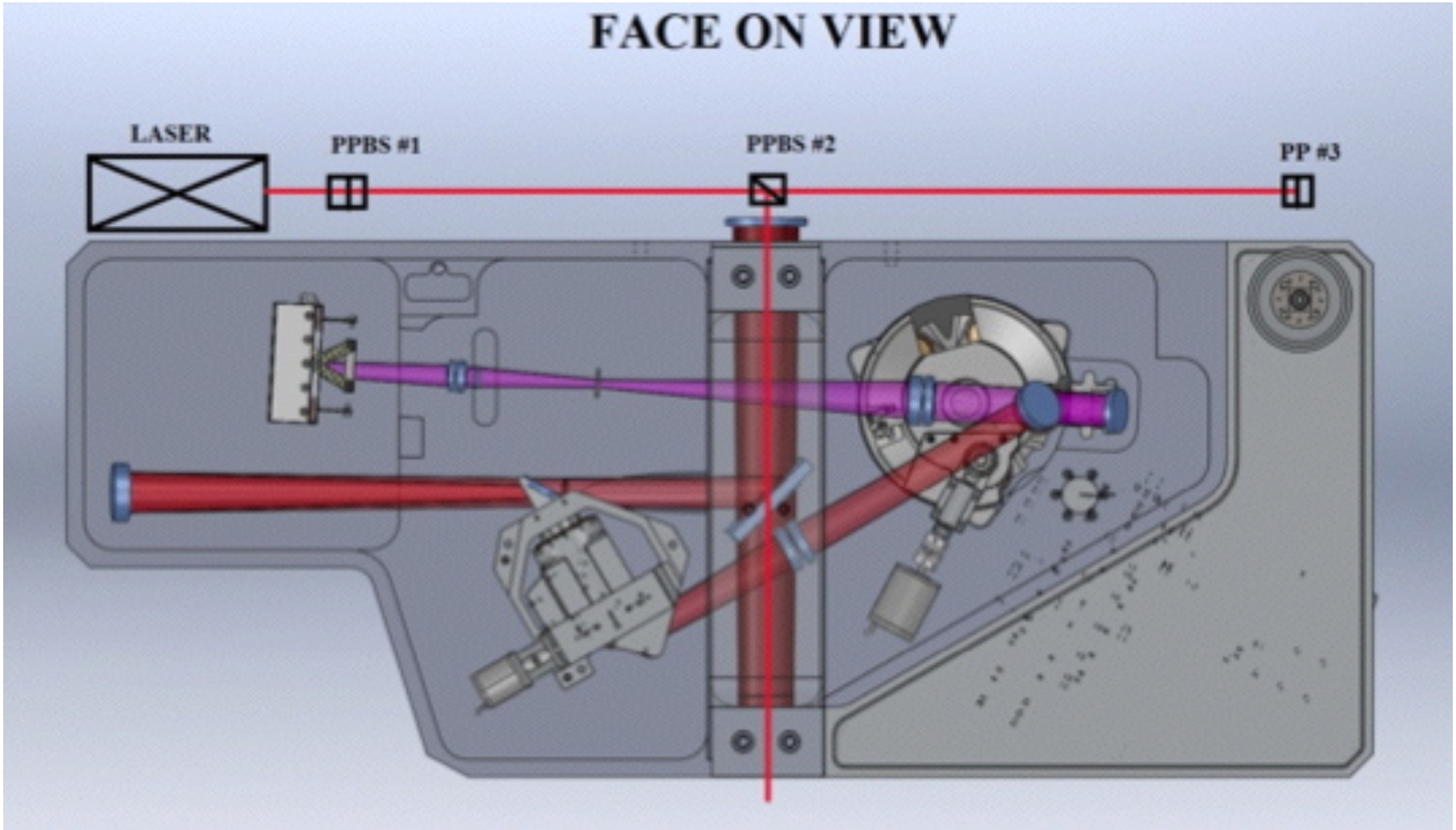
Example optical specification: OAPs

Parameter	*OAP 1*	*OAP 2*	*Tolerance/Note*
WORKING TEMP	77K	77K	±2 K
SUBSTRATE	Al 6091	Al 6061	
CONIC SHAPE	Parabola	Parabola	
FOCAL LENGTH/mm	845.86 CC	845.86 CC	±0.1% (0.85 mm)
OFF-AXIS DISTANCE (*x*-axis) see drawing	3.000 degrees 44.33 mm	3.000 degrees 44.33 mm	±0.005 degrees ±0.05 mm
OFF-AXIS DISTANCE (*x*-axis) inner edge	0.34 degrees 5.0 mm	1.31 degrees 19.3 mm	
OFF-AXIS DISTANCE (*x*-axis) outer edge	5.07 degrees 75.0 mm	4.69 degrees 69.3 mm	
IRREG: >1.0 line/mm (figure)	<0.06 waves RMS <0.30 waves pk-valley	<0.06 waves RMS <0.03 waves pk-valley	At 0.63 μm, over 22 mm diameter beam footprint
IRREG: ~0.1 line/mm	<0.02 waves RMS	<0.02 waves RMS	At 0.63 μm, over 22 mm diameter beam footprint
IRREG: roughness	<5 nm RMS	<5 nm RMS	Assumes irreg. ∝ scale$^{-0.5}$
WIDTH/mm (*x*-axis)	80.0 mm	50.0 mm	See drawing
HEIGHT/mm (*y*-axis)	206.0 mm	206.0 mm	See drawing
CENTER THICKNESS/mm	34.3 mm	34.3 mm	See drawing (height/6)
CLEAR APER ($x \times y$)/mm	66 × 186 mm	34 × 157 mm	
COATING	Gold	Gold	
QUANTITY	1	1	

Optical Alignment Plan

General strategy:

- Alignment tolerances derived from Zemax tolerance analysis
- Fabrication of optical bench and mounting fixtures to basic precision machine shop tolerances
- Use CMM for accurate positioning of fiducials on optical mounts
- Setup laser to define optical axis
- Sequentially enter optical elements on laser beam
- Measure centrations using CCD mounted in a mounting blank referenced to the optical mount, shim to align
- Individual alignment of rotator, OAP unit, gratings, and lens barrels before assembly onto bench
- Use pupil viewer to align cold stop to secondary on telescope


FACE ON VIEW
LASER
PPBS #1
PPBS #2
PP #3

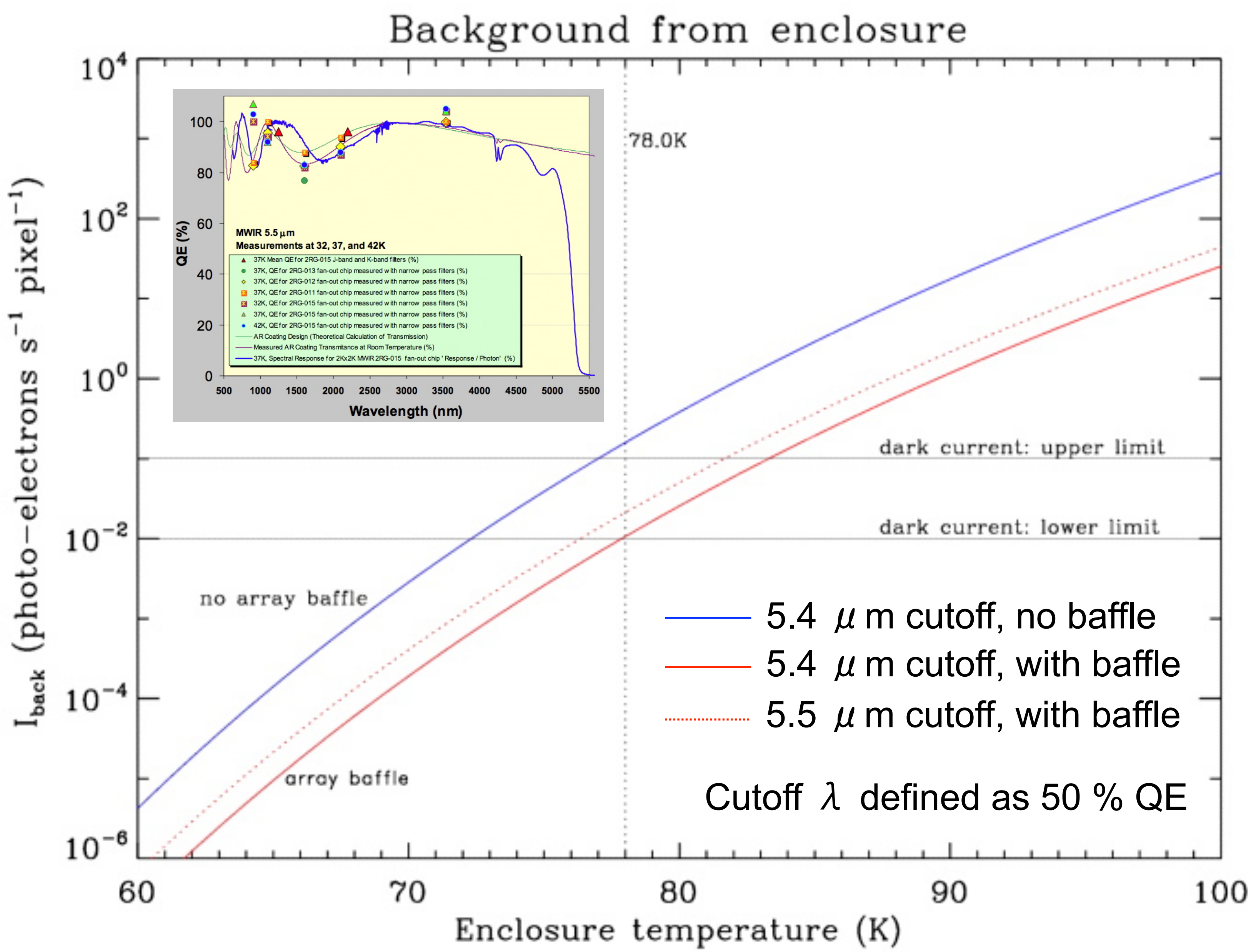
Optical Alignment Plan

1. Mount laser to top of optical bench
2. Center beam on optical axis using fiducial masks at entrance and exit ports of optical bench
3. Align foreoptics mirrors
4. Mount and align rotator and camera lens
5. Align spectrograph mirrors
6. Mount and align gratings and camera lens
7. Mount optical bench into cryostat
8. Align cryostat on telescope using pupil viewer

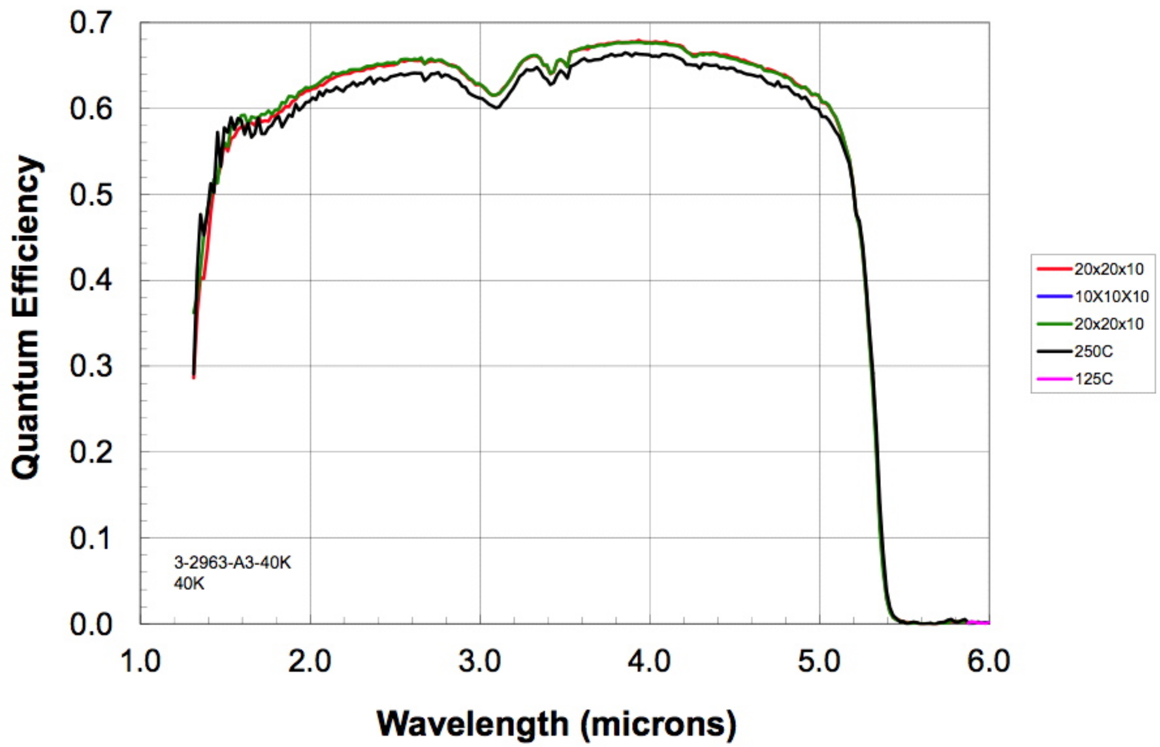
For details see alignment documentation

Summary of high-level thermal design requirements

1. Optical enclosure temperature < 78 K, stability < 1 K
2. Detector array cooling/warming rate < 0.5 K/min
3. Lens element cooling/warming rate < 0.5 K/min (see thermal FEA for spectrograph triplet lens)
4. Spectrograph array temperature 38 K, stability < 0.1 K
5. Guider array temperature 30 K, stability < 0.1 K
6. Immersion grating temperature 80 K, stability < 0.05 K for 0.3 pixels
7. If used, liquid nitrogen hold-time must be longer than two days
8. Cooling/warming times must be no longer than three days with goal of two days


Background from enclosure
78.0K
dark current: upper limit
dark current: lower limit
no array baffle
array baffle
5.4 μm cutoff, no baffle
5.4 μm cutoff, with baffle
5.5 μm cutoff, with baffle
Cutoff λ defined as 50 % QE
Enclosure temperature (K)
I_back (photo-electrons s^-1 pixel^-1)
MWIR 5.5 μm
Measurements at 32, 37, and 42K
QE (%)
Wavelength (nm)

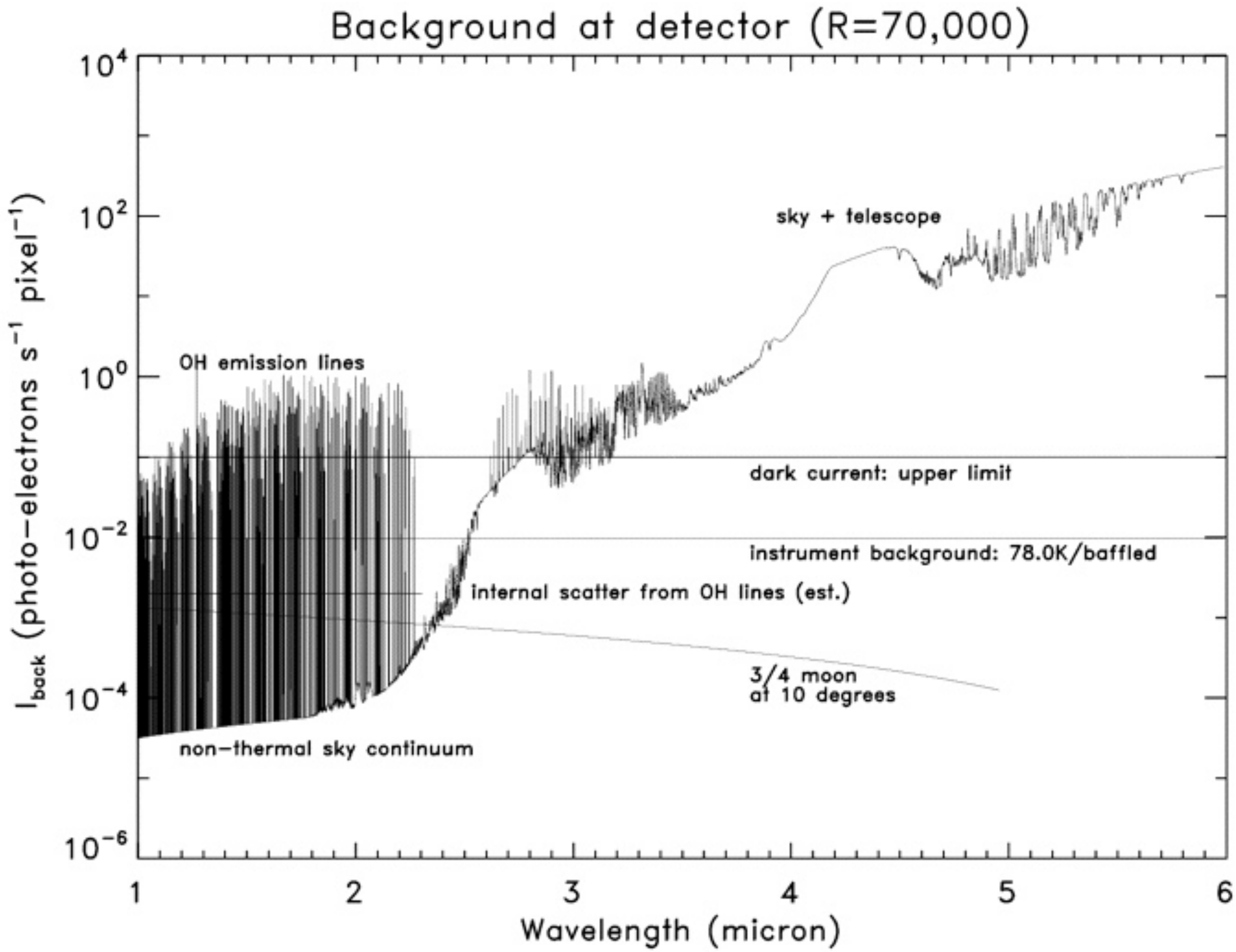
MWIR PEC Spectral – Layer 3-2963-A3 at T = 40 K



Teledyne spec.

$\lambda_{CO} = 5.3\ \mu m$

Typical range 5.1-5.5 μm


Background at detector (R=70,000)
sky + telescope
OH emission lines
dark current: upper limit
instrument background: 78.0K/baffled
internal scatter from OH lines (est.)
3/4 moon
at 10 degrees
non-thermal sky continuum
I_{back} (photo-electrons s^{-1} $pixel^{-1}$)
Wavelength (micron)
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
1
2
3
4
5
6