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INITIAL OPERATION CONCEPTS DEFINITION DOCUMENT

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1 INTRODUCTION

1.1 Purpose

This document describes the operation of the infrared high-resolution immersion grating spectrograph for IRTF (iSHELL) as required to carry out the observations described in the science case. It serves a number of purposes. It presents an end-to-end system level description of iSHELL, the factors affecting the observing and a context for developing ideas and operational scenarios. The document will be updated as work progresses.

This is not a requirements document and the content is for information only. Eventually the operations manual will follow from this document.

1.2 Applicable and Reference Documents

Reference	Document Title	Document Number	Issue
AD1	Science Case	iSHELL-SPEC-00001-0001	1.0
AD2	Science Requirements Document	iSHELL-SPEC-00002-0001	1.0
AD3	Controller Requirements Document	iSHELL-SPEC-00003-0001	1.0
AD4	Functional Performance Requirements Document	iSHELL-SPEC-00004-0001	1.0

1.3 Abbreviations

ADC	Analog-to digital converter
ARC	Astronomical Research Cameras (array controller vendor)
CRIRES	Cryogenic infrared echelle (R~70,000) spectrograph at VLT
CU	Calibration unit in iSHELL
DV	Data viewer display
FM#	Fold mirror number
FR	Facility requirement
FPRD	Functional and Performance Requirements Document
FOV	Field of view
FSR	Free spectral range (wavelength/order)
FWHM	Full width half maximum
GUI	Graphical user interface
H2RG	Hawaii 2 RG detector array
IG	Immersion grating
iSHELL	Immersion grating echelle spectrogrph
LXD	Long wavelength cross-dispersed mode
MIM	Multiple instrument mount at IRTF
NDR	Non-destructive read
OAP	Off-axis parabola
OCDD	Operation Concepts Definition Document
PSF	Point spread function

PV	Pupil viewer
R	Resolving power ($\lambda/\Delta\lambda$)
RMS	Root mean squared
RV	Radial velocity
SG	Science grade array
S/N	Signal (S) to noise (N) ratio
SpeX	Medium resolution (R=100-2500) XD spectrograph and imager at IRTF
SR	Science requirement
SRF	Spectral response function (slit profile at detector as a function of wavelength)
SV	Slit viewer
SXD	Short wavelength cross-dispersed mode
TBC	To be confirmed
TBD	To be decided
TCS	Telescope control system at IRTF
TFP	Telescope focal plane
XD	Cross-dispersed/disperser

2 SCIENCE REQUIREMENTS SUMMARY

The highest-level instrument requirements are requirements dictated by facility needs. The decision to build a high-resolution infrared spectrograph for IRTF comes from overall strategic plans, the availability of funding and resources, and not just from purely scientific considerations. We call these requirements Facility Requirements (FR).

FR_1. iSHELL shall be a 1-5 μm high-resolution echelle spectrograph for use at the cassegrain focus of IRTF. It will employ silicon immersion gratings to keep the instrument sufficiently compact to mount at this focus. Dan Jaffe's group at the University of Texas, at Austin, shall provide the silicon immersion gratings. iSHELL shall replace CSHELL

FR_2. iSHELL shall use one Teledyne Hawaii-2RG 2048 x 2048 detector array for spectroscopy

FR_3. The iSHELL project shall provide users with a complete data reduction tool similar in capability to Spextool, which was developed for use with SpeX data

The primary science aim of iSHELL is to obtain ~1-5.3 μm spectroscopy at a resolving power of R≥70,000. The science targets range from point sources to planets and require slit lengths in the range 5 (TBD) to 25 arcseconds. In addition, a finite one-shot wavelength range is required depending upon the particular science case. To be useful the instrument must also meet sensitivity requirements. Some science cases require very high S/N so it is important that S/N is not limited by systematic errors. iSHELL needs to be stable enough and provide adequate calibration to achieve long-term (months) radial velocity precisions of <10 m/s. Finally, it is important to achieve good observational efficiency. This results in 13 science-derived requirements (SR):

SR_1. Spectral resolving power R≥70,000

SR_2. $J \geq 10.5$, $H \geq 10.0$, $K \geq 9.5$, $L' \geq 7.4$, $M' \geq 5.0$ for S/N =100 in 3600 s at R=70,000

SR_3. The instrument shall have the capability to position any wavelength in the range 1.2-5.2 μm in the center of the array cross-dispersion axis and the simultaneous wavelength (SR_4) range shall be continuous

SR_4. Simultaneous (one-shot) wavelength range ≤ λ/10

SR_5. Slit width matched to R=70,000 shall be 0.375″

SR_6. Smallest spectral resolution element shall be sampled by 3.0 pixels

SR_7. Slit lengths 5″, 10″, 15″, and 25″

SR_8. The slit must be capable of alignment to any position angle on the sky

SR_9. Systematic noise effects shall not limit the measured S/N to less than 1000 (goal)

SR_10. Without special calibration iSHELL shall enable the measurement of velocity to ≤ 1 km/s

SR_11. iSHELL shall enable the measurement of radial velocity to ≤ 10 m/s (optimal)

SR_12. Spectral response function must be known to within ± 0.01 to achieve a radial velocity precision of ≤ 10 m/s

SR_13. The instrument shall be capable of taking and storing full array data at a sustained rate of up to 10 full data frames per minute (standard readout) with a goal of 30 full data frames per minute (fast readout)

SR_14. iSHELL shall have "open shutter" efficiencies of ≥ 67% for 10 min observation, and ≥ 92% for a one-hour observing block

SR_15. To accommodate changes in the science case over the lifetime of the instrument iSHELL shall be designed for easy accessibility

SR_16. The instrument shall enable measurement absolute flux to an accuracy of ≤ 1 %

Top-level engineering requirements flow down from the science-derived requirements. The wavelength range dictates the type of detector required. Sensitivity is a requirement for S/N and therefore results in requirements for instrument throughput, instrument background sources through their noise contributions (e.g. cold optical bench temperature, cold stop in front of the slit), and detector properties (e.g. QE, dark current, and read noise). To optimize sensitivity the slit width is matched to the seeing. The seeing disk needs to be well sampled to avoid introducing noise into the extracted spectra and this sets the pixel scale of the spectrograph. The resolving power, slit width, slit length, and simultaneous wavelength coverage set the detector size, and also, given the limited size of the instrument envelope (resulting in a relatively small collimated beam diameter), necessitate the use of a silicon immersion grating for dispersion. Good image quality at the spectrograph detector is required to achieve the desired resolving power. To achieve high S/N requires good flat fielding through detector stability and low scattered light (globally and in the wings of the instrument spectral response function). To achieve the desired long-term radial velocity precision requires adequate calibration (gas cells and a laser frequency comb are options) and instrument stability (low flexure, mechanism reproducibility, temperature stability). Optimum observing efficiency requires the use of an infrared slit viewer for acquisition and guiding, and for quick reconfiguration of the instrument to change observing or calibration modes.

A complete description of the high-level instrument requirements can be found in the Science Requirements Document. The science requirements are turned into detailed instrument requirements through the process of instrument design. This process is described in the relevant instrument design documents. The detailed instrument requirements are given in the Functional Performance Requirements Document (FPRD or Instrument Specification Document). An overview of the resulting design of iSHELL is described in the following section.

3 INSTRUMENT DESCRIPTION

3.1 Overview

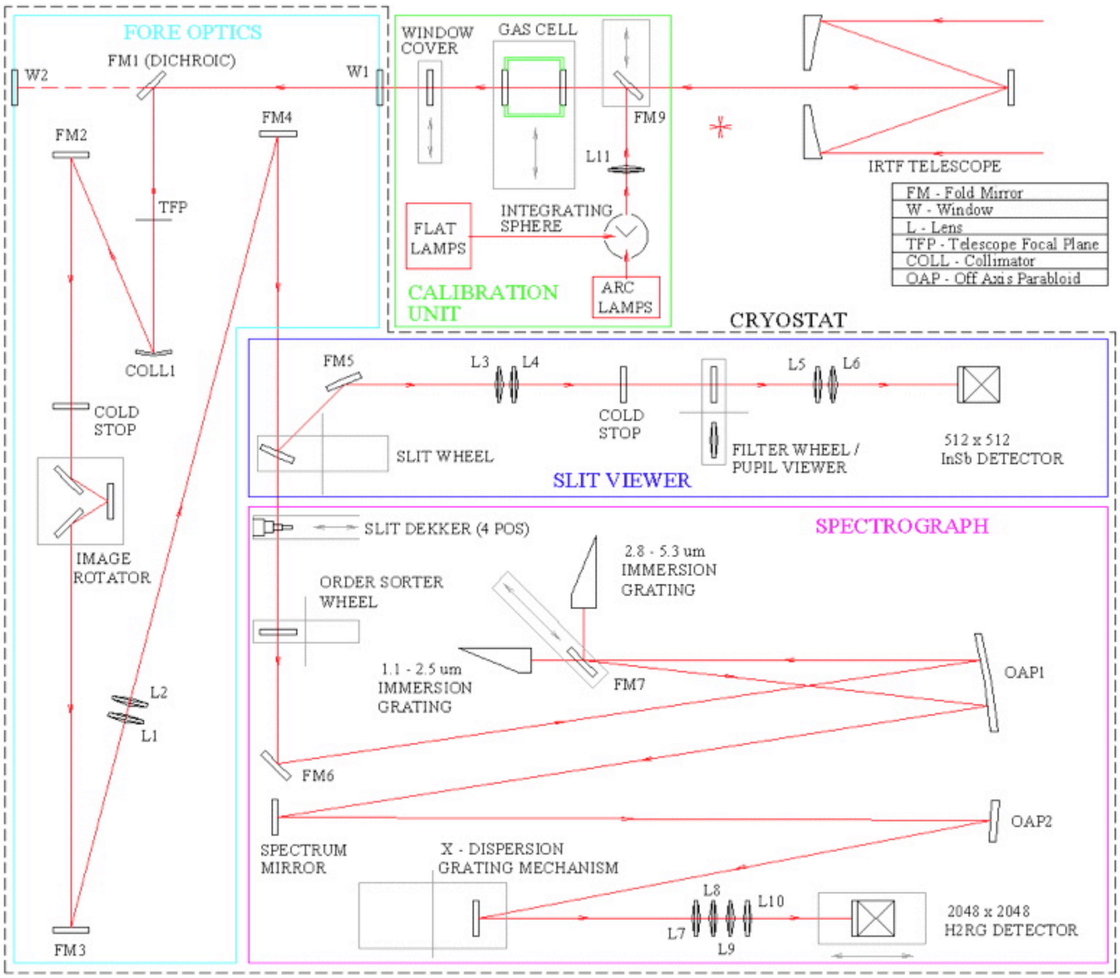


Figure 1. iSHELL schematic layout

Figure 1 shows a schematic layout of iSHELL. The iSHELL cryostat is mounted on the multiple instrument mount (MIM) at the cassegrain focus. At this focus location the beam speed is f/38. Inside the cryostat are three major optical sub-assemblies: the fore-optics, the slit viewer (SV), and the spectrograph. In the fore-optics the f/38 beam from the telescope enters the cryostat through the entrance window and comes to a focus at the telescope focal plane (TFP). The TFP is re-imaged onto the slit wheel by a collimator-camera system. A pupil image is formed following the collimator mirror and the system cold stop is placed here. A k-mirror image rotator is located immediately behind the cold stop. There is an option to replace the first fold mirror with a dichroic to provide iSHELL with a CCD guider.

Reflective slits in the slit wheel send the field surrounding the slit into the slit viewer. Here a refractive collimator-camera re-images the slit field onto a Raytheon 512x512 InSb array. A filter wheel in the slit viewer allows a selection of filters to be used for object acquisition, guiding, and scientific imaging. A lens in the filter wheel is used to image the telescope pupil. This pupil viewer (PV) provides a means to align the cryostat on the MIM.

The f/38 beam enters the spectrograph through the slit and order-sorting filter wheels. It is then folded and collimated at the first off-axis parabola (OAP1). The silicon immersion grating (IG) is located at the pupil following OAP1. An in/out mirror close to the pupil is able to select either of two IGs (IG1 covers 1.1-2.5 μm and IG2 covers 2.8-5.3 μm). The IG is tilted slightly so that the emerging beam is reflected at OAP1 to form a dispersed image of the slit at the spectrum mirror. The beam reflected at the spectrum mirror is re-collimated at OAP2 and forms a second "white" pupil image at the cross-disperser (XD) mechanism. Gratings in the XD wheel send the beam into the spectrograph camera lens, which images the resulting spectrum onto a 2048x2048 H2RG array.

A calibration unit is located on top of the cryostat. It contains illuminating optics, an integrating sphere, arc and flat-field lamps, and a gas cell. An in-out mirror above the entrance window is used to project calibration light into the instrument. A gas cell is mounted on a two-position stage between the entrance window and in-out mirror so that it can be placed into the beam for radial velocity (RV) science observations.

The cryostat is of similar size to SpeX ($\approx 1m^3$) and uses the same cooling scheme. It contains an optical bench to which the optical sub-assemblies are mounted. The optics and bench are cooled to ≈75K using a liquid nitrogen can. The radiation load on the cold structure is minimized by surrounding it with a radiation shield, which is cooled using the first stage of a Cryodyne 1050 CP closed-cycle cooler. The spectrograph and slit viewer arrays are cooled to 38K and 30K respectively, using the second stage of the cooler. Cooling to operational temperature will take about three days (components in the mechanism wheels take longest to cool). The cryostat will contain nine cold mechanisms, which will be driven by cold motors.

iSHELL uses a 2048x2048 H2RG array in the spectrograph and a 512x512 Aladdin 2 InSb array in the slit viewer. Both arrays are required to operate independently. The read noise goal for the spectrograph is better than 5 e^- RMS with multiple sampling. Astronomical Research Camera (ARC) Generation 3 controllers are used for both arrays. The H2RG array requires a 12-slot housing and the smaller InSb array requires a 6-slot housing.

3.2 Fore-optics

The layout of the fore-optics and slit viewer is shown in Figure 2. The f/38 beam from the telescope enters the cryostat through the CaF_2 entrance window and comes to a focus at the 42″ diameter telescope focal plane (TFP).

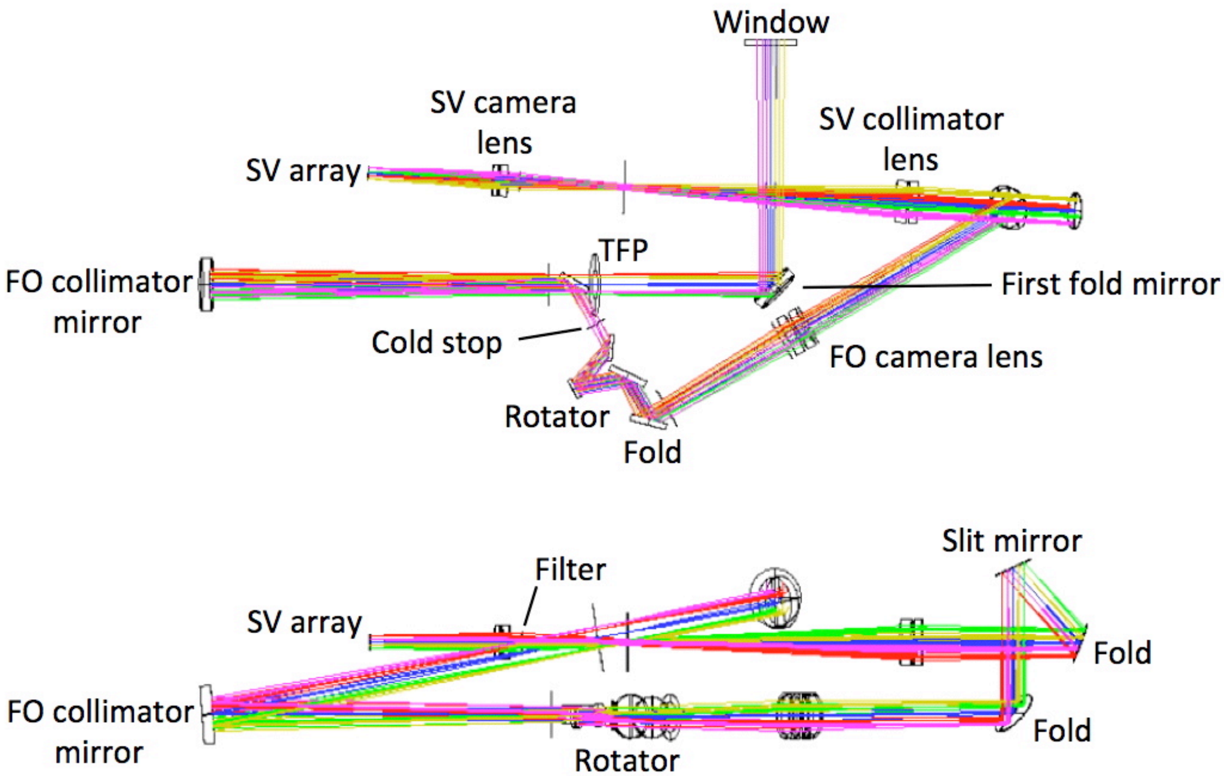


Figure 2. Raytrace of fore-optics and slit viewer. The distance from the window to the fore-optics collimating mirror is about 810 mm

The TFP is re-imaged onto the slit wheel by a collimator-camera system. A 10 mm diameter image of the pupil is formed following the spherical collimating mirror and the system cold stop is placed here. It is necessary to place the cold stop before the slits since diffraction at the slits would blur the image of the pupil on a cold stop following the slits and result in higher backgrounds at thermal wavelengths. The cold stop is also the best place to baffle to minimize off-axis scattered light from the telescope. Located immediately behind the cold stop is the k-mirror image rotator. Rotating the k-mirror changes the position angle of the sky on the slit. A BaF_2–LiF achromatic doublet lens images the beam exiting the rotator into the slit wheel.

3.3 Slit Viewer

Gold-coated slit mirrors in the slit wheel send the 42″ field surrounding the slit into the slit viewer. Here a refractive collimator-camera re-images the slit field onto a Raytheon 512x512 InSb array with an image scale of 0.06″ per pixel. The collimator and camera lenses are both BaF_2–LiF achromatic doublets. A filter wheel containing about 15 positions allows a selection of 19 mm diameter filters to be used for object acquisition, guiding, and scientific imaging (see Table 1). 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.

Table 1. 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	

3.4 Spectrograph

The layout of the spectrograph is shown in Figure 3. The f/38 beam enters the spectrograph through the slits that are aligned at 22.5 degrees to the incoming beam. Aligning the slits at this angle is advantageous for the overall instrument layout. To minimize scatter into the spectrograph metal-coated substrate-type slits are employed. A gold coating with a slit aperture is lithographically applied to the front side of an antireflection-coated CaF_2 substrate. Since the coating is less than one micron thick, the knife-edge is extremely sharp. A backside metal coating is used to absorb ghosts that are formed in the substrate. Individual slit mirrors are about 25 mm in diameter and are housed in a 5-position wheel (see Table 2). A slit dekker mechanism immediately behind the slit wheel (i.e. close to focus) controls slit length.

Table 2. Slit viewer filter wheel

Position #	*Slit width*	*Slit length*	*R*
1	0.375″	25.0″	72,000
2	0.75″	25.0″	39,000
3	1.50″	25.0″	20,000
4	4.00″	25.0″	7,500
5	Blank-off/mirror (darks/slit-less imaging)		

A slit dekker mechanism placed about one mm behind the slit wheel (i.e. close to focus) is used to control slit length (see Table 3). The defocus at the edge of the slits is about one pixel at the spectrograph detector. The use of a dekker reduces the number of slit mirrors from 16 to 4.

Table 3. Slit dekker wheel

Position #	*Slit length*	*Notes*
1	Blank	For darks
2	5.0″	2.79 mm long
3	10.0″	5.57 mm long
4	15.0″	8.36 mm long
5	25.0″	13.93 mm long

An order-sorting filter wheel immediately follows the slit dekker. Order sorters are used to limit the wavelength range to the free spectral range (FSR) of the grating cross disperser being used. A preliminary list of the filters required is given in Table 4. Each filter is about 6 x 10 mm in area and about 3 mm thick.

Table 4. Order sorter filter wheel

Position #	***Filter***	***Notes***
1	Blank	
2	1.05-1.45 μm	*J*-band XD
3	1.40-1.90 μm	*H*-band XD
4	1.80-2.60 μm	*K*-band XD
5	2.70-4.20 μm	*L/L′*-band XD
6	4.50-5.50 μm	*M*-band XD
7	TBD	
8	TBD	
9	TBD	
10	Open	

Following the order sorter the beam is folded and collimated at the first off-axis parabola (OAP1). Two R3 silicon immersion gratings (IG) are located at the pupil following OAP1 (only one IG is drawn in Figure 3). An in/out mirror close to the pupil selects either of two IGs (IG1 covers 1.1-2.5 μm and IG2 covers 2.8-5.3 μm). Each IG is tilted by 1.025 degrees ('gamma' angle) in the out-of-plane grating direction so that the dispersed beam at OAP1 is reflected towards the cross disperser. OAP1 forms a dispersed image of the slit at the spectrum mirror flat. The out-of-plane angle tilts the re-imaged slit at the spectrograph detector by about one degree (depending on wavelength) with respect to the detector columns. The front face of each IG is also wedged by –0.8 degrees in the same sense to steer the un-dispersed ghost reflection away from the optical path and onto a baffle to the side of OAP1. The wedge also refracts internal reflections at the front face of the IG away from the optical path. At OAP2 the beam from the spectrum mirror is re-collimated and forms a second "white" pupil image at the cross-disperser (XD) mechanism. The OAPs are diamond-turned aluminum mirrors with off-axis angles of 3.0 degrees.

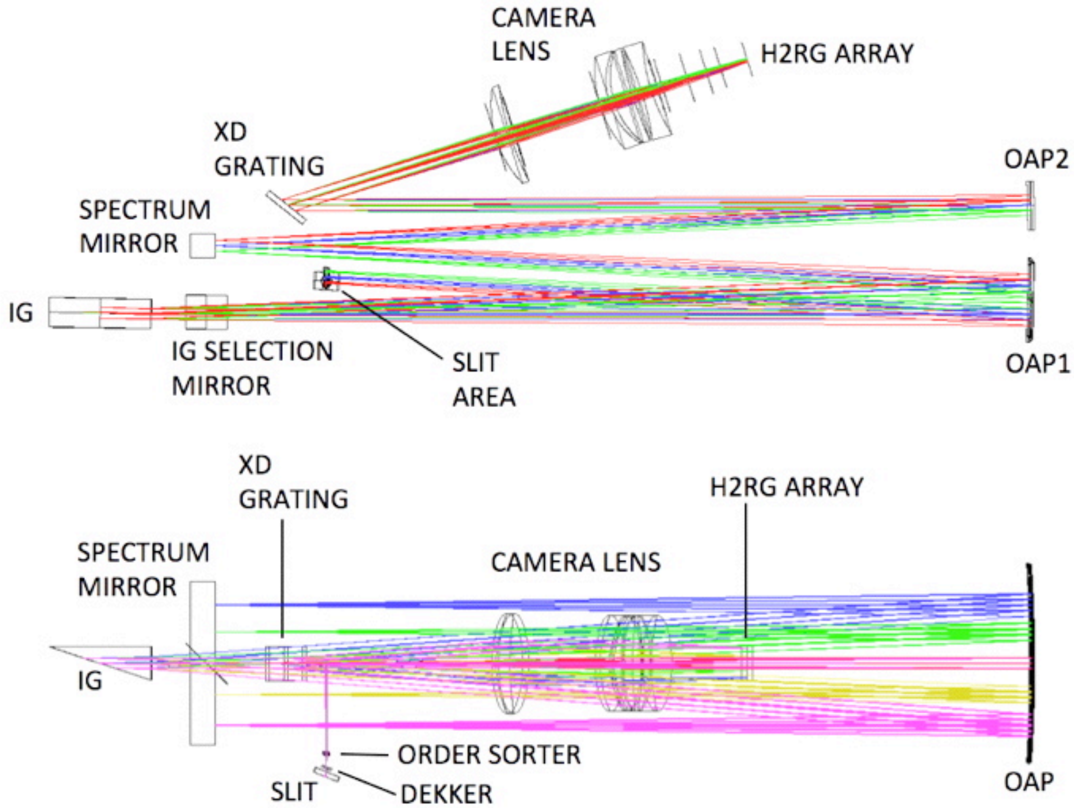


Figure 3. Raytrace of the spectrograph. For scale the camera lenses are 100 mm in diamter and the distance from the spectrum mirror to OAP1 is 838 mm. The spectrograph is folded as shown

Gratings in the XD wheel diffract the beam into the spectrograph camera lens and the camera images the spectrum onto a 2048x2048 H2RG array. The camera consists of a BaF_2-ZnS-LiF three-element lens. Each lens is about 100 mm in diameter. The XD wheel contains about a dozen different gratings. Individual gratings cover the *J*, *H*, *K*, *L*/*L′*, or *M* bands, and the grating blaze of a particular grating depends upon the band and the required slit length. Once a particular grating is selected by rotating the XD wheel, the wheel is tilted about the axis of the grating to select the wavelength orders required. The wheel is designed for tilt in the range ± 5 degrees. In most cases one tiltable grating is sufficient to cover an entire waveband but in the cases of *K* and *L/L′* two gratings are needed.

A provisional list of the gratings occupying the XD wheel and the resulting spectral formats are given in Table 5. The spectral formats given by the exposure name are plotted in Figures 4-22. Within the limits set by non-overlapping orders at short wavelengths and by the ± 5-degree tilt limit of the XD wheel, the wavelength range is continuously variable (i.e. the orders can be moved up and down the array). To enable the spectral extraction software to automatically locate spectral orders, the minimum separation of orders is set to 10 pixels. The minimum set of gratings requires eight slots in the XD wheel. Of the eight gratings listed in Table 5 two are custom gratings (expensive) and six are replicas (cheap). The two *M*-

band gratings are the same type of grating. The two gratings occupy two different slots but are aligned differently so that they cover both the short and long wavelength ends of the FSR (see Figure 19). This is necessary since the *M*-band orders overfill the array.

If the mechanical design permits more gratings may be added to the XD wheel. Options might include formats with 5 arc-second long slits at *J*, *H*, and *K*, with significantly increased one-shot wavelength coverage (this assumes that the slits are long enough to fit and subtract background without nodding along the slit), and a 25 arc-second long slit mode for Mars methane observations at 3.29 μm.

Table 5. List of cross dispersers and spectral formats available in iSHELL

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

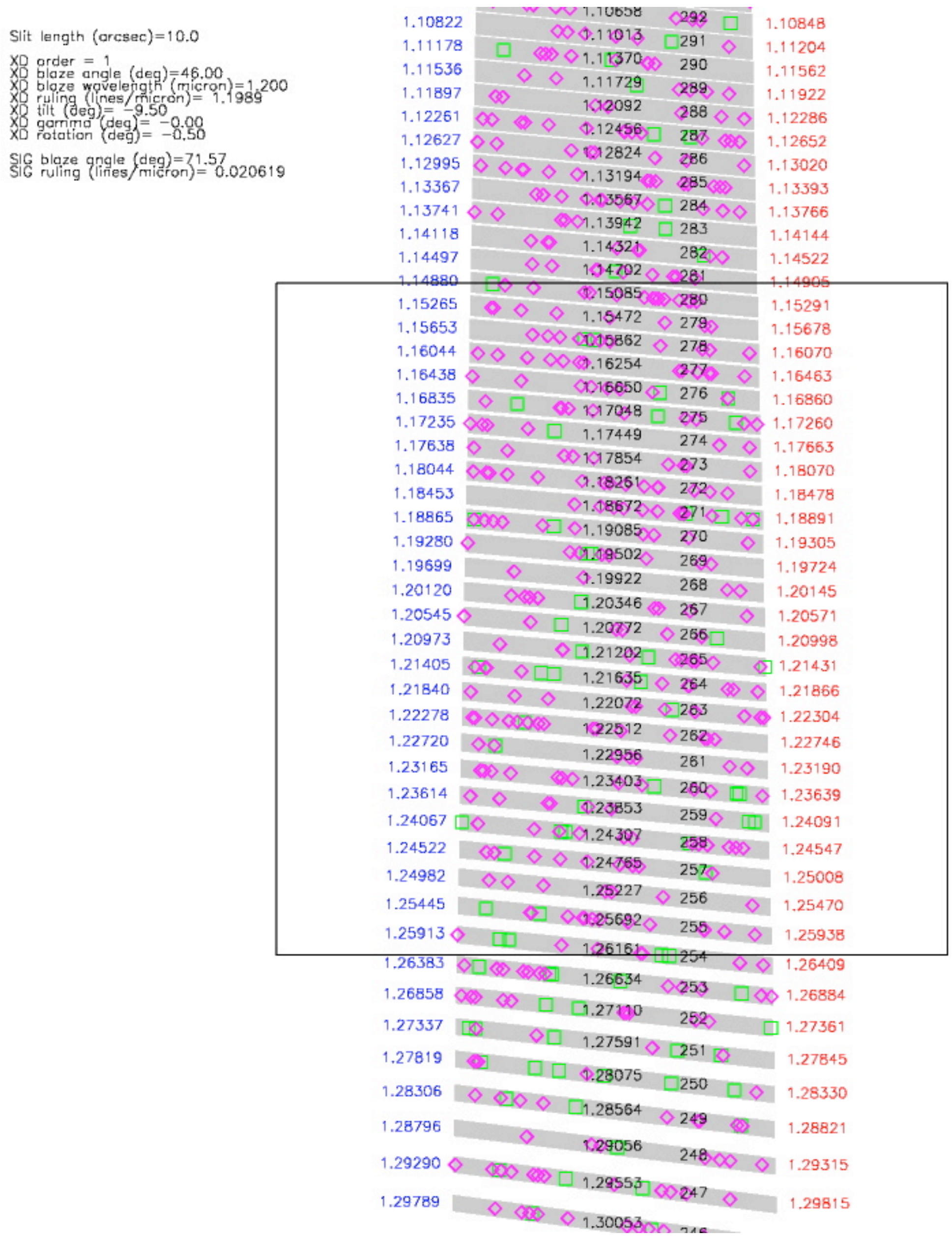


Figure 4. Exposure J1 (see Table 5), slit length 10″, 1200 line per mm grating. The FSR of each spectral order is plotted. The short wavelength limit (about 1.15 µm) is set by the need to keep orders separated by at least 10 pixels. A box indicates the H2RG array. Symbols indicate the position of argon (green square) and thorium (purple diamond) arc lamp lines.

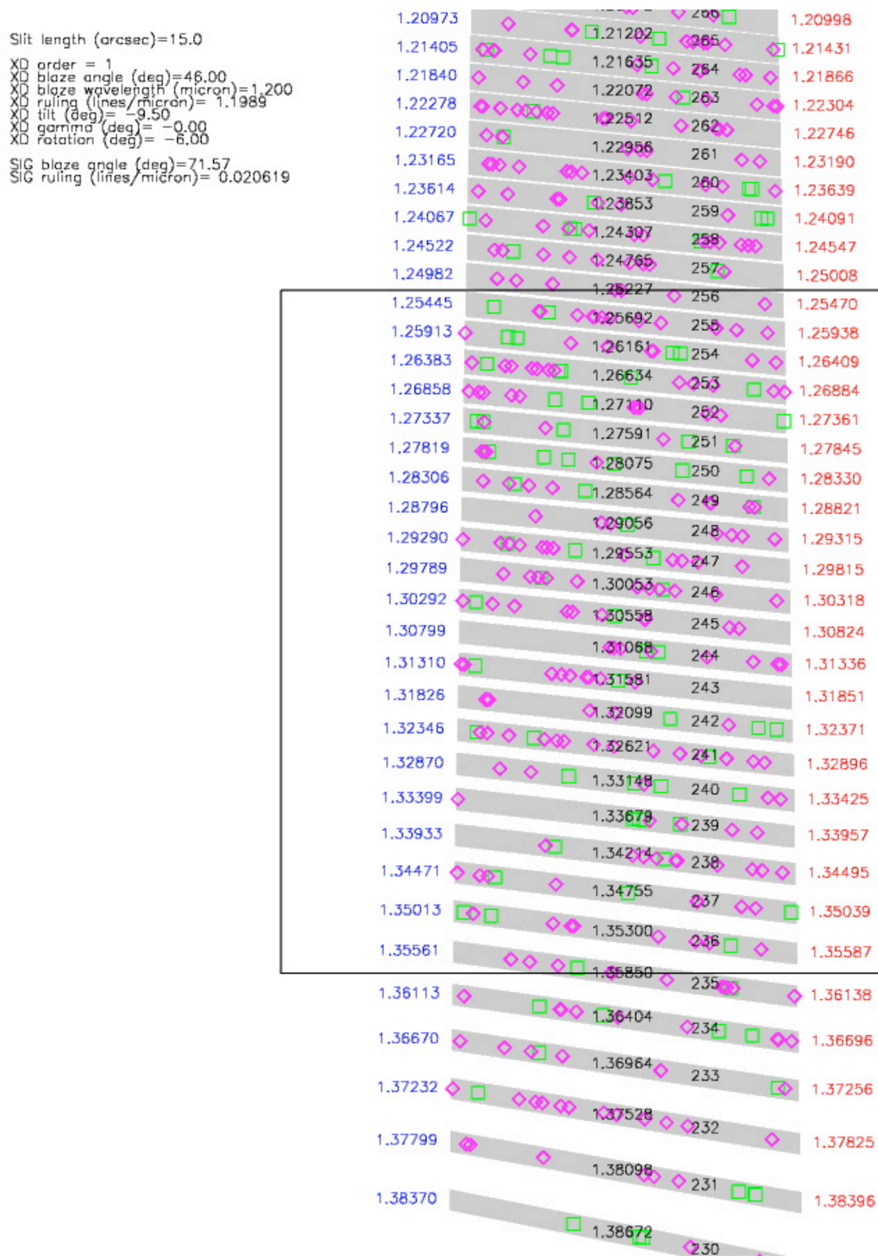


Figure 5. Exposure J2 (see Table 5), slit length 15″, 1200 line per mm grating. The box indicates the H2RG array.

Figure 6. Exposure H1 (see Table 5), slit length 10″, 847 line per mm grating. The box indicates the H2RG array.

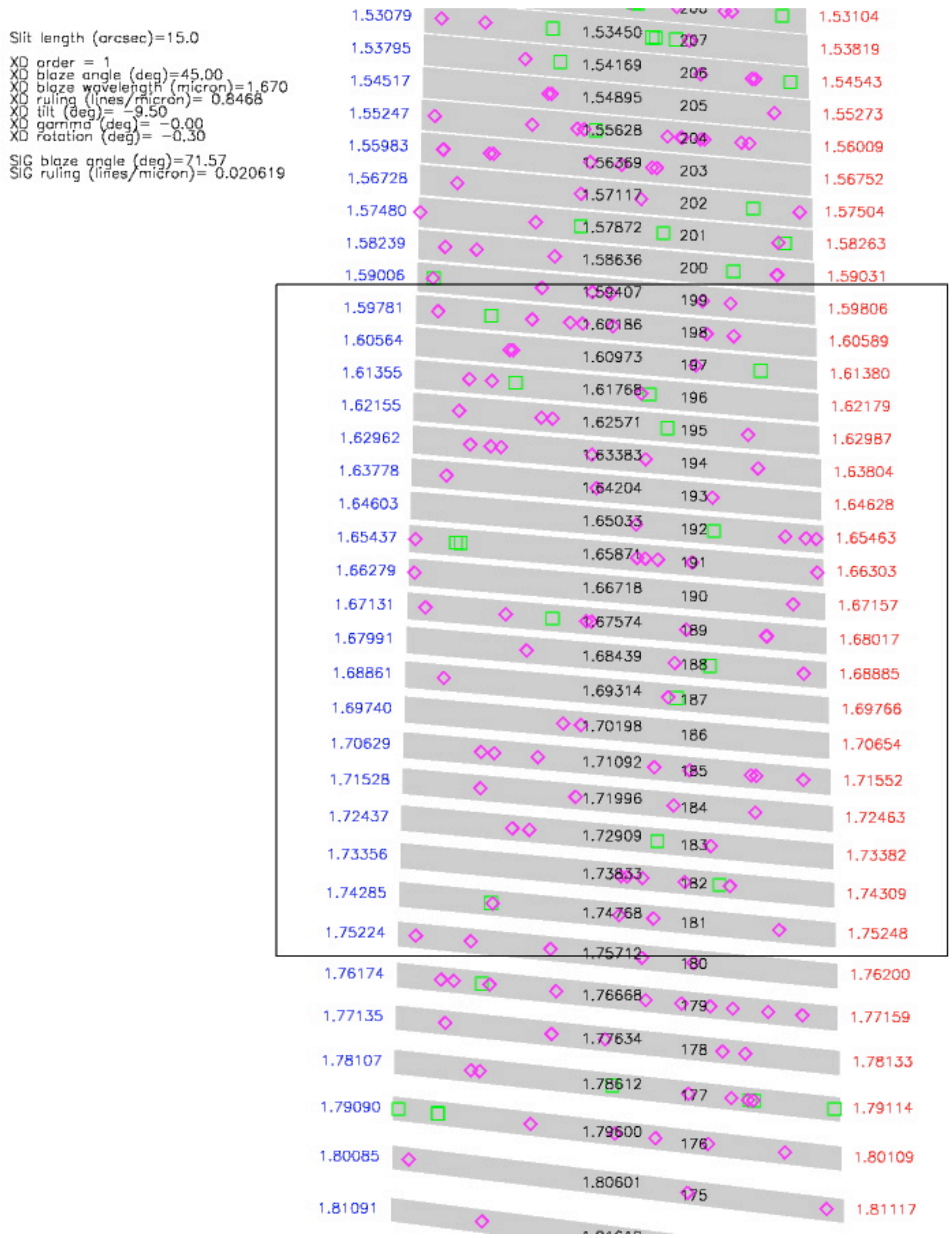


Figure 7. Exposure H2 (see Table 5), slit length 15″, 847 line per mm grating. The short wavelength limit (about 1.60 µm) is set by the need to keep orders separated by at least 10 pixels. The box indicates the H2RG array.

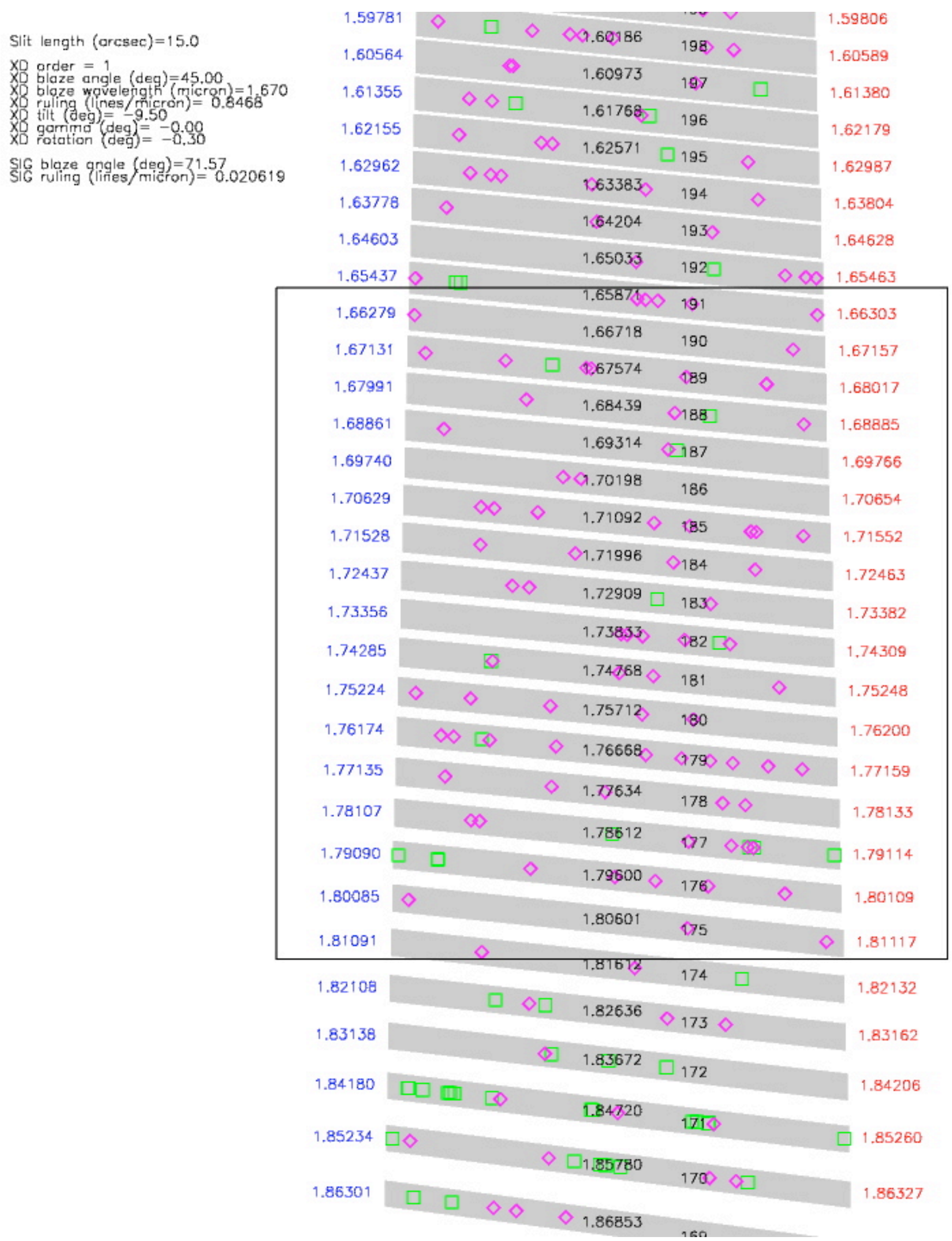


Figure 8. Exposure H3 (see Table 5), slit length 15″, 847 line per mm grating. The box indicates the H2RG array.

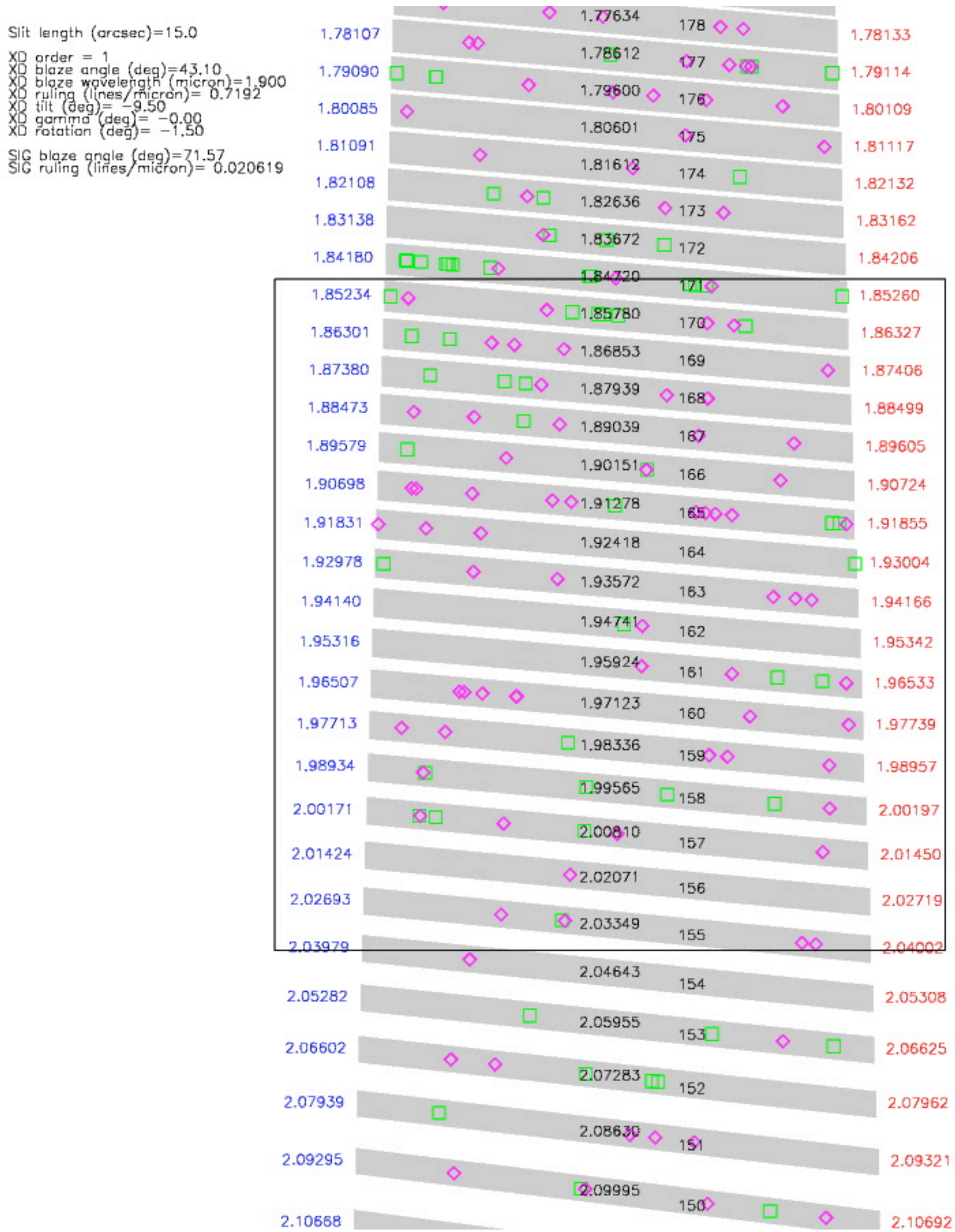


Figure 9. Exposure K1 (see Table 5), slit length 15″, 720 line per mm grating. The box indicates the H2RG array.

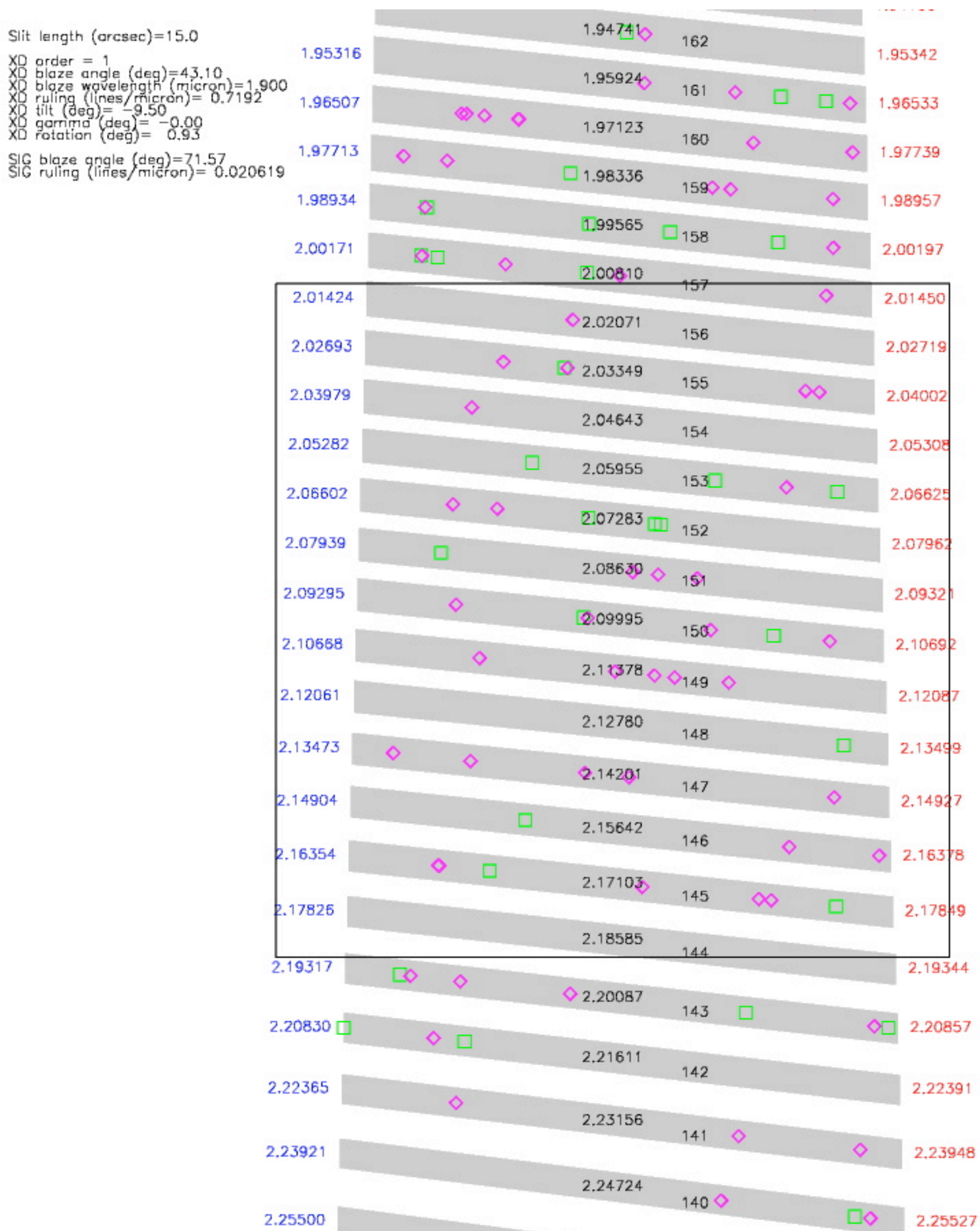


Figure 10. Exposure K2 (see Table 5), slit length 15″, 720 line per mm grating. The box indicates the H2RG array.

Figure 11. Exposure K3 (see Table 5), slit length 15″, 600 line per mm grating. The box indicates the H2RG array.

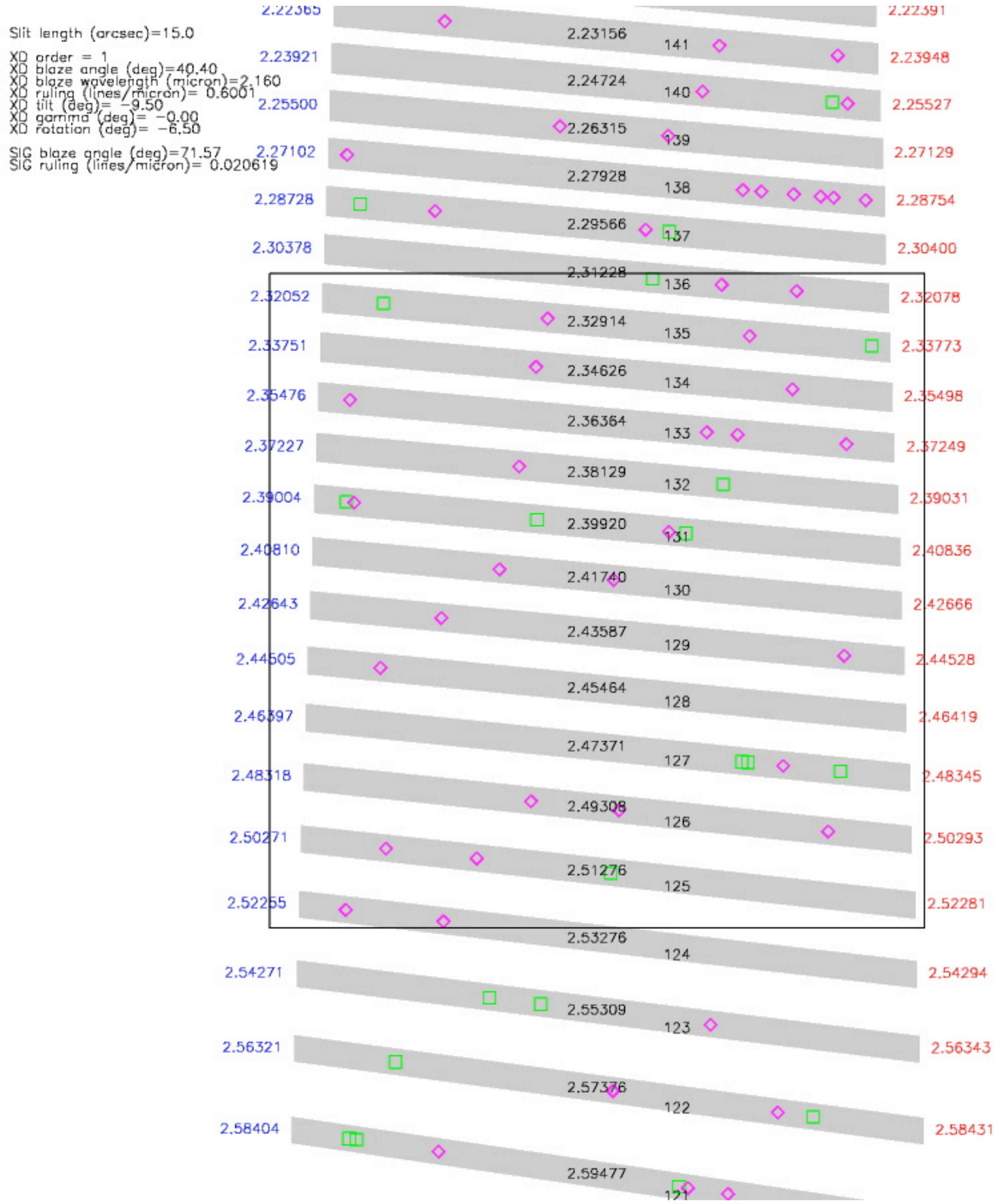


Figure 12. Exposure K4 (see Table 5), slit length 15″, 600 line per mm grating. The box indicates the H2RG array.

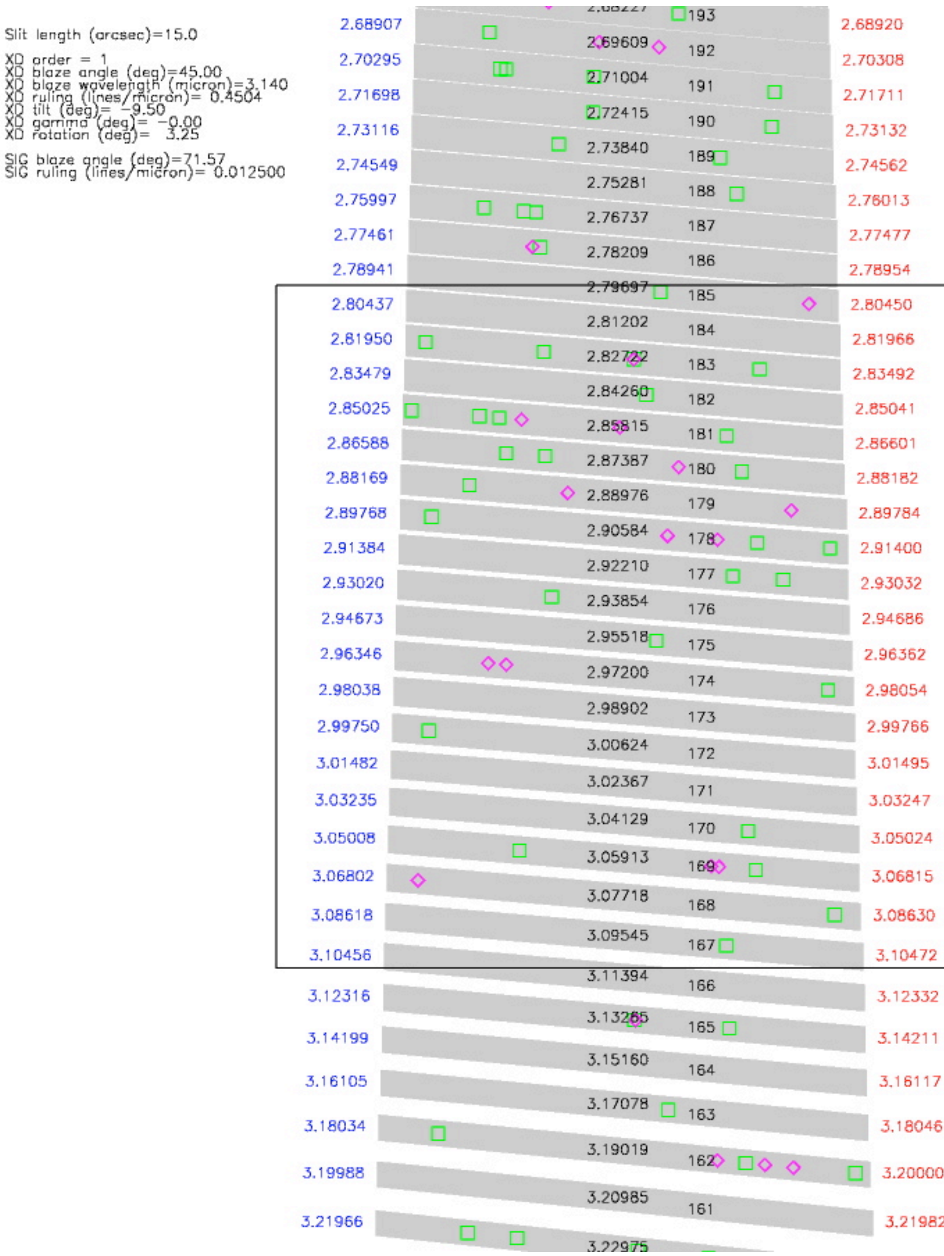


Figure 13. Exposure L1 (see Table 5), slit length 15″, 450 line per mm grating. The short wavelength limit (about 2.80 μm) is set by the need to keep orders separated by at least 10 pixels. The box indicates the H2RG array.

Figure 14. Exposure L2 (see Table 5), slit length 15″, 450 line per mm grating. The box indicates the H2RG array.

Figure 15. Exposure L3 (see Table 5), slit length 15″, 450 line per mm grating. The box indicates the H2RG array.

Figure 16. Exposure L4 (see Table 5), slit length 15″, 360 line per mm grating. The short wavelength limit (about 3.28 μm) is set by the need to keep orders separated by at least 10 pixels. The box indicates the H2RG array.

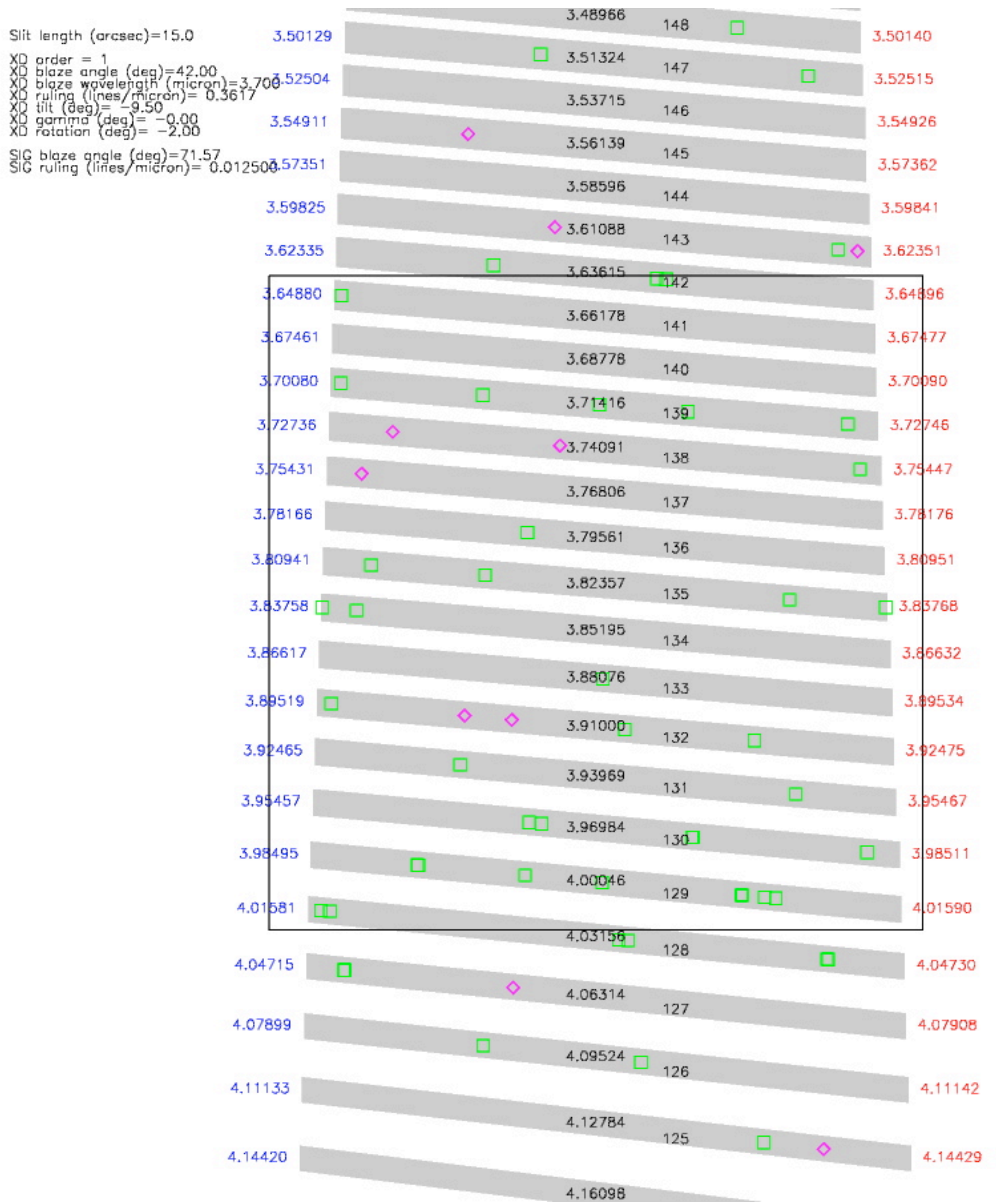


Figure 17. Exposure L5 (see Table 5), slit length 15″, 360 line per mm grating. The box indicates the H2RG array.

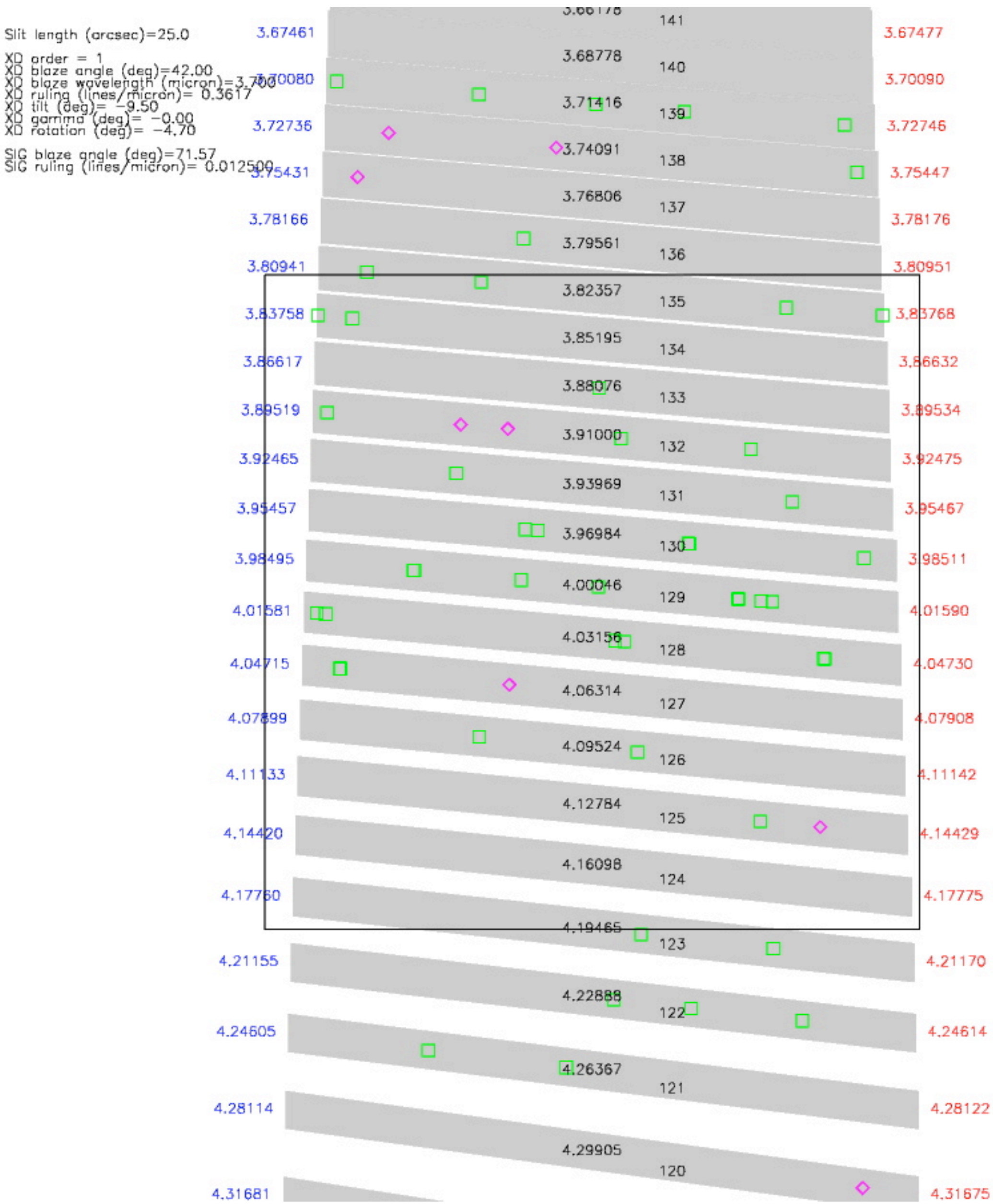


Figure 18. Exposure L6 (see Table 5), slit length 25″, 360 line per mm grating. The short wavelength limit (about 3.81 µm) is set by the need to keep orders separated by at least 10 pixels. The box indicates the H2RG array.

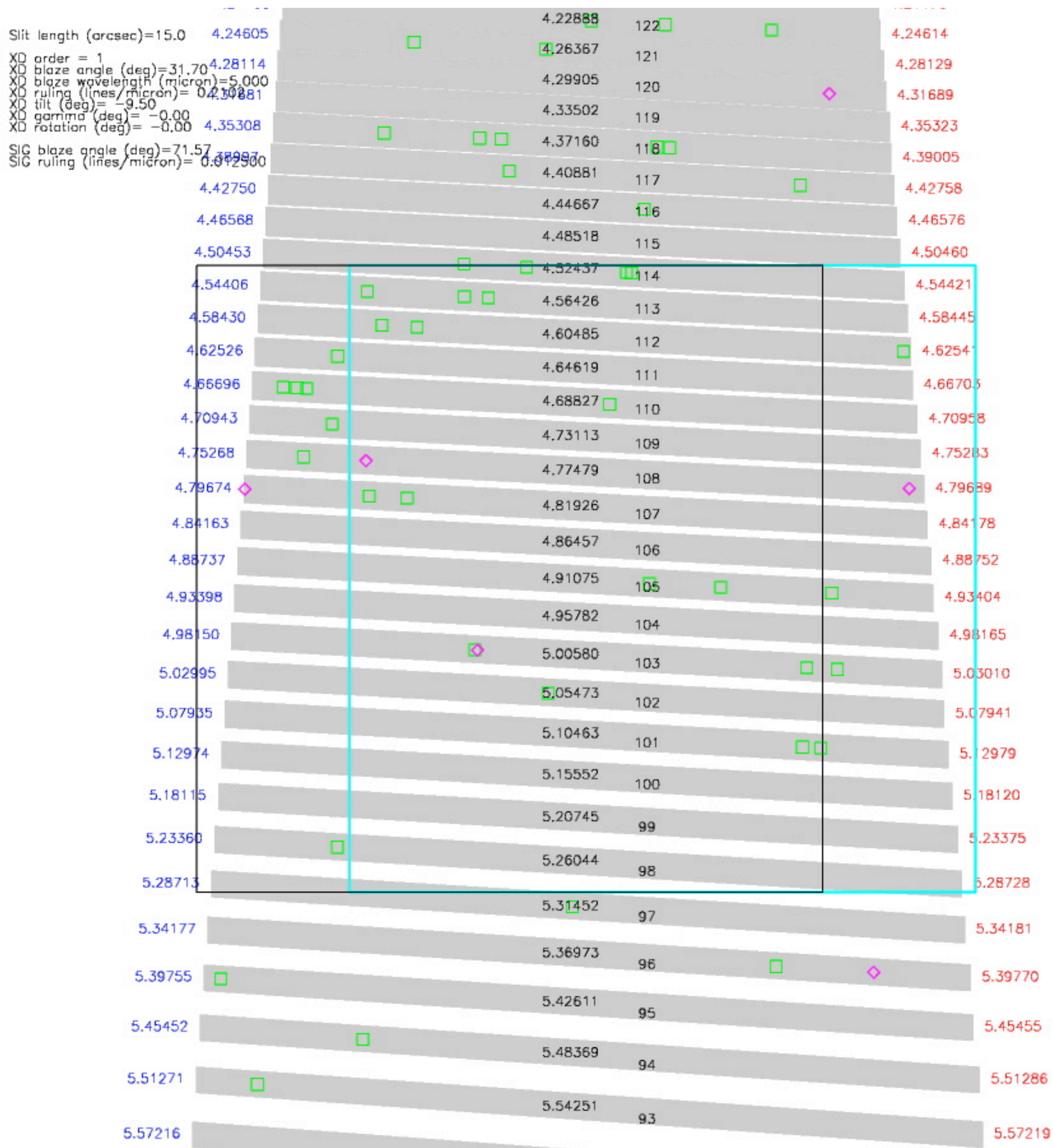


Figure 19. Exposures M1 (black box) and M2 (blue box) (see Table 5), slit length 15″, 210 line per mm grating. The short wavelength limit (about 4.55 µm) is set by the need to keep orders separated by at least 10 pixels. The boxes indicates the H2RG array. To cover the full FSR two exposures are required with two different XD gratings (same grating in different slots but with different tilts in the dispersion direction).

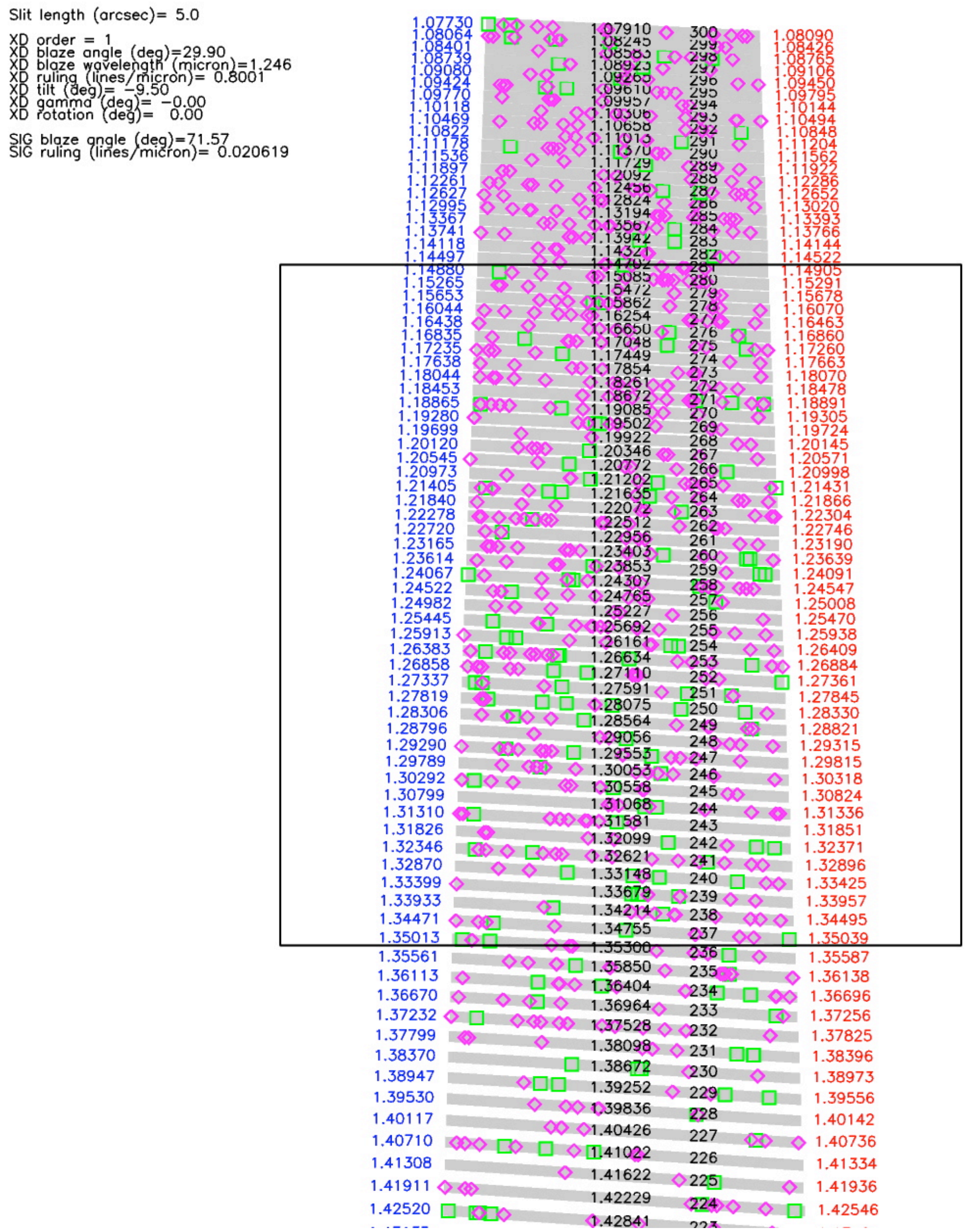


Figure 20. Exposure J (see Table 5), slit length 5″, 800 line per mm grating. The short wavelength limit (about 1.50 μm) is set by the need to keep orders separated by at least 5 pixels. The box indicates the H2RG array.

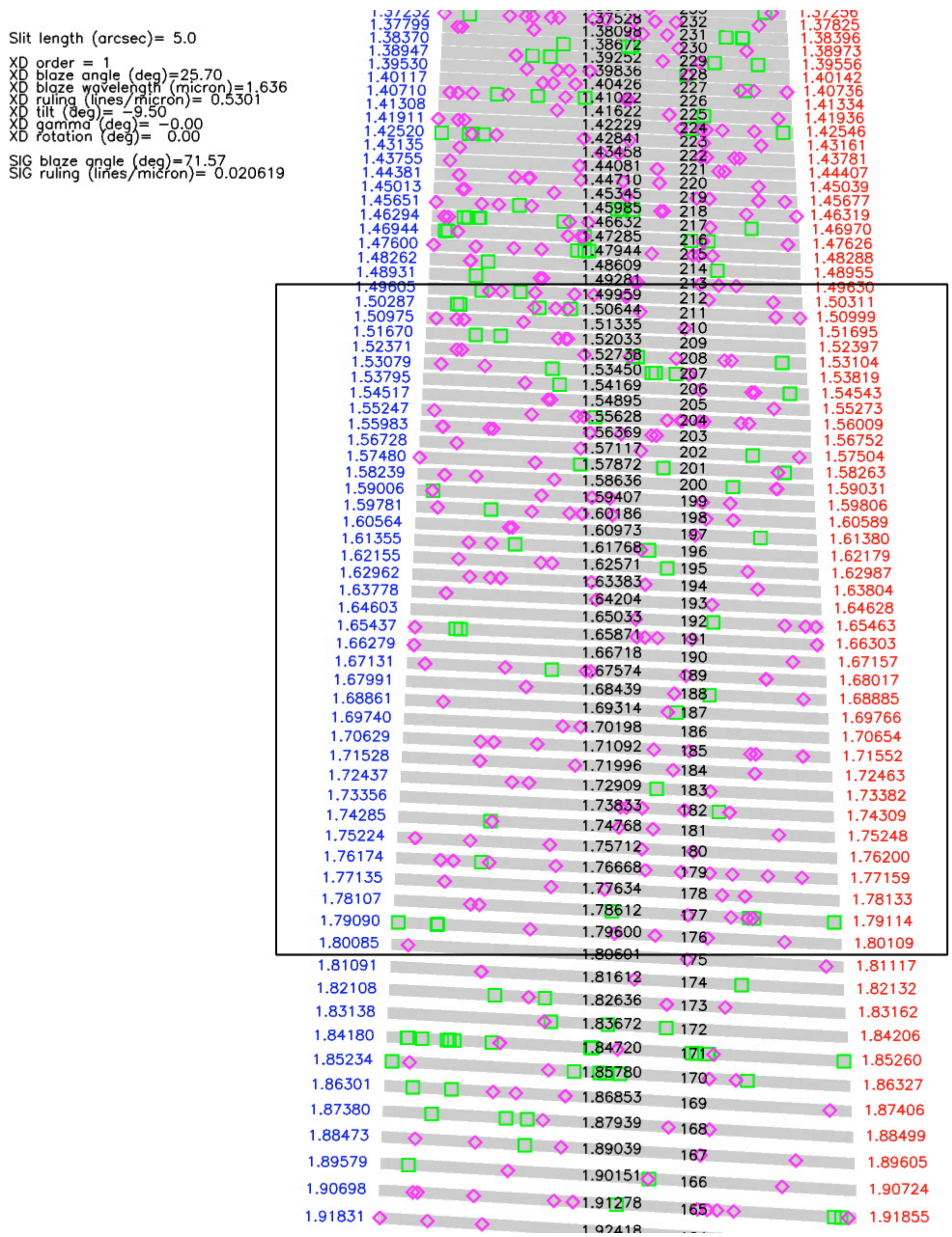


Figure 21. Exposure H (see Table 5), slit length 5″, 530 line per mm grating. The short wavelength limit (about 1.50 μm) is set by the need to keep orders separated by at least 5 pixels. The box indicates the H2RG array.

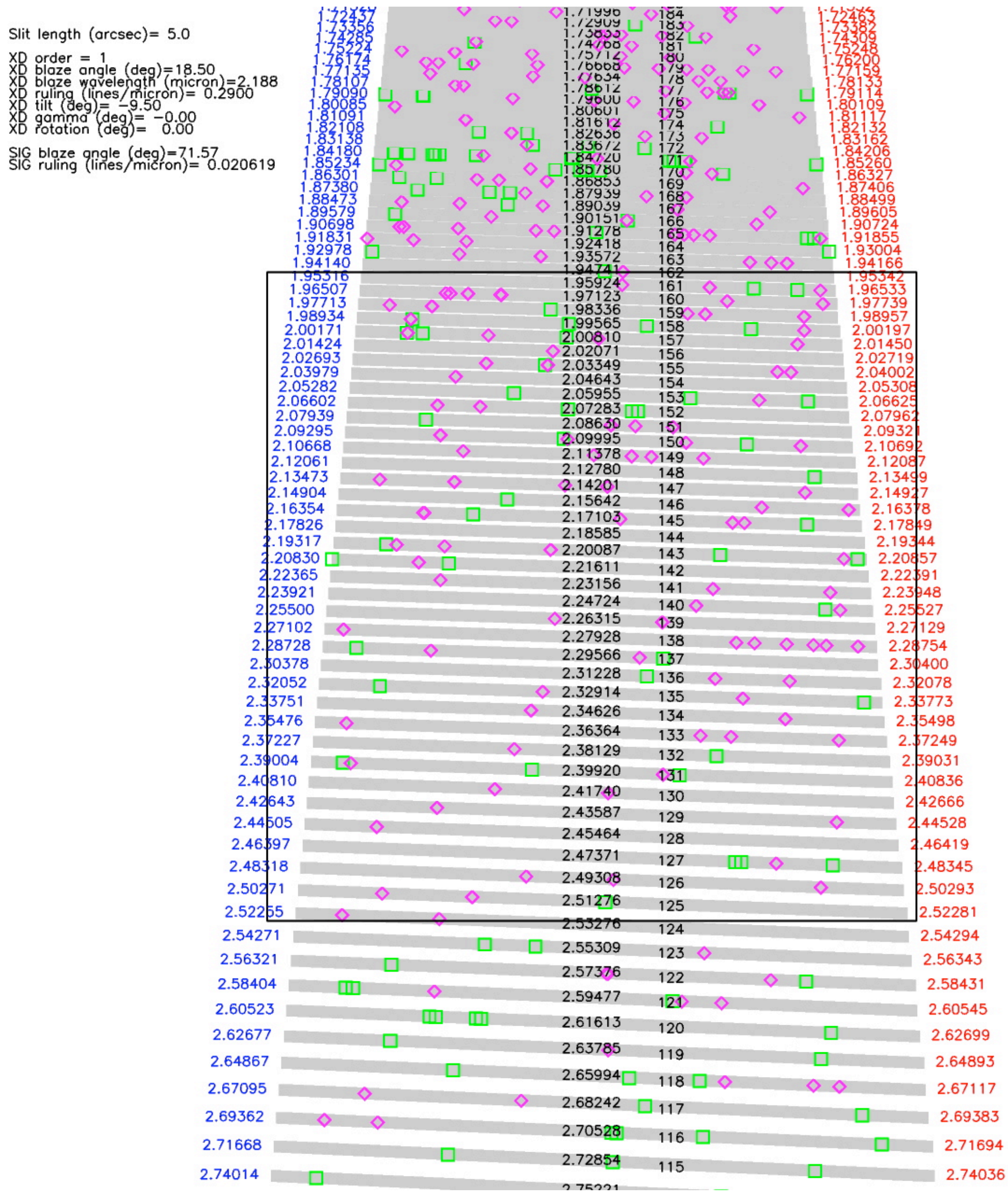


Figure 22. Exposure K (see Table 5), slit length 5″, 290 line per mm grating. The short wavelength limit (about 1.96 μm) is set by the need to keep orders separated by at least 5 pixels. The box indicates the H2RG array.

3.5 *Calibration Unit*

In concept iSHELL's calibration system is similar to that used in SpeX. The uniform flux distribution across the exit aperture of an integrating sphere is reimaged onto the telescope focal plane (TFP) inside the cryostat at a magnification sufficient to cover the longest slit. The function of the integrating sphere is to integrate and scramble the spatial structure in the flux from lamps placed at the three entrance apertures into a uniform (flat) distribution at the exit port. This is done by an arrangement of baffles inside the sphere that force rays entering the sphere to undergo multiple reflections before exiting. A highly reflective non-specular and spectrally flat coating is applied to the surface of the sphere (*Infragold* from Labsphere) to enhance uniformity and throughput.

In the optical layout for iSHELL (see Figure 23) a 600 mm focal length spherical mirror re-images a magnified virtual image of the integrating sphere exit port (10 mm diameter) onto the TFP at one to one magnification (30 mm diameter – sufficient to cover the longest slit). An achromatic lens (a LiF/BaF_2 doublet) is placed at the image of the entrance pupil (the secondary mirror) in the spherical mirror (643 mm behind the mirror). The exit port of the integrating sphere is then placed 186 mm behind the lens ((1200-643)/3) to form a three-times magnified virtual image of the exit port (30 mm) at 1200 mm from the spherical mirror (i.e. at a distance of two focal lengths). The aperture of the lens is adjusted to match the required input beam speed (about 15 mm gives f/38.3).

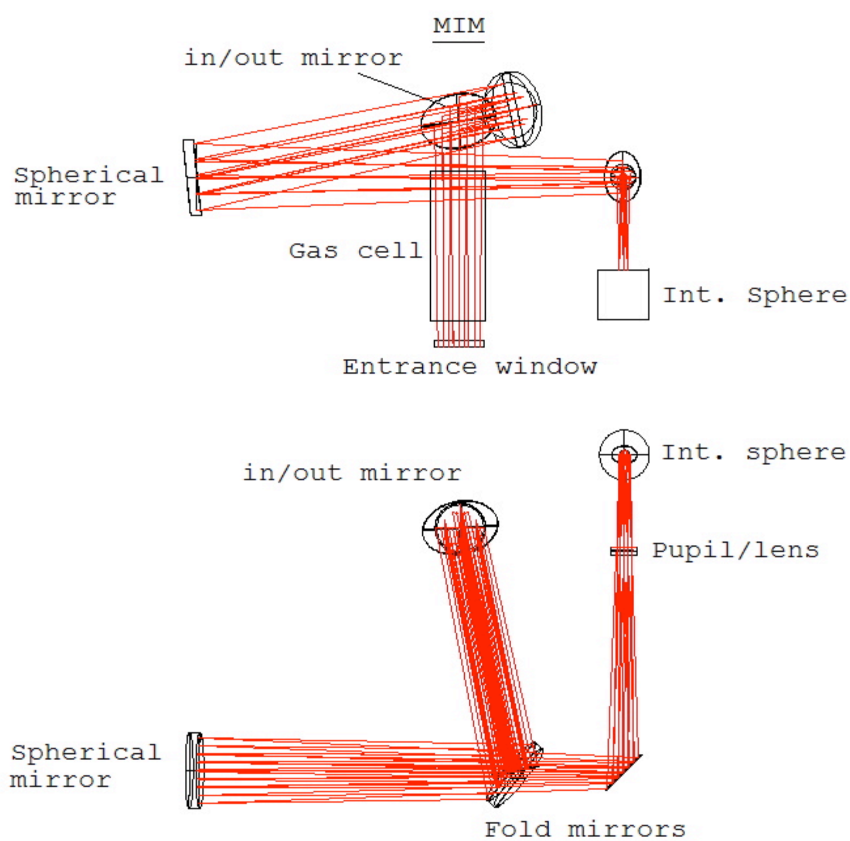


Figure 23. Optical layout of calibration system. Side view (top), plan view (bottom). For scale the integrating sphere is 50 mm diameter and the gas cell 150 mm long.

The integration times needed to meet the S/N requirements are calculated from simple considerations of lamp brightness, lamp illumination geometry ($A\Omega$), and integrating sphere throughput (see Mathcad document). The brightness of the flat field lamps is determined by the filament size and temperature. The temperature is set by the need for the flux to pear in the near infrared (1.15 μm for a standard QTH lamp at 3200 K and 3.34 μm for a standard IR lamp at 1100 K). Therefore lamp brightness effectively scales with lamp size (filament area). Working at resolving powers of up to R=2000 SpeX requires only relatively small lamps to limit flat field integrations to about one minute. The lamps were positioned about 20 mm in front of the 10 mm diameter input ports (see Figures 24).

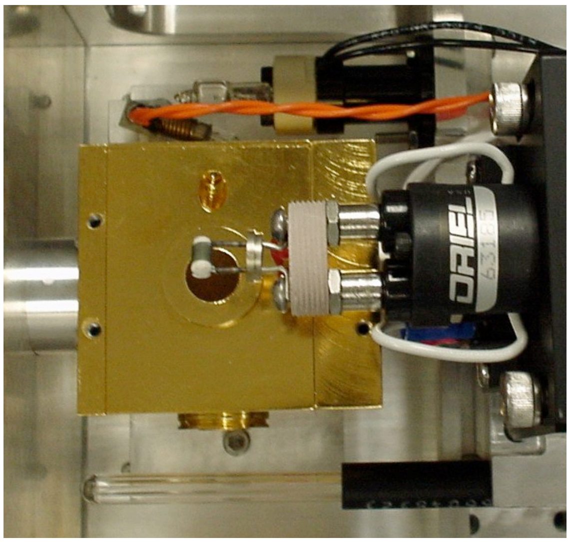


Figure 24. SpeX integrating sphere showing QTH lamps (top), IR lamps middle), argon arc lamp (bottom), positioned in front of their respective input ports.

Since iSHELL works at resolving of up to R=70,000 about 35 times more flux is needed to achieve the similarly short integration times. Given the space limitations this cannot be achieved by increasing the brightness (size) of the lamps. The best solution is to intercept more photons from the lamps by using optical concentrators (1-2 orders of magnitude more is relatively simple to do). This will also require more space but not significantly.

Since spectral lines from the Argon arc lamp are unresolved even at R=70,000, flux is not an issue. More of a concern is the number of lines. We need at least three lines per order to provide a good wavelength solution. A simple Argon arc lamp does not provide sufficient lines. A Thorium-Argon arc lamp of the type used in CRIRES seems like the best solution for iSHELL. However, the lamp is larger than the simple Argon arc. Even then there are fewer lines at longer wavelengths (> 3 μm) and so telluric features will to be used where necessary.

3.6 ***Cryostat***

The cryostat is of similar size to SpeX ($\approx$1m^3) and uses the same cooling scheme. It contains an optical bench to which the optical sub-assemblies are mounted. The optics and bench are cooled to $\approx$75K using a liquid nitrogen can. The radiation load on the cold structure is minimized by surrounding it with a radiation shield, which is cooled using the first stage of a Cryodyne 1050 CP closed-cycle cooler. The spectrograph and slit viewer arrays are cooled to 38K and 30K respectively, using the second stage of the cooler. For stable performance the arrays will be controlled to ± 0.01K and the immersion grating to ± 0.1K. Cooling to operational temperature will take about three days.

The cryostat will contain nine cold mechanisms, which will be driven by cold motors. In addition the calibration unit will need three warm mechanisms. The types of mechanisms needed and some preliminary requirements are given in Table 6.

Table 6. Mechanism requirements

Mechanism	*Temp*	*Type*	*Range*	*Repositioning precision*	*Element size*
CB mirror	~280 K	In/out	2 positions	± 0.5 mm	Beam
Gas cell	~280 K	In/out	2 positions	± 0.5 mm	Beam
Window cover	~280 K	In/out	2 positions	± 0.5 mm	Beam
K-mirror	75 K	Continuous	> 360 degrees	± 0.1 deg on sky (1 pixel)	Beam
Slit wheel	75 K	Detent	5 positions	± 1 pixel	30 mm diameter 5 mm thick
Slit dekker wheel	75 K	Detent	5 positions	± 1 pixel	30 mm diameter ~1 mm thick
SV filter wheel	75 K	Detent	15 positions	± 0.1 mm	25 mm diameter ~5 mm thick
Order sorter wheel	75 K	Detent	10 positions	± 0.1 mm	6 x 10 mm ~3 mm thick
IG selection mirror	75 K	In/out	2 positions	± 0.1 mm	Beam
XD wheel	75 K	Detent	15 positions (TBD)	± 1 pixel (15 arcsec)	~32 x 50 mm to ~32 x 40 mm ~ 7 mm thick
XD wheel tilt	75 K	Continuous	± 5 degrees	± 1 pixel (15 arcsec)	n/a
Spectrograph focus	75 K	Continuous	± 2 mm	± 50 μm	n/a

3.7 Instrument Control Software

The software requirements are discussed in a separate document. Here we provide a simple systems level description of the software components and subsystems.

The instrument is driven by commands issued from a Graphical User Interface (GUI). There can be multiple instances of the GUI or command port. This allows for remote observing, observing support, and troubleshooting. The GUI also provides a graphical presentation of the instrument configuration and status. A quick-look data viewer (DV) allows spectra and images to be seen and analyzed as they are received. DV also provides a means for target acquisition and guiding. The GUI and DV interface with the telescope control system to receive telescope information and to send requests for telescope offsets (positioning and guiding), with the instrument computer to move mechanisms etc., and with the array controllers.

Instrument control software subsystems:

- Command interface
- Network configuration
- GUI
- Telescope interface

- Mechanism control
- Temperature control
- Calibration source control
- Array control
- Data storage
- Quick-look display (DV)
- Macro capability
- Housekeeping and logging information

3.8 Instrument Control Hardware

The function of the instrument controller is to move and sense the position of mechanisms, control the temperature of components (arrays, immersion gratings, gas cell), turn calibration light sources on and off, and to provide housekeeping information (e.g. temperatures, motor currents). A block diagram of a potential control scheme is given in Figure 25. The scheme is very similar to that being planned for the SpeX upgrade. Motors, position sensors, and lamps, interface with a PC controller via the required interface devices (drivers and pulse generators, AC power switches etc.). The interface devices are located in the cooled rack mounts and communicate with the PC located in the computer room over the local area network. The arrays are controlled via independent PCs over optical fiber links. Keeping these systems independent is optimum for operations since they can be rebooted separately when required.

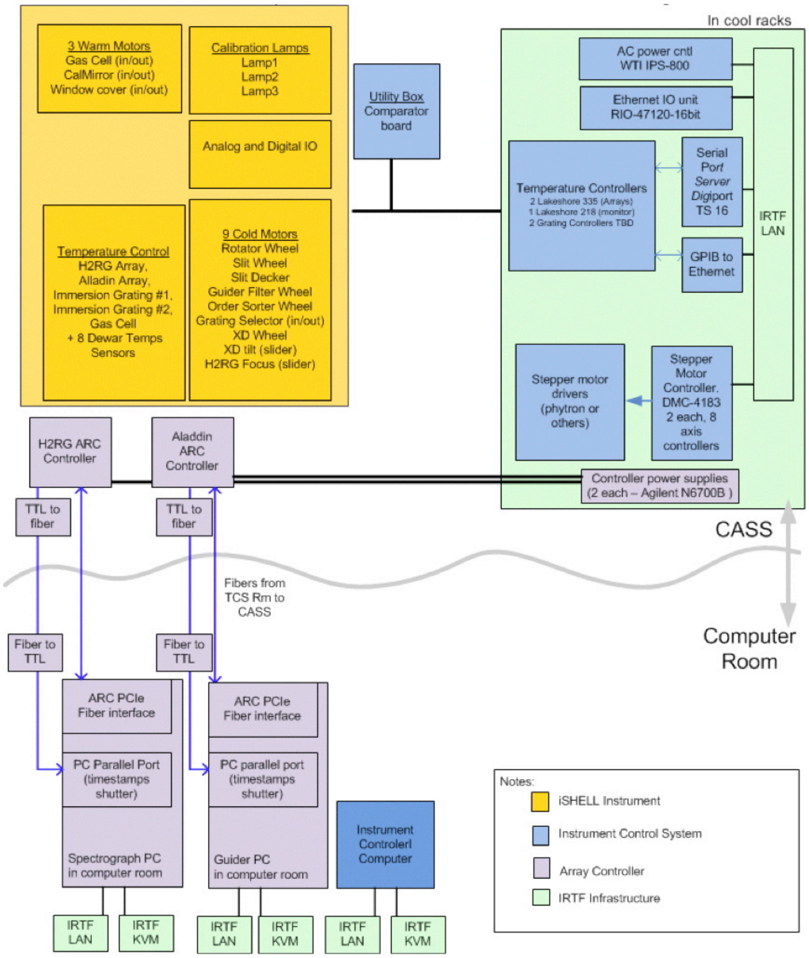


Figure 25. Instrument control

3.9 Array Control

iSHELL uses a 2048x2048 H2RG array in the spectrograph and a 512x512 Aladdin 2 InSb array in the slit viewer. Both arrays are required to operate independently. The read noise goal for the spectrograph is better than 5 e^- RMS with multiple sampling. Astronomical Research Camera (ARC) Generation 3 controllers are used for both arrays. We decided not to use Teledyne ASIC controllers since we are also upgrading SpeX and NSFCAM to H2RG arrays and because the slit viewers use existing Raytheon InSb arrays. The H2RG array requires a 12-slot housing (dimensions 33x16x27 cm) containing: one ARC-22 fiber optic timing board, one ARC-32 IR and CCD clock driver board, and five 8-channel IR video boards (16-bit A/Ds, pre-amps, and biases). Four video boards are needed to read out the 32 channels of the H2RG plus a fifth board for the windowed output and reference channels. The H2RG is wired for 32 outputs since we require integration times as short as 0.4 sec (300 KHz). The smaller InSb array requires a 6-slot housing (dimensions 33x16x14 cm) containing: one ARC-22 fiber optic timing board, one ARC-32 IR and CCD clock driver board, and one 8-channel IR video boards (16-bit A/Ds, pre-amps, and biases). Power for each controller is provided by an Agilent N6700B supply. Manganin ribbon cabling is used for internal array wiring as in SpeX.

The controller and spectrograph array must encompass a large performance space, ranging from faint object and low background spectroscopy (~30 s array read out time with multiple reads), to very bright object spectroscopy (~1 s array read out time). This is achieved by trading off read out time for read noise where required through the use of several read out modes: slow read out full array, standard read out full array, fast read out full array, and occultation (sub-array) mode. The guider array has similar read out modes.

3.10 Arrays

Using the iSHELL grant and the SpeX Upgrade grant we funded a foundry run at Teledyne to fabricate H2RG arrays. The first foundry run produced arrays that suffered from the indium diffusion fault and resulted in arrays that had >5% bad pixels (increasing exponentially with storage temperature. A second foundry run for 'bake stable' (fixed) devices produced an excellent science grade (SG) array for SpeX (see Table 7 – to comply with ITAR regulations the performance parameters are approximate.). A third foundry run due in mid-2013 should produce a similar quality array for iSHELL. All the IRTF H2RG arrays are wired for 32 outputs for fast read out when needed.

Table 7. Performance of candidate H2RG arrays for iSHELL

Parameter	*Unit*	*Specification*	*SG*
Cutoff wavelength	μm	5.1-5.5	5.3
QE at 0.8 μm	%	≥ 70	81
QE at 2.0 μm	%	≥ 70	84
QE at 3.5 μm	%	≥ 70	80
QE at 4.4 μm	%	≥ 70	78
Median dark @ 0.175V and 37 K	e/s	≤ 0.05	0.02
Median read noise (single CDS) 100kHz	e RMS	≤ 15	13
Well at 0.175 V bias (5% deviation from linear)	e	≥ 65,000	67,000
Crosstalk	%	≤ 4	3
Residual image	%	≤ 0.1	0.02
Operability (bad pixels)	%	≥ 95	99.1
Cluster: 50 or more bad pixels	%	≤ 1% of array	0

The iSHELL infrared slit viewer will use the good engineering grade 512x512 Aladdin 2 InSb array from SpeX. (SpeX will use the science grade InSb array from its spectrograph that is being replaced by the new H2RG during its upgrade).

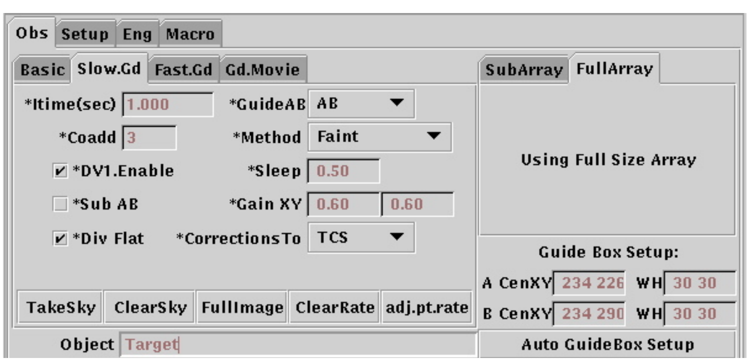
4 OBSERVING WITH iSHELL

4.1 Observing Modes Summary

iSHELL has three basic spectroscopy modes. Short cross-dispersed mode (SXD) covers observations done at ~1-2.5 μm. Radial velocity (RV) mode is a subset of SXD mode in which observations are made through a gas cell. Long cross-dispersed mode (LXD) covers observations done at ~2.8-5.3 μm. In addition, the infrared slit viewer that is used for acquisition and guiding, can also be used for scientific imaging. Each of these modes can be further sub-divided into standard exposures (Table 5 and Figures 4-22) and the standard exposure settings can also be adjusted to place a particular wavelength in the center of the array.

4.2 Acquisition and Guiding

Target acquisition and guiding is executed with the infrared slit viewer. Due to the high background at wavelengths longer than ~2.5 μm this is usually done in the *J, H, K*, or similar wavelength narrow-band filters. Once the target is acquired it is placed in the slit by offsetting the telescope and guiding started. Since guiding is implemented by offsetting the telescope, guiding is necessarily slow and corrects telescope tracking at rates of <0.3 Hz. In most cases guiding will be done on spill-over from the target star in the slit. Alternatively, a guide star in the FOV of the slit viewer can be used. The centroid of extended objects can be guided on by increasing the size of the guide box. The guiding scheme is very similar to that successfully used in SpeX (see Figure 27). The only differences are the smaller FOV and pixel scale (42″ diameter and 0.10″/pixel respectively). With further development it may also be possible to guide on features in extended objects (in particular, planets) by using cross-correlation techniques. Since iSHELL works at high resolving powers its targets will be intrinsically brighter than those observed with SpeX, making guiding easier.



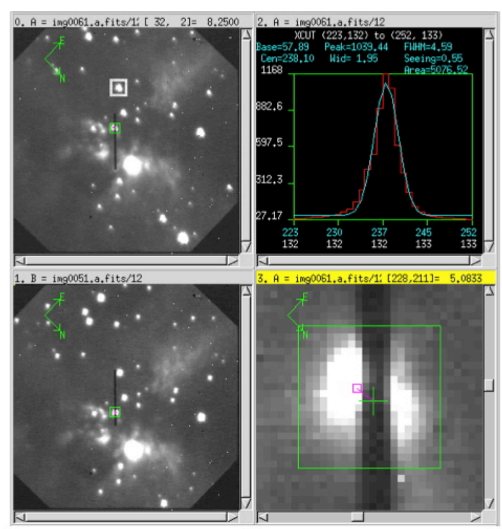


Figure 27. SpeX guider GUI and display

The acquisition and guiding procedure is as follows:

1. Slew telescope to target, pointing ± 5″ (~2 min)
2. Select slit and SV filter (~1 min)

3. Image target with SV and adjust rotator as necessary (~1 min)
4. Refocus telescope if necessary
5. Re-image target and offset telescope to guide box. Start slow guiding (~1 min)
6. Start spectrograph integration. Typical integration times range from a few minutes to one hour

Some observing programs may also require use of the telescope's off-axis optical guider. In these instances guiding can be monitored in the infrared with the SV.

4.3 Observing Modes Description

4.3.1 SXD Mode

In this mode the 1.1-2.5 μm immersion grating is selected together with the appropriate cross-dispersing grating, and *J*, *H*, or *K* order-sorting filter. The exact wavelength orders observed are set by tilting the cross disperser, which moves the orders up or down the array. Different slit widths give different resolving powers. The *J*, *H* and *K* cross dispersers must use slits no longer than 15″, and no longer than 10″ in the short wavelength orders at *J* and *H* (see Figures 4-22 and Tables 2-5). At resolving powers of R=70,000 there is effectively no sky background in between the widely separated OH emission lines at *J*, *H*, and *K* (see Figure 28). Background comes from dark current and scattered light. In principle a spectrum can extracted from a dark subtracted and flat-fielded object frame and any scattered light fitted along the slit. However, the slits are long enough for point sources to be nodded within the slit, automatically subtracting dark current and scattered light. If space permits a 5″ long slit is an option for increased simultaneous wavelength coverage. Calibration uses calibration unit flat and arc lamp exposures. Absolute flux calibration of point source spectra requires the use of wide slits to minimize slit losses.

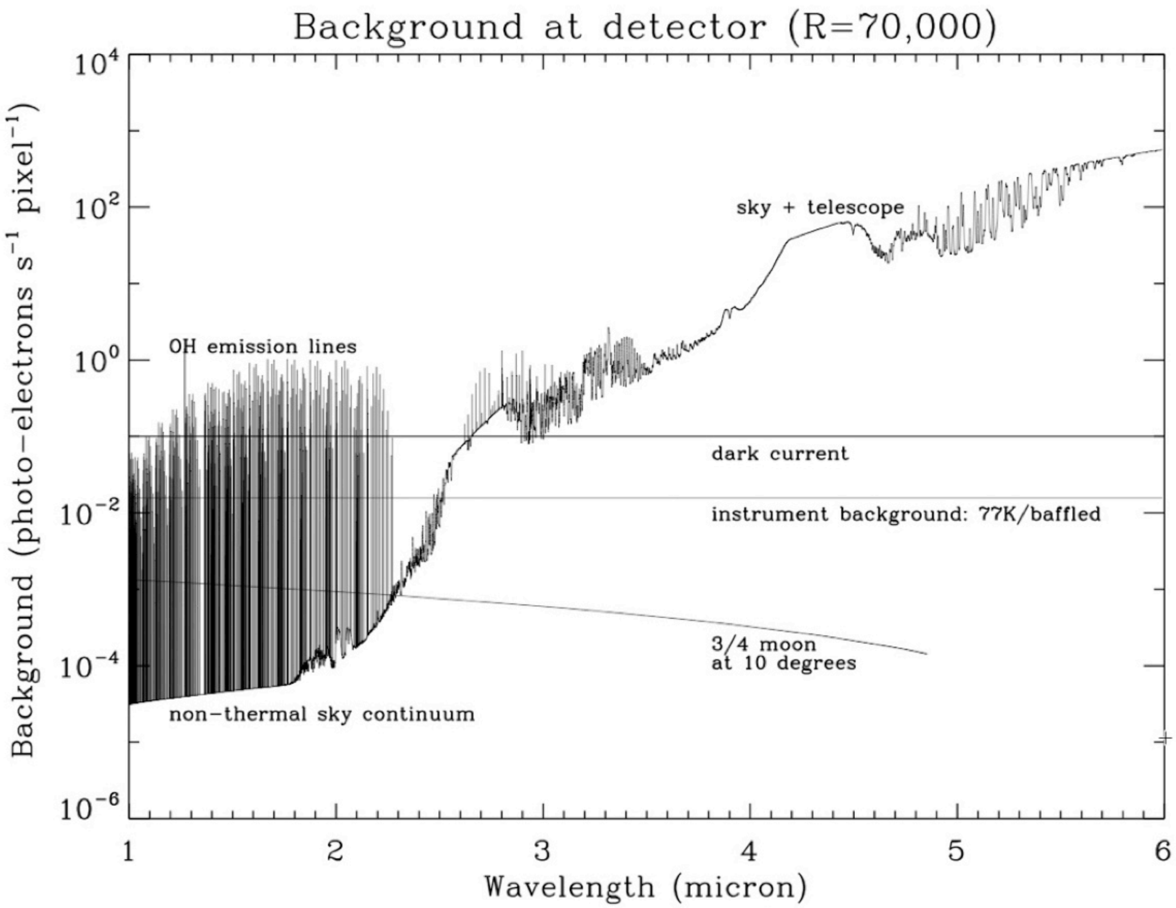


Figure 28. Predicted background at the array in ISHELL assuming a resolving power of R ~ 70,000 matched to a 0.375″ slit, a slit efficiency of 0.4 (0.7″ seeing at K), and an average instrument throughput of 0.1

4.3.2 RV Mode

RV mode is a subset of SXD mode with the cross disperser and order sorter set up for the *K* band, and the slit configured for highest resolving power (R=70,000). Observations are made through the NH_3 gas cell placed in beam just above the entrance window. Absorptions in the gas impose a precise wavelength fiducial on the stellar spectra. Ideally the instrument spectral response function should also be measured by observing unresolved arc lines. Any changes in the instrument spectral response function between observations (short term and long term) can then be incorporated into the RV measurement code. During RV observing runs mechanisms in the spectrograph path should not be moved to optimize stability.

4.3.3 LXD Mode

In this mode the 2.8-5.3 μm immersion grating is selected together with the appropriate cross-dispersing grating, and *L*, *L′*, or *M* order-sorting filter. The exact wavelength orders required are set by tilting the cross disperser, which moves the orders up or down the array. Different slit widths give different resolving powers. The *L* and *M* cross dispersers must use slits no longer than 15″, and the *L′* cross disperser no longer than 25″ to separate the orders (see Figures 13-19 and Tables 2-5). At resolving powers of R=70,000 the sky and telescope becomes the dominant background at wavelengths longer than about 2.7 μm (see Figure 28) and so point sources are nodded within the slit to subtract the background. Calibration uses calibration unit flat and arc lamp exposures. Telluric features supplement wavelength calibration in this mode since the number of measurable arc lines is much reduced at wavelengths longer than about 3 μm. Absolute flux calibration of point source spectra requires the use of wide slits to minimize slit losses.

4.3.4 Imaging

The primary function of the SV is for acquisition and guiding (see Section 4.2), and for focusing light onto the slit. Although it is not a fundamental requirement, science imaging with the slit viewer is also very desirable, both to support iSHELL programs and to support non-iSHELL programs that would otherwise require an instrument change. Science imaging with iSHELL will require a set of standard filters and additional calibration (e.g. linearity correction). As a result, imaging with iSHELL will need to support nodding and dithering. Flat fielding at wavelengths less than 2.5 μm will require sky flats. Sky or dome flats at longer wavelengths do not work since flux comes from the telescope instead of through it. At longer wavelengths photometric precision is improved by keeping the object and standard on the same part of the array, or by dithering to average out the flat field errors. Typical backgrounds at the array are shown in Figure 29.

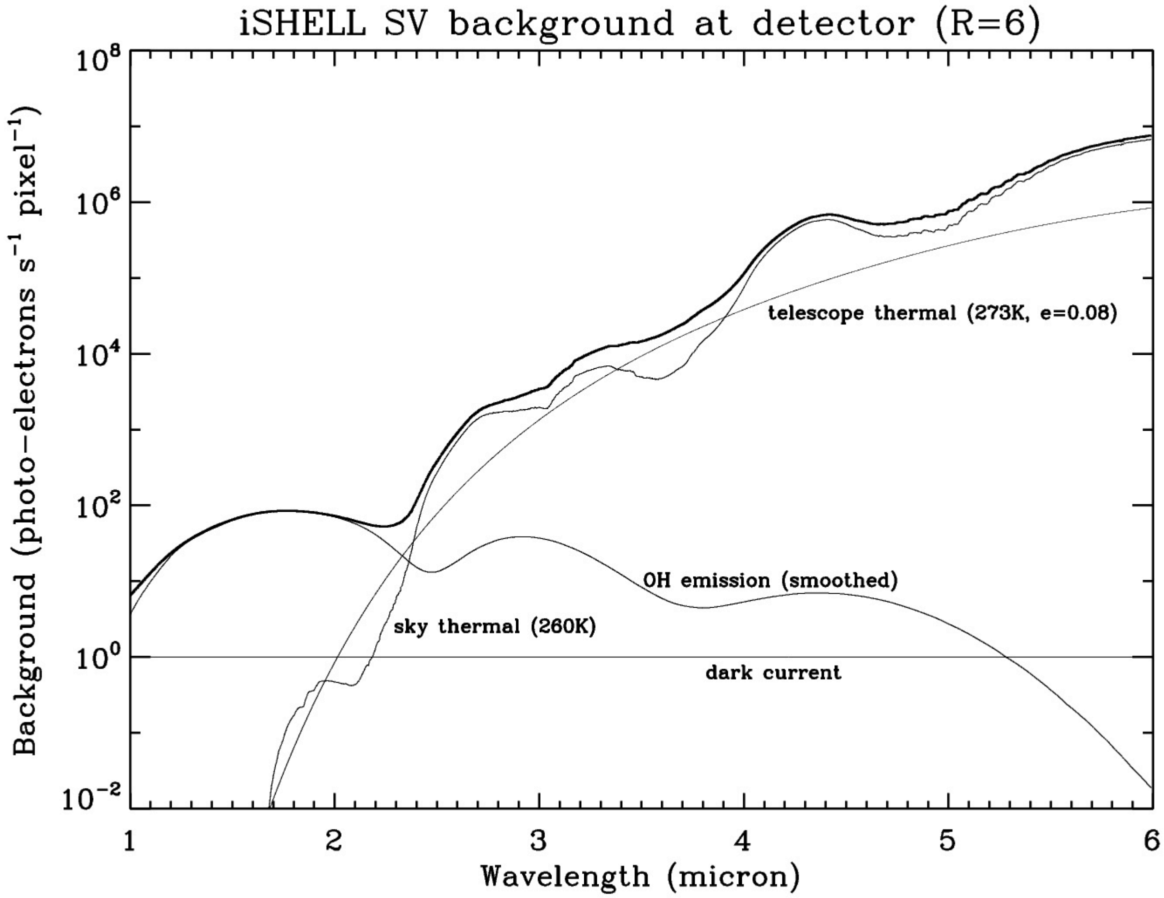


Figure 29. Predicted background at the SV array in for broadband filters (R≈6). The model assumes a pixel size of 0.06″ and a throughput of about 0.2. The image scale has since been changed to 0.1″ per pixel (three times more background).

4.4 *Sensitivity*

The instrument parameters that are needed to estimate spectral sensitivity are given Table 9.

Table 8. Instrument sensitivity parameters: spectrograph

Parameter	**iSHELL**
Resolving power (R)	70,000
Spectral sampling	3 pixels per slit width
Wavelength coverage	1.15-5.3 μm
Spatial sampling	0.125″ per pixel
Slit width	0.375″
Detector	2040x2040 H2RG
Read noise (multiple reads)	5 e RMS
Dark current	0.1 e/s
Throughput	0.10 (see Table 9)

A realistic FWHM at 2.2 μm is used in the sensitivity model and the FWHM is scaled with wavelength according to Kolmogorov turbulence ($\lambda^{-0.2}$ dependence, confirmed with SpeX measurements). The seeing profile is then convolved with a diffraction-limited profile and the light transmitted by the rectangular slit (slit efficiency) calculated. At IRTF the night-time median *K*-band FWHM is about 0.7″ (see Figure 30).

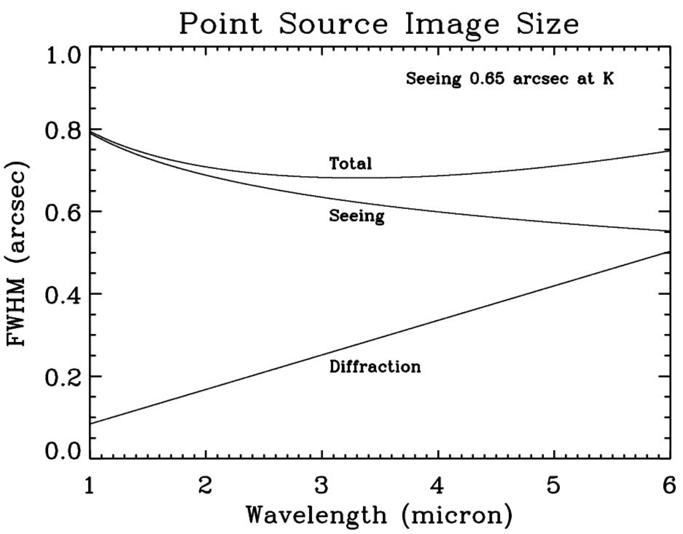


Figure 30. Point source image size

The slit efficiency is plotted for a point source image size of 0.7″ (seeing convolved with diffraction) with 0.375″ (R=70,000) and 0.75″ (R=39,000) wide slits (see Figure 31). Imperfect guiding and focus will further reduce slit efficiency.

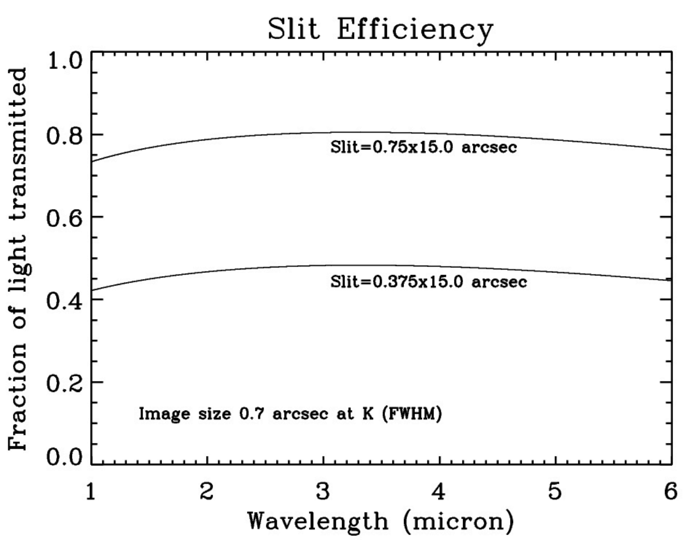


Figure 31. Slit efficiency

The throughput of iSHELL used in the sensitivity calculation is estimated from the instrument design (see Table 9). The efficiency of the slit is not included in throughput estimates since it is dependent on image size (seeing etc.).

Table 9. 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 as 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
Spectrograph		
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	0.25/0.19	At blaze peak/average across blaze
Total FO + Spectrograph	0.18/0.13	At blaze peak/average across blaze @ about *H* and *K*

The atmospheric transmission code ATRAN was used to compute a telluric transmission spectrum (R=70,000) for an air mass of 1.15 (60° elevation) and 2 mm of precipitable water (average for Mauna Kea). Thermal emission from the sky was calculated by assuming a sky emissivity (1 – sky transmission) and a sky temperature of 263 K. Estimates of the non-thermal continuum are from Maihara et al. (1993).

Sky emission lines (nearly all OH) are included even though they only cover at most 0.5% of pixels in any particular waveband (maximum in the *H*-band) at a resolving power of R=70,000. Thermal background from the telescope and cryostat window was calculated assuming a temperature of 273 K and an emissivity of 0.1 (typical measurements are about 0.06 for IRTF). The predicted thermal background from the instrument is small compared to the dark current. See Figure 28.

Due to the high dispersion (R=70,000) and small pixel-field-of-view (0.125 ″/pix), the sensitivity of iSHELL is limited by detector performance at wavelengths shorter than 2.5 μm. Hawaii-2RG detectors have advertised dark currents of less than 0.1 e/s and should achieve a read noise of about 5 e RMS with multiple non-destructive reads (NDRs). The quantum efficiency of the array is about 80%. See Table 7 for details of H2RG array performance.

4.4.1 Spectroscopy

The results of the sensitivity model for the spectrograph discussed above are tabulated in Table 10 (point source) and Table 11 (extended source).

Table 10. ISHELL one-hour point source sensitivity (read noise 5 e RMS, dark 0.1 e/s, seeing 0.7″, throughput 0.1)

R	S/N	Magnitude (Vega)					Line flux (erg s^{-1} cm^{-2})				
		J	*H*	*K*	*L*	M	*J*	*H*	*K*	*L*	*M*
72,000	**100**	10.4	9.9	9.5	7.4	5.0	$3.5x10^{-15}$	$2.5x10^{-15}$	$1.8x10^{-15}$	$2.6x10^{-15}$	$1.2x10^{-14}$
72,000	**10**	13.2	12.7	12.3	10.0	7.5	$2.6x10^{-16}$	$1.9x10^{-16}$	$1.4x10^{-16}$	$2.4x10^{-16}$	$1.2x10^{-15}$
39,000	**100**	11.4	10.9	10.5	8.3	5.9	$2.6x10^{-15}$	$1.9x10^{-15}$	$1.4x10^{-15}$	$2.2x10^{-15}$	$1.0x10^{-14}$
39,000	**10**	14.2	13.7	13.2	10.9	8.4	$2.2x10^{-16}$	$1.6x10^{-16}$	$1.1x10^{-16}$	$2.0x10^{-16}$	$1.0x10^{-15}$

Table 11. ISHELL one-hour extended source sensitivity (read noise 5 e RMS, dark 0.1 e/s, seeing 0.7″, throughput 0.1)

R	S/N	Magnitude $arcsec^{-2}$ (Vega)					Line flux (erg s^{-1} cm^{-2} $arcsec^{-2}$)				
		J	*H*	*K*	*L*	*M*	*J*	*H*	*K*	*L*	*M*
72,000	**100**	10.4	9.8	9.4	7.2	4.9	$3.6x10^{-15}$	$2.7x10^{-15}$	$2.0x10^{-15}$	$3.0x10^{-15}$	$1.4x10^{-14}$
72,000	**10**	13.2	12.6	12.2	9.8	7.4	$2.7x10^{-16}$	$2.1x10^{-16}$	$1.5x10^{-16}$	$2.7x10^{-16}$	$1.3x10^{-15}$
39,000	**100**	11.6	11.0	10.6	8.4	6.0	$2.3x10^{-15}$	$1.8x10^{-15}$	$1.3x10^{-15}$	$2.1x10^{-15}$	$9.7x10^{-15}$
39,000	**10**	14.3	13.7	13.3	10.9	8.5	$1.9x10^{-16}$	$1.5x10^{-16}$	$1.1x10^{-16}$	$2.0x10^{-16}$	$9.6x10^{-16}$

4.4.2 Imaging and guiding

Due to its finer pixel scale, the slit viewer in iSHELL will have slightly less sensitivity than the slit viewer in SpeX at *J*, *H*, and *K*. iSHELL shares the same type of engineering grade Aladdin 2 512x512 InSb array as SpeX. The magnitude limit for guiding on spill over from a target in the slit is *JHK*~15 in ~10 s in median seeing. The imaging sensitivity is given in Table 12.

Table 12. Slit viewer sensitivity 60s 10σ

Magnitude (Vega)			
J	*H*	*K*	*L′*
18.0	17.1	16.6	11.7

4.5 Calibration

4.5.1 Spectrograph

The Calibration Unit provides most of the calibration sources. Observing the sky provides the remainder. Anticipated calibrations include:

- Dark and bias frames (blank-off)
- Flat field frames (flat-field lamps)
- Detector flat field (no spectrograph optics) for scattered light modeling (LED located close to white pupil)
- Frames containing wavelength fiducials (arc lamps and sky telluric spectra)
- Observations of a flat-field lamp through a gas cell. This is required to validate the long-term wavelength stability of the arc lamps
- Observation of arc lines to measure instrument SRF
- Observations of telluric standard stars to remove telluric features from science spectra
- Observations of target stars photometric standard stars through wide slit for flux calibration of spectra. The telluric and photometric standard stars can be the same if suitable
- Radial velocity 'standards'
- Fast rotating A-type stars: astronomical blackbody sources which maybe used as calibrator references for gas cell work

4.5.2 Slit Viewer

Observing the sky provides all the calibration sources since light sources in the Calibration Unit are too bright. Anticipated calibrations include:

- Dark and bias frames (blank-off)
- Flat field frames (sky)
- Star field frames for image scale and position angle

4.6 Detector Configurations

Anticipated functions include:

4.6.1 Spectrograph Array

- Readout modes, full array and multiple (≥3) sub-arrays
    - Single read (reset, wait, and read) for troubleshooting

    - Double read (reset, read, wait, and read), with multiple reads (NDRs up to 128) to reduce read noise, and sample up the ramp (requirement for RV mode)
- All the individual reads must be stored, including the pedestal read. This is required for accurate linearity correction
- Range of full array exposure times
    - Slow readout (on-chip exposure times 3600s to 60s), read noise ≤ 5 e RMS
    - Standard readout (on-chip exposure times 60s to 5s), read noise ≤ 15 e RMS
    - Fast readout (on-chip exposure times 5s to ~1s), read noise ≤ 100 e RMS
- Should be capable of co-adding up to 100 on-chip integrations in the controller where one co-add is a single read out (single or double)
- Basic mode parameters
    - On-chip integration time (single or double)
    - Co-adds
    - Beam A, B, or AB
    - Cycles
    - Store data over network, or on local disk, save on or off
    - Viewable during execution
- Movie mode parameters
    - On-chip integration time (single or double)
    - Co-adds
    - Beam A, or B
    - Continuous until stop
    - Store data on local disk
    - Not viewable during execution
- Must have the ability to measure dark currents of ~0.01 e/s
- Bias settings (well depths) of zero, low, medium, and high
- Background reads or reset rate and timing parameters will be settable (e.g. to minimize persistence)
- Time stamping of data frames. Using the host computer and Network Time Protocol to synchronize the system clock (UT) precisions of 200 milliseconds are obtained. A GPS will be used when higher precisions when required (better than 1 microsecond)

4.6.2 Slit Viewer Array

- Readout modes, full array and multiple (≥3) sub-arrays
    - Single read (reset, wait, and read) for troubleshooting
    - Double read (reset, read, wait, and read), with multiple reads (NDRs up to 128) to reduce read noise
- All the individual reads must be stored, including the pedestal read. This is required for accurate linearity correction
- Range of full array exposure times
    - Slow readout (on-chip exposure times 300s to 10s), read noise ≤ 15 e RMS
    - Standard readout (on-chip exposure times 10s to 1s), read noise ≤ 70 e RMS
    - Fast readout (on-chip exposure times 1s to <0.1s), read noise ≤ 100 e RMS
- Should be capable of co-adding up to 500 on-chip integrations in the controller where one co-add is a single read out (single or double)

- Basic mode parameters
    - On-chip integration time (single or double)
    - Co-adds
    - Beam A, B, or AB
    - Cycles
    - Store data over network, or on local disk, save on or off
    - Viewable during execution
- Movie mode parameters
    - On-chip integration time (single or double)
    - Co-adds
    - Beam A, or B
    - Continuous until stop
    - Store data on local disk
    - Not viewable during execution
- Slow guide mode parameters
    - Guide box centroid, calculate TCS offset
    - Guide on (in beam A, B, or AB) or off (no offsets sent to TCS)
    - On-chip integration time (single or double)
    - Co-adds
    - Continuous until stop
    - Store data over network, or on local disk, save on or off
    - Viewable during execution
- Must have the ability to measure dark currents of ~0.1 e/s
- Bias settings (well depths) of zero, low, medium, and high
- Background reads or reset rate and timing parameters will be settable (e.g. to minimize persistence)
- Time stamping of data frames. Using the host computer and Network Time Protocol to synchronize the system clock (UT) precisions of 200 milliseconds are obtained. A GPS will be used when higher precisions when required (better than 1 microsecond)

5 Handling iSHELL DATA

5.1 Data Rates

Array data is saved in FITS format. A single readout (single read or double correlated sample read) is stored in 16 bit (2 Byte) per pixel files. Co-added frames are stored with 16 or 32 bit (2 or 4 Byte) pixel values, depending on the number of co-adds. Array data size per frame:

- Spectrograph array 2048 x 2048 x 2 Bytes (typically) = 8.4 MB
- Slit viewer array 512 x 512 x 2 Bytes (typically) = 0.5 MB

A reasonable estimate for the highest data rate comes from asteroseismology projects where the fast cycle time of infrared arrays is exploited. In this case using a minimum exposure time of 2 s and a cycle time of 6 s would give a data rate of 3.8 GB per hour and a total of 30 GB per night if sustained for 8 hours. Probably more typical would be a rate of one frame per minute given a data rate of 0.5 GB per hour and about 5 GB per night.

5.2 Software Requirements

5.2.1 Quick look

A quick-look viewer displays images as they are received and allows simple arithmetic analysis using frame buffers. The image display options include header information, line cuts, and statistics. Interactive features include drawing guide boxes and offsetting the telescope using cursor or keyboard inputs, and automatic focus routines. The Data Viewer (DV) currently in use already provides this functionality. iSHELL will use DV.

An add-on component to DV will allow spectra to be extracted from spectral images using a simplified version of the spectral extraction package and default extraction parameters so that S/N can be estimated in real time.

5.2.2 Data reduction

iSHELL produces cross-dispersed spectral images very similar to those produced by SpeX but at higher resolving power. The required functionality of the data reduction package required for iSHELL is therefore very similar to that built for SpeX ('Spextool'). A flowchart of the reduction steps is shown in Figure 32. The procedure requires the following data frames:

- Target spectrum
- Telluric standard spectrum
- Arc lamp spectrum and/or sky telluric spectrum for wavelength calibration
- Flat field frames
- Dark and bias frames
- Bad pixel image
- Linearity data

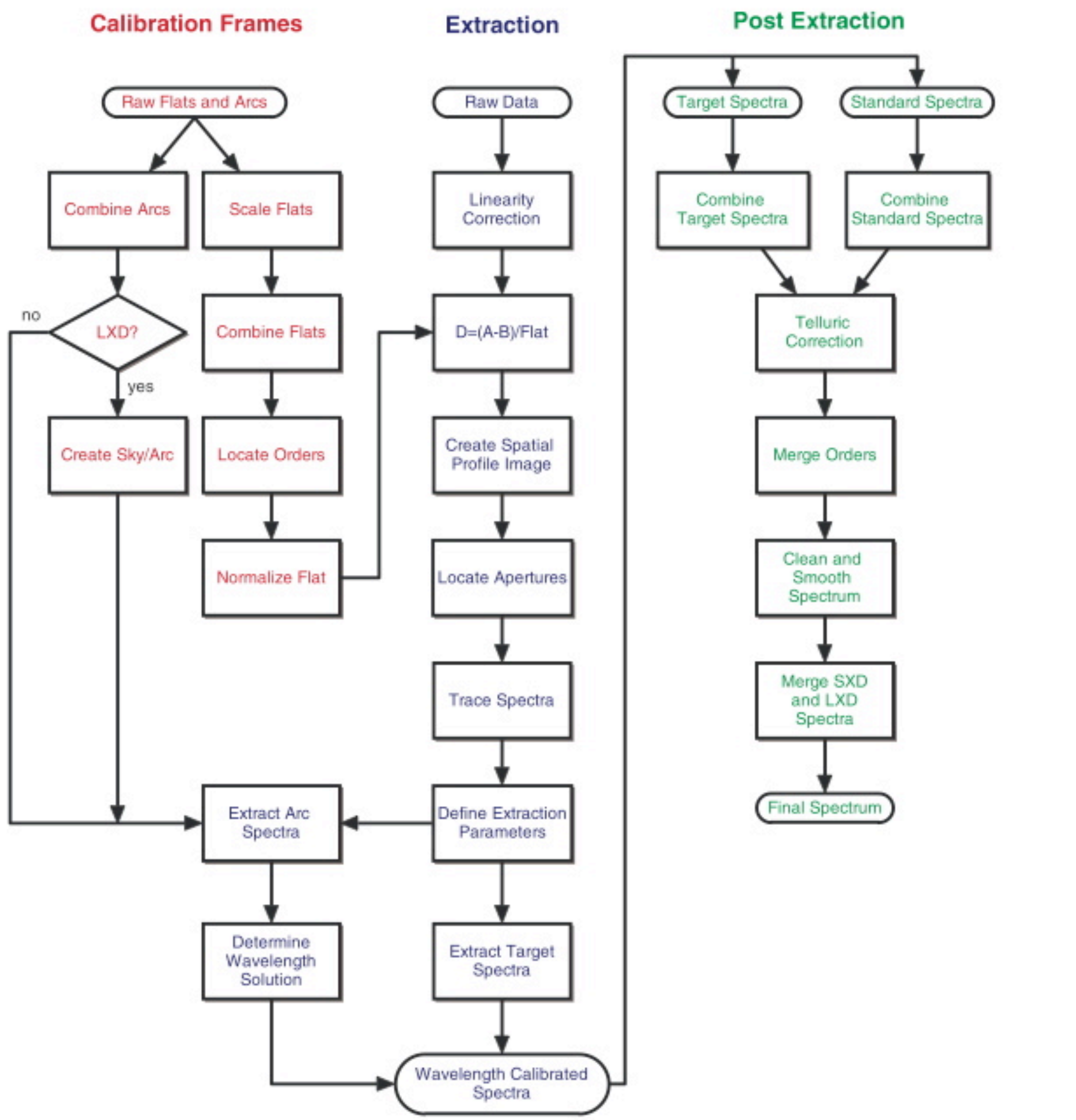


Figure 32. Flowchart showing the steps in the reduction process (Cushing *et al*. 2004, PASP 116:362-376)

An option not included in this procedure is to use a telluric model (e.g. ATRAN) to remove telluric features from target spectra. Some observing programs (e.g. radial velocity and Mars methane observations) require special reduction procedures which are not part of the standard package.

6 EXAMPLE OBSERVING SCENARIOS

Example observing scenarios are used to illustrate how the instrument is used and to develop software.

6.1 Detecting Exoplanets in the First 3 Myr (Prato et al.)

6.1.1 Scientific background

Despite tremendous progress in detecting exoplanets little is yet known about the youngest generation of planets. A surprising result has been that so many gas giant planets are much closer to their central stars than was thought possible. These systems challenge our understanding of the role of planet migration on the evolution of planetary systems and the mechanisms by which close-in planets form. The standard core accretion model requires timescales of several million years to form Jupiter-mass planets, whereas gravitational instabilities can form these massive planets within 1 Myr. The most direct means for identifying the timescale for planet formation and migration is to look for planets around young stars via radial velocity (RV) modulation. However, RV noise induced by star spots is expected to be high in young stars because of their greater activity. Due to the reduced contrast of star spots in the infrared the RV modulation of star spots should be much reduced in the infrared. In contrast, any RV modulation induced by a planet is constant in the visible and infrared. Targets that show no reduction of RV amplitude in the infrared are good candidates for young planets (e.g. BP Tau in Fig 33). The magnitudes of the targets are in the range 6-8. RV standards will also be observed to characterize the RV errors of the observations.

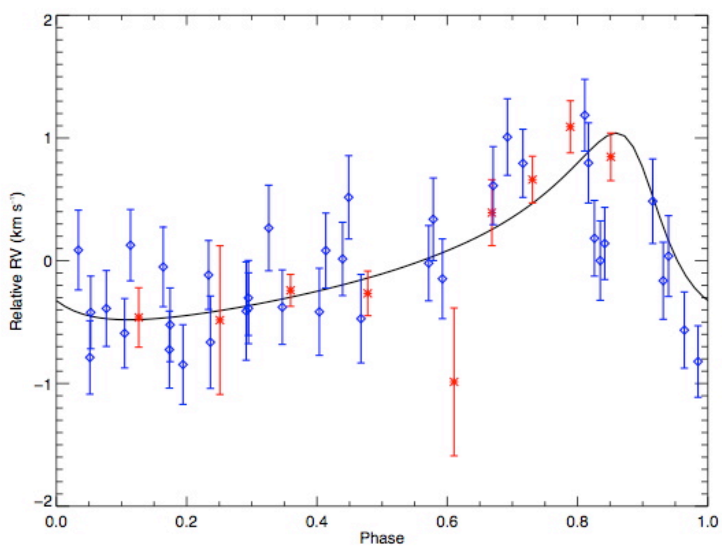


Figure 33. The combined optical (blue diamonds/McDonald) and K-band (red stars,/IRTF) radial velocities of BP Tau versus relative phase plotted with the best-fit orbital solution (black line). Planet 6 M_{JUP} and orbital elements *P*=8.28 days, *a*=0.069 AU, and *e*=0.53 (Crockett *et al.*).

Using the CO band-head in young stars and telluric features for the wavelength fiducial, CSHELL is currently achieving RV precisions of about 100 m/s over a period of a few months. Through the use of a

NH$_3$ gas cell and its broader wavelength range iSHELL should approach RV precisions of 10 m/s. The observing program started with CSHELL will be significantly enhanced with the use of iSHELL.

6.1.2 Planning the observation

An optical RV survey for variability a few hundred young star in the Taurus star-forming region and the Pleiades is already being conducted at the McDonald and Kitt Peak observatories. It has already been established that optical RV variations uncorrelated with line bisector variations are not sufficient to guarantee planetary companion detection. The iSHELL observations will focus on targets with large RV signatures at optical wavelengths. The RV signatures of these targets are most likely a combination of star spots and massive planetary companions. Observing runs of several days will be planned. Since typical orbital periods will be several days these run will then be able to cover a significant portion of the orbital phase. Several runs will be required for complete phase coverage.

6.1.3 Required observations

Observations will be taken in the RV mode of iSHELL. This configuration is SXD mode with the *K*-band order sorter and with the gas cell in the beam. The narrow slit is selected to give R=70,000. The XD grating is setup to position the grating orders covered by the NH$_3$ gas cell in the center of the array (see Figure 34). Guiding is done on the science targets using the SV. For optimum RV stability the configuration of the spectrograph is not changed during the observing run.

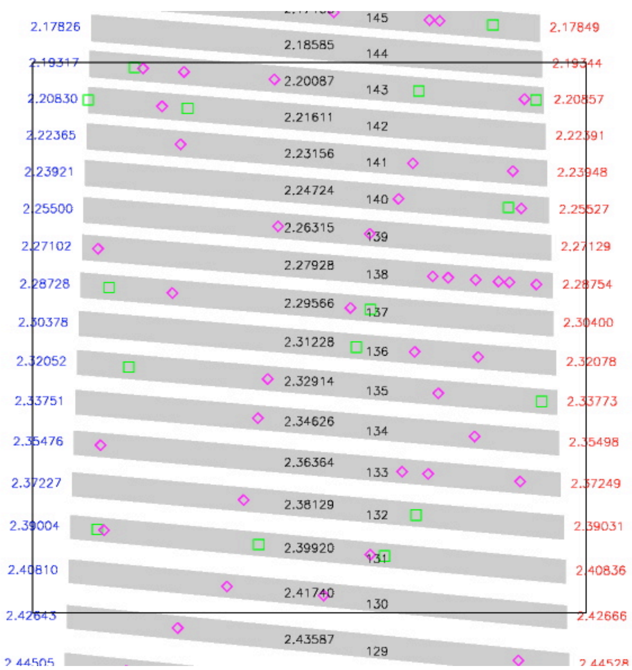


Figure 34. XD setup for RV mode: SXD mode, *K* order sorter (R=72,000, 0.38x15″ slit, XD 2.16 μm blaze at 40.4 degree). The NH$_3$ gas cell covers the orders 135-137

To reach the required RV precision a S/N of about 200 is needed. The science targets have magnitudes down to about 8. About half a magnitude of sensitivity is lost in the gas cell and so the fainter targets are effectively *K*=8.5 requiring integrations times of about one hour. A typical setup would be 600 s x 1 co-add x 3 cycles where each cycle is an AB pair with the target nodded within the 15″ long slit, for a total integration time of 3600 s. The nodded pairs subtract off dark current and any scattered light. The requirement for 6 separate frames (3 AB cycles) is to median-out cosmic rays and noisy pixels. For the brighter RV standards (*K*=6) a typical set up would be 100 s x 1 co-add x 3 AB cycles.

Observing through the gas cell provides an accurate wavelength fiducial and also minimizes the effect of any changes in the instrument since the target and fiducial light paths are identical. Nevertheless, any changes in the instrument can still result is systematic RV errors since absorption lines in the star and in the gas cell have different intrinsic widths and changes in the instrument SRF effect both differently. This can result in a systematic RV shift between the stellar lines and the fiducial gas cell absorption lines. Changes in the instrument SRF can be tracked by measuring the profiles of unresolved lines. The measured SRF can then be included in the RV analysis. At the resolving power if iSHELL Th-Ar arc lines are probably not fully resolved and so we will try to use these to track changes in the SRF. Since arc lamps have a finite lifetime two lamps will measured to provide a bootstrap calibration should one set fail. Fringes from a laser frequency comb would provide a better source of unresolved and stable lines.

6.1.4 Daytime calibration

Occasional calibration sequences to be performed as needed

- Spatial flat-field frames (TBC -to fit scattered light)
  - Select blank in order sorter
  - Turn on internal flat-field lamp
  - Set exposure time for high S/N (>1000)
  - Record an internal flat-field frame and display on the Quick Look
  - Turn off internal flat-field lamp

- Dark frames
  - Select blank in order sorter
  - Set exposure times as needed (for science frame, flat field, or SRF)
  - Record dark frames and display on the Quick Look

6.1.5 Start of night setup

- Setup RV mode
  - Open window cover
  - Move calibration mirror out
  - Move gas cell in
  - Rotator 0 degree position angle
  - 0.375″x 15″ slit
  - Select *K* filter in order sorter
  - Select SXD IG (FM7 out, see Figure 1)
  - Select 600 lines per mm XD grating. Array focus follows XD position (lookup table)
  - Tilt XD to put spectral orders 135-137 in center of array (see Figure 34)

6.1.6 Setup prior to observation

- Focus telescope using SV
- Acquisition and Guiding Setup
  - Slew telescope to science target
  - Select non-thermal filter in SV filter wheel (e.g. *K* or narrow-band *K* depending on brightness of target)
  - Take image with SV (42″ FOV, 0.10″/pixel) and display in DV
  - Setup AB guide boxes to guide on spill-over from target in slit (default positions for 0.375″x15″ slit) and offset telescope to place target in guide box A
  - Start guiding (slow guide mode). Guide in the A and B beams. Typical integration time 1.0 s x 3 co-adds
  - Check nod position
  - Continue guiding

6.1.7 Science observation sequence

With the SV guiding and the instrument correctly configured, science integrations can start.

- Set the exposure time (e.g. 600 s x 1 co-adds x 3 AB cycles for *K*=8) and read out mode (full array read up ramp).
- Record science exposures and display on Quick Look
- Stop guiding

6.1.8 Calibration sequence

Maintain telescope tracking at science target. This will ensure that the calibration data are taken at the same telescope position to duplicate any flexure. The calibration sequences will be run as observing macros.

- SRF measurement and wavelength calibration
  - Turn on the arc lamps. Wait till they stabilize (TBD)
  - Move CU mirror in (FM9 in Figure 1)
  - Set exposure time for high S/N (>1000) on a number of lines (this might require several different exposures)
  - Record arc frames and display on the Quick Look
  - Turn off arc lamps

- Spectral flat-field frames (for spectra)
  - Turn on flat-field lamp (QTH)
  - Set exposure time for high S/N (>1000)
  - Record a flat-field frame and display on the Quick Look
  - Turn off flat-field lamp

- Dark frames
  - Select blank in order sorter
  - Set exposure times for SRF measurement

- Record dark frames and display on the Quick Look.

6.1.9 Next RV science target or standard

- Slew telescope to next target and acquire
  - Select *K* filter in order sorter
  - Take acquisition image with SV
  -

6.1.10 End of night shutdown

During RV observing runs the instrument configuration should be changed as little as possible to maintain stability.

- Safe instrument
  - Close window cover
  - Move calibration mirror in
  - Select blank in order sorter
  - Select blank in SV filter wheel

6.2 H_3^+ Observations of Jupiter (Miller et al.)

6.2.1 Scientific background

The upper atmosphere of planets forms a key interface between the planet itself and its space environment. The jovian magnetosphere is the largest structure in the Solar System with the exception of the solar wind. Its upper atmosphere consists of a coexisting neutral thermosphere and an ionized ionosphere, both of which play important roles in the magnetosphere-atmosphere interaction. Energetic electrons precipitating from the magnetosphere into the upper atmosphere form the H_3^+ ion and emission from this ion is a key tracer of energy inputs into the atmosphere. Electric fields and energy deposited by these electrons generate ion winds. Through Joule heating and ion drag neutral winds are also generated. The winds significantly modify the magnetosphere/atmosphere interaction. The energy generated in this way is at least 100 times more than the global insolation of Jupiter. Some of the strongest H_3^+ emission lines are the Q-branch rotation-vibration lines at 3.9-4.1 μm. Doppler measurements of these lines provides critical information about the ion wind velocities (typically a few km s^{-1}), and simultaneous line ratios of several lines allows temperatures and column densities to be derived.

These observations are important in their own right but they will also be important in calibrating measurements to be made by the Juno mission to Jupiter. Juno will be launched in 2011 and will execute a yearlong science mission on arrival at Jupiter in 2016. Juno will use a variety of instruments to map atmospheric composition, temperature structure, cloud opacity and dynamics, together with characterizing the three dimensional structure of Jupiter's polar magnetosphere and auroras. Although Juno has a EUV imager that is sensitive to neutral H_2 emission from the lower thermosphere and upper mesosphere it has no capability to measure ion winds and H_3^+ emissions from the middle thermosphere, where ionization is at its maximum, and magnetosphere-atmospheric coupling is most efficient and affecting. Therefore it is proposed that iSHELL make H_3^+ observations coordinated with Juno measurements. The combined data set, used in conjunction with a 3D jovian ionosphere-thermosphere-magnetosphere model, will allow a more complete picture of energy transfer and related dynamics of the jovian atmosphere and magnetosphere.

6.2.2 Planning the observation

The iSHELL observation sequences need to be coordinated with Juno mission observations and the Juno science team. Juno will operate from a highly elliptical 11-day orbit. Jupiter will be a daytime for IRTF object during parts of the yearlong mission. The feasibility and utility of daytime iSHELL observations will need to be assessed.

6.2.3 Required observations

Observations will be taken in LXD mode with the *L*-band order sorter. The narrow slit is selected to give R=70,000 (4 km s^{-1}), with a slit length of 25″ orientated east-west across the planet (perpendicular to noon meridian). The XD grating is setup to position the 3.9-4.1 μm Q-branch lines in the center of the array (see Figure 35). A raster scan of the auroral/polar regions will be made starting with the slit slightly off the pole and scanning in ~0.5″ steps equator-ward. At opposition Jupiter will subtend 48″ on the sky, and the full extent of the aurorae, which extend down to latitudes as low as 50 degrees, will be about 30″ east-west. Consequently, the maximum slit length of 25″ can cover most of the aurorae. Even though it will not get full limb-to-limb coverage a spectrum will be taken at the equator to assess H_3^+ emission and ion properties on the body of the planet.

For acquisition and positioning the slit on the planet, SV images will be taken with the *L′* filter, which gives good planet-wide images of thermal and H_3^+ emission. Narrow-band images in the Q_1 line at 3.953 μm (λ/Δλ=200) will be taken immediately before and after the raster scans to correct the raw spectral line Doppler shifts for any uneven illumination across the slit. An alternative is to obtain spectral images by widening the slit (3″ gives R=10,000). Guiding will be done using an off-axis guide star and the telescope's optical guider, with the guide rates corrected to follow Jupiter. SV images will be taken simultaneously with spectra to record the position of the slit on Jupiter.

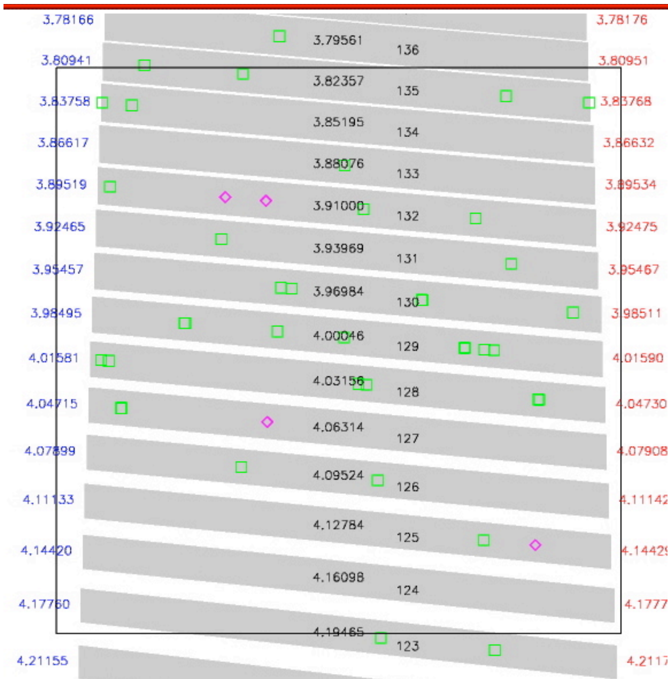


Figure 35. XD setup for long slit observation of H_3^+ in Jupiter, L′ order sorter (R=72,000, 0.38x25″ slit, XD 3.7 μm blaze at 42.0 degree). The highest priority orders are 126-132 (3.9-4.1 μm).

Experience with CSHELL indicates that integrations times of about two minutes per raster scan position (one minute on object and one minute on sky) are required for good S/N on the H_3^+ lines. Narrow-band images of the aurorae in the 3.953 μm Q_1 line will also require a few minutes (object and sky). About 10 spectra per hemisphere are required to get complete coverage of the auroral regions. This requires an elapsed time of about one hour including overheads for positioning and imaging. In addition telluric and flux standard stars will be needed. For absolute spectral calibration both the planet and the standard star will be observed through the wide slit.

6.2.4 Start of night setup

- Setup LXD mode
  - Window cover open
  - Calibration mirror out
  - Gas cell out
  - Rotator 0 degree position angle
  - 0.375″x 25″ slit
  - Select *L* filter in order sorter
  - Select LXD IG (FM7 in)
  - Select 360 lines per mm XD grating. Array focus follows XD position (lookup table)
  - Tilt XD to put spectral orders 126-132 in center of array (see Figure 35)

6.2.5 Setup prior to observation

- Focus telescope using SV
- Acquisition and Guiding Setup
  - Slew telescope to science target
  - Select 3.953 μm (λ/Δλ=200) filter in SV filter wheel
  - Take image (AB if necessary) with SV (42″ FOV, 0.10″/pixel) and display in DV
  - Rotate slit to position angle perpendicular to Jupiter's noon meridian and position slit on planet (take SV images as necessary)
  - Locate and setup guide star for guiding in the optical with the off-axis guider with guide rates set to follow Jupiter
  - Start guiding
  - Check nod position (set to nod off Jupiter onto sky)
  - Continue guiding

6.2.6 Science observations and calibration sequence

With the off-axis camera guiding and the instrument correctly configured, science integrations can start. Use an observing macro to sequence spectrograph and SV integrations, and telescope moves (to raster scan aurorae).

- Science observations of Jupiter
  - Record SV auroral image (3.953 μm, 60 s x 1 co-add x 1 AB cycle) before start of scan
  - Record spectrum (60 s x 1 co-adds x 1 AB cycles). Option of more cycles to median-out hot pixels
  - During spectrograph integration record SV image to locate slit (30 s x 1 co-add x 1 A cycle in A beam and 30 s x 1 co-add x 1 B cycle in B beam)
  - On completion of spectrograph integration move the telescope ~0.5″ along noon meridian
  - Repeat sequence (in the form of an observing macro) for the desired number of scan positions
  - Record SV auroral image (3.953 μm, 60 s x 1 co-add x 1 AB cycle) after completion of scan
  - Stop guiding

- Standard star observations
  - Short slew (< 10 deg) to telluric standard star
  - Select non-thermal filter in SV filter wheel (e.g. *K* or narrow-band *K* depending on brightness of target)
  - Take image with SV (30″x30″ FOV, 0.06″/pixel) and display in DV
  - Setup AB guide boxes to guide on spill-over from target in slit (default positions for 0.375″x 25″ slit) and offset telescope to place star in guide box A
  - Start guiding (slow guide mode). Guide in the A and B beams. Typical integration time 1.0 s x 3 co-adds
  - Check nod position

- Continue guiding
- Record spectra (60 s x 1 co-adds x 3 AB cycles for *K*=8)
- Stop guiding

- Wavelength calibration (macro)
  - Turn on the arc lamps. Wait till they stabilize (TBD)
  - Move CU mirror in (FM9 in Figure 1)
  - Set exposure time for good S/N (>100) on a number of lines
  - Record arc frames and display on the Quick Look
  - Turn off arc lamps

- Spectral flat-field frames (macro)
  - Turn on flat-field lamp (infrared)
  - Set exposure time for high S/N (>1000)
  - Record a flat-field frame and display on the Quick Look
  - Turn off flat-field lamp
  - Move CU mirror out

- Absolute flux calibration (detailed steps as above)
  - Select 3.0″x 25″ slit
  - Reacquire standard star
  - Setup AB guide boxes to guide on reflected light from star in slit
  - Start guiding and record spectra
  - Setup for spectral flats and arcs (macro)
  - Reacquire Jupiter
  - Setup for off-axis guiding
  - Record spectra with wide slit
  - Record SV images as needed

6.2.7 End of night shutdown

- Safe instrument
  - Close window cover
  - Move calibration mirror in
  - Select blank in order sorter
  - Select blank in SV filter wheel