iSHELL OBSERVING MANUAL

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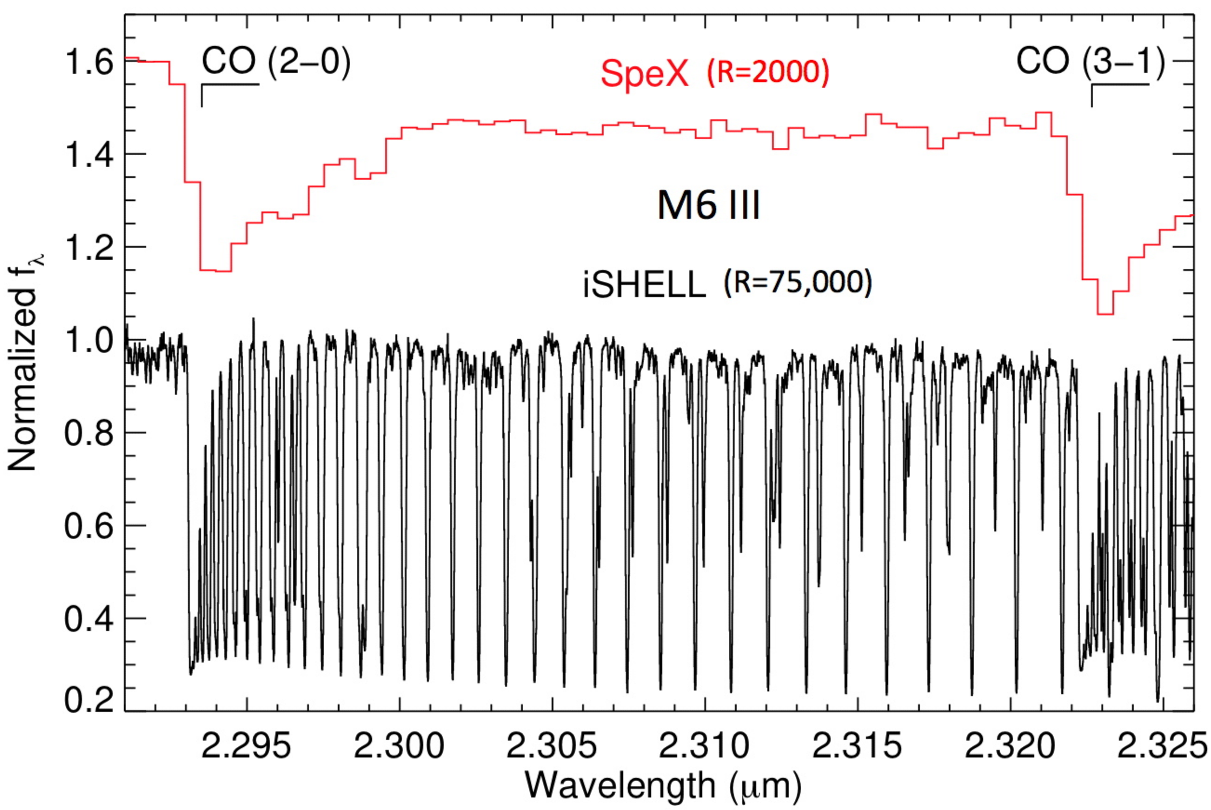

NASA Infrared Telescope Facility
Institute for Astronomy
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iSHELL

Contents

1 Purpose

The purpose of this document is to provide iSHELL observers with a guide to the new instrument. Commissioning on the telescope started in September 2016. Shared risk observing started October 2016. It is hoped that a beta version of the data reduction package (iSHELLtool) will be available by December 2016.

2 Introduction

iSHELL is a 1.1-5.3 μm cross-dispersed high-resolution echelle spectrograph. A resolving power of R=70,000 is matched to a slit width of 0.375″. Wider slits are also available. Different wavelength ranges are selected by choosing from the six cross-dispersing (XD) gratings and selecting an allowed XD tilt position. Object acquisition and guiding is done with an infrared slit-viewing camera. The position angle of the slit on the sky can be changed with an internal instrument rotator. Changing most instrument configurations takes no longer than about one minute; changing the grating takes about two minutes. A calibration system for wavelength calibration and flat fielding is provided. Accurate wavelength calibration will require use of telluric features.

iSHELL is operated with two GUIs in a manner identical to the IRTF's medium resolution spectrograph, SpeX. One GUI runs the spectrograph and the other the IR slit viewer. The GUIs can be run remotely by VNC.

3 Instrument Description

The cryostat is comprised of three sections: foreoptics, slit viewer and spectrograph (see Figure 1). A calibration unit containing integrating sphere, lamps and illumination optics is located on the top of the cryostat vacuum jacket. Like other IRTF instruments iSHELL is stowed on the back of the telescope and can be moved into position within about 20 minutes.

In the foreoptics the telescope focal plane (TFP) is re-imaged onto the slit. An image of the telescope secondary is formed on a cold stop located just in front of a K-mirror image rotator.

A circular 42 arcsec FOV is re-imaged onto a 512×512 Aladdin array in the slit viewer at 0.10 arcec/pixel. This FOV under fills the array. To limit aberrations in the spectrograph the beam speed into the slit is f/38.3 and so the FOV is limited by the practical size limit of the slit mirrors. The filters in the slit-viewer filter wheel are listed in Table 1.

The spectrograph is a white pupil design. The slits in the slit wheel are listed in Table 2. Slit length is set by a Dekker slide, which is located immediately behind the slit wheel (see Table 3). An order-sorting filter wheel follows the Dekker (see Table 4). From the slit the beam is collimated by an off-axis parabolic mirror (OAP) and the beam is dispersed at a 1.1-5.3 μm silicon immersion grating. Following recollimation at a second OAP the beam is cross dispersed (XD) at gratings housed in a turret wheel. Different XD gratings cover different wavelength ranges. A separate mechanism tilts the wheel to move orders up and down the array. The beam from the XD gratings is focused onto a 2048×2048 H2RG by a camera lens.

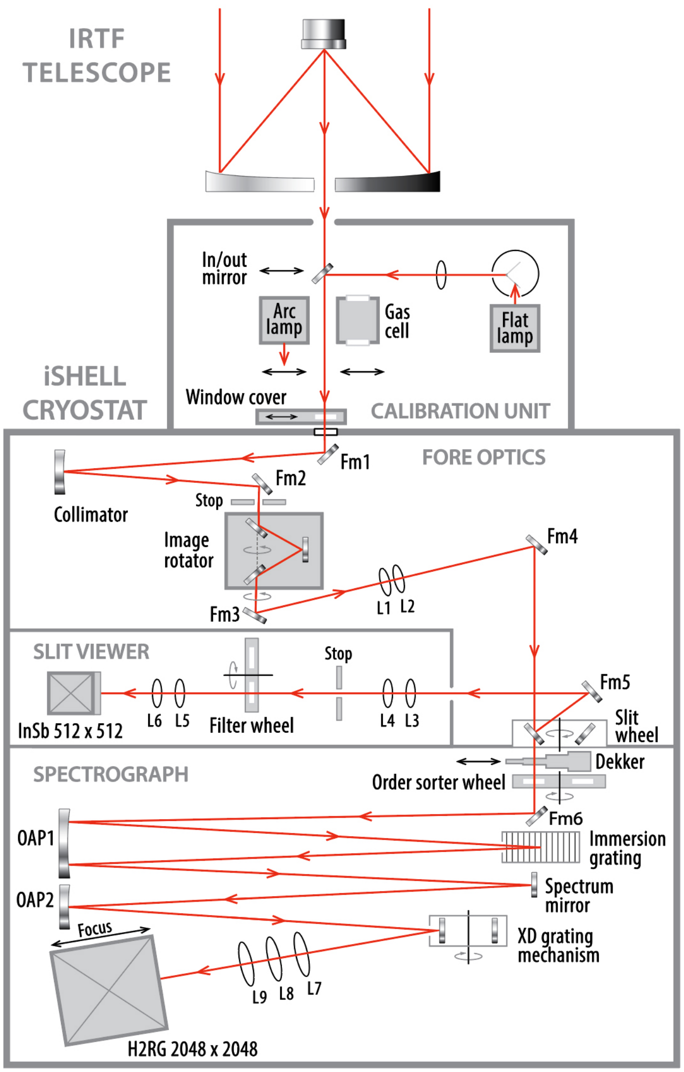

Figure 1. Schematic layout of iSHELL. The cryostat vacuum jacket contains the foreoptics, slit viewer and spectrograph. The calibration unit is warm and mounts to the top of the vacuum jacket.

Figures 2-8 show images of the XD spectral formats plotted across the free spectral range. The XD grating turret can be rotated to select one of the six available wavelength ranges (gratings *J*, *H*, *K*, *L, L'* and *M*) and the selected grating tilted to put the desired spectral orders on the array. Details of the XD gratings and the corresponding wavelength ranges and useable slit lengths are given in Table 5. Since the *M* band orders overfill the array two different XD gratings and two exposures are required for contiguous coverage (see Figure 8).

Table 1. Filters in the slit-viewer filter wheel.

Position #	*Filter*	*Notes*
0	K_{MK}	2.027-2.363 μm (guide)
1	J_{OS}	1.05-1.45 μm (guide)
2	Pupil Viewer lens +3.464 μm (5%)	Pupil diameter 325 pixels, spatial resolution 3.6 pixels (33 mm on primary)
3	Blank	
4	*nbM*	5.1 μm 2% (Orton Jupiter imaging)
5	3.464 μm	5% (H_3^+ acquisition)
6	L'_{MK}	3.424-4.124 μm (daytime comet acquisition)
7	continuum *K*	2.26 μm 1.5% (guide)

Table 2. Slit wheel

Position #	*Slit width*
0	**4.0″**
1	**Mirror**
2	**0.375″**
2	**0.75″**
3	**1.50″**

Table 3. Slit Dekker slide

Position #	*Slit length*	*Notes*
0	**5.0″**	2.79 mm long
1	**15.0″**	8.36 mm long
2	**25.0″**	13.93 mm long

Table 4. Order sorter filter wheel

Position #	*Name*	*Filter*
0	**Blank**	Blank
1	**Blank**	Blank
2	**Blank**	Blank
3	J_{OS}	1.05-1.45 μm
4	H_{OS}	1.40-1.90 μm
5	K_{OS}	1.80-2.60 μm
6	L_{OS}	2.70-4.20 μm
7	M_{OS}	4.50-5.50 μm

Table 5. List of cross dispersers and spectral formats available in iSHELL. The actual wavelength ranges are accurate to within about one order. See also Figures 2 to 8.

Mode	*Wavelength coverage (μm)*	*Order Sorter*	*XD tilt (degrees)*	*Slit length (arcsec)*	*XD (line/mm)*	*Blaze wavel. (μm)*	*Blaze angle (deg.)*	*Orders Covered (approx.)*
J1	1.11-1.22	J_{OS}	53.8	5.0	1200	1.10	41.3	481-436
J2	1.20-1.30	J_{OS}	58.3	5.0	1200	1.10	41.3	442-405
J3	1.27-1.36	J_{OS}	61.8	5.0	1200	1.10	41.3	416-386
H1	1.48-1.67	H_{OS}	44.0	5.0	720	1.90	43.1	354-314
H2	1.55-1.74	H_{OS}	45.7	5.0	720	1.90	43.1	338-300
H3	1.64-1.82	H_{OS}	48.1	5.0	720	1.90	43.1	319-287
K1	1.94-2.23	K_{OS}	40.5	5.0	497	2.25	34.0	268-232
K2	2.09-2.38	K_{OS}	43.0	5.0	497	2.25	34.0	249-219
K3	2.26-2.55	K_{OS}	45.9	5.0	497	2.25	34.0	230-205
Kgas	2.18-2.47	K_{OS}	44.5	5.0	497	2.25	34.0	240-212
L1	2.74-3.02	L_{OS}	50.0	15.0	450	3.10	45.0	189-172
L2	2.96-3.24	L_{OS}	53.9	15.0	450	3.10	45.0	175-160
L3	3.20-3.48	L_{OS}	58.5	15.0	450	3.10	45.0	161-149
Lp1	3.28-3.66	L_{OS}	48.0	15.0	360	3.70	42.0	158-142
Lp2	3.57-3.95	L_{OS}	52.3	15.0	360	3.70	42.0	144-132
Lp3	3.83-4.18	L_{OS}	52.3	15.0	360	3.70	42.0	135-125
Lp4	3.83-4.14	L_{OS}	55.7	25.0	360	3.70	42.0	133-125
M1	4.52-5.25 s	M_{OS}	40.4	15.0	210	5.0	31.7	113-98
M2	4.52-5.25 l	M_{OS}	40.4	15.0	210	5.0	31.7	113-98

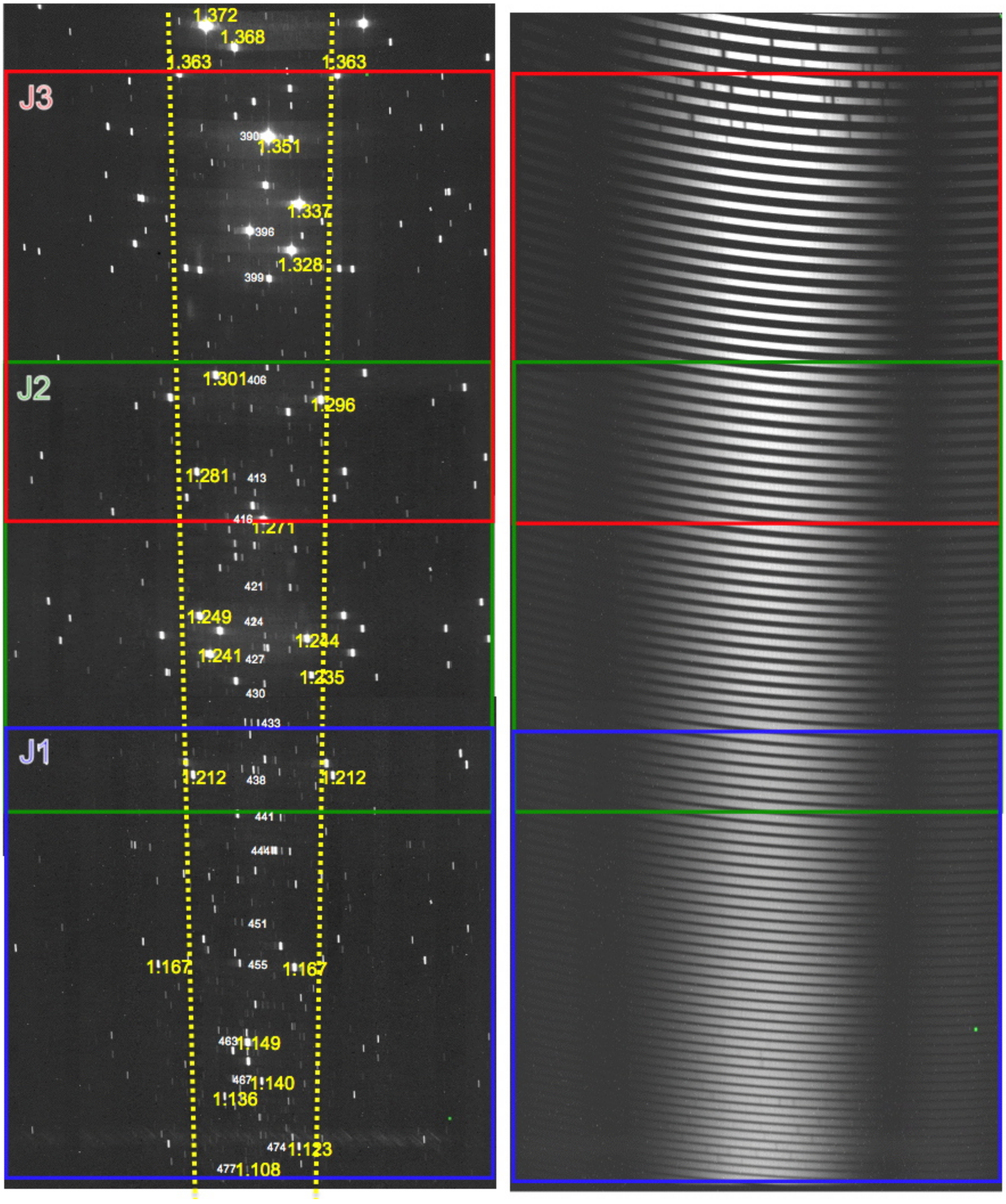

Figure 2. The J1 (blue), J2 (green) and J3 (red) exposures (see Table 5), slit length 5″, 1200 line per mm grating. ThAr lamp (left) and QTH lamp flat fields (right). The free spectral range (FSR) is shown (yellow).

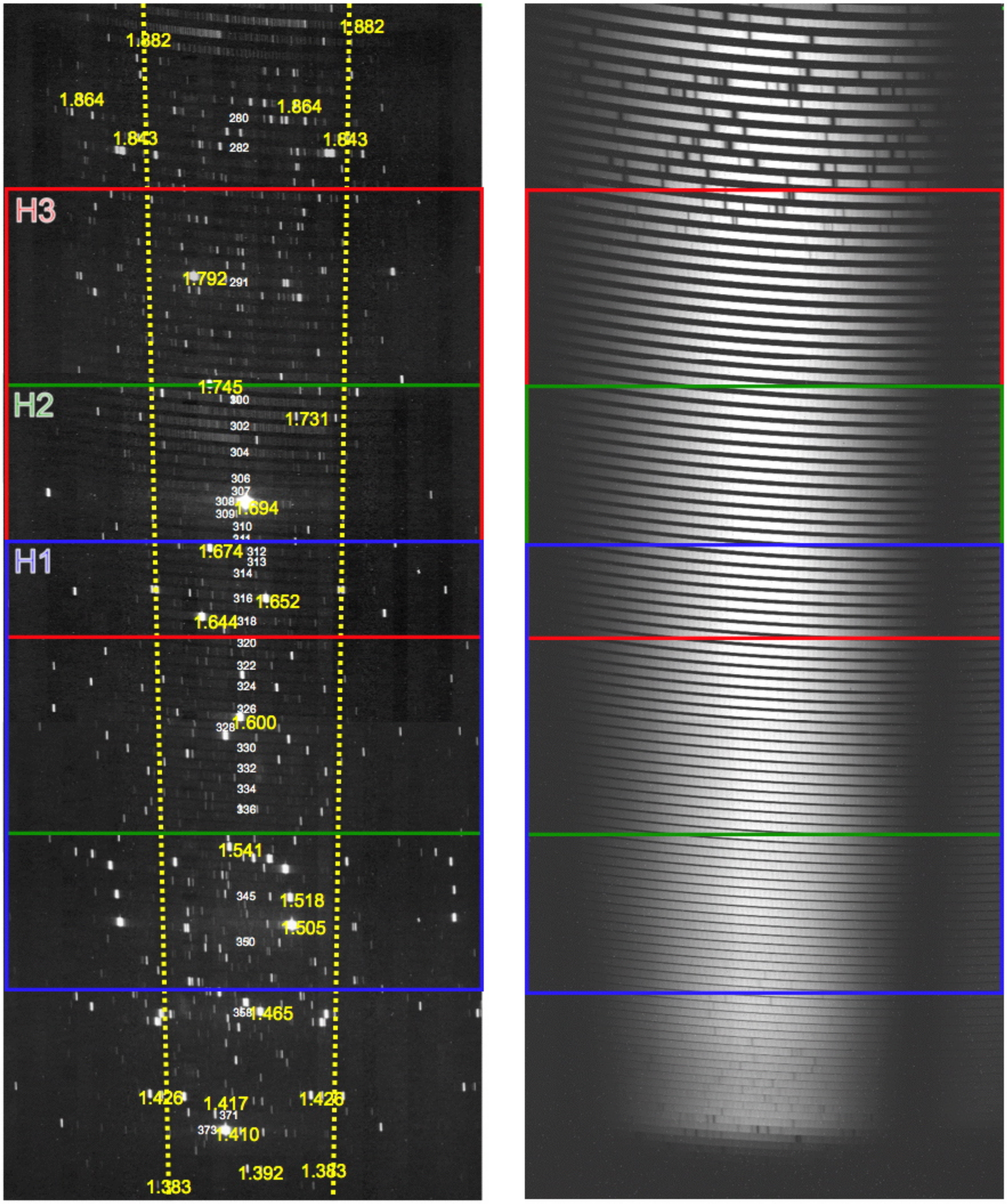

Figure 3. The H1 (blue), H2 (green) and H3 (red) exposures (see Table 5), slit length 5″, 720 line per mm grating. ThAr lamp (left) and QTH lamp flat fields (right). The free spectral range (FSR) is shown (yellow).

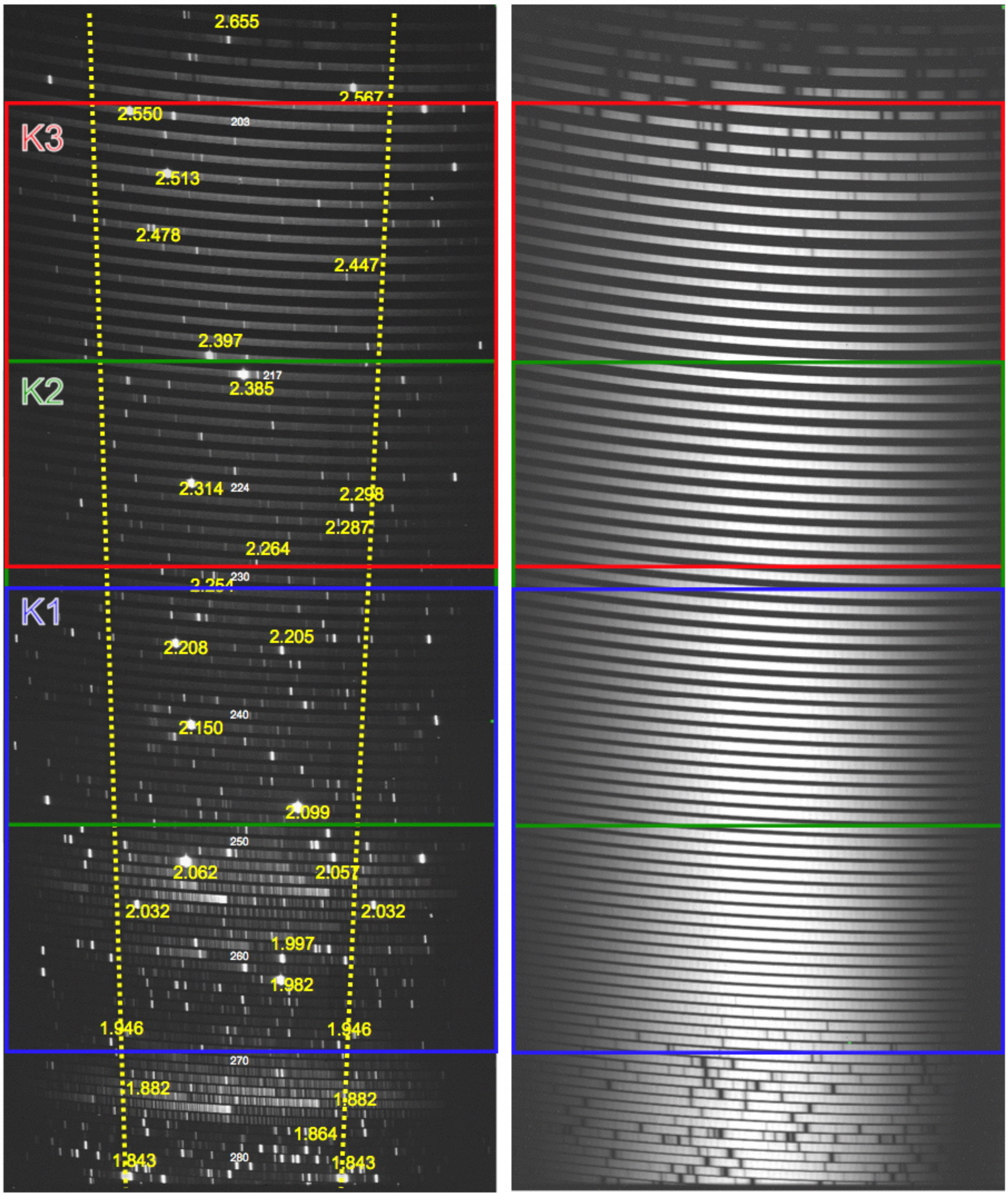

Figure 4. The K1 (blue), K2 (green) and K3 (red) exposures (see Table 5), slit length 5″, 497 line per mm grating. ThAr lamp (left) and QTH lamp flat fields (right). The free spectral range (FSR) is shown (yellow).

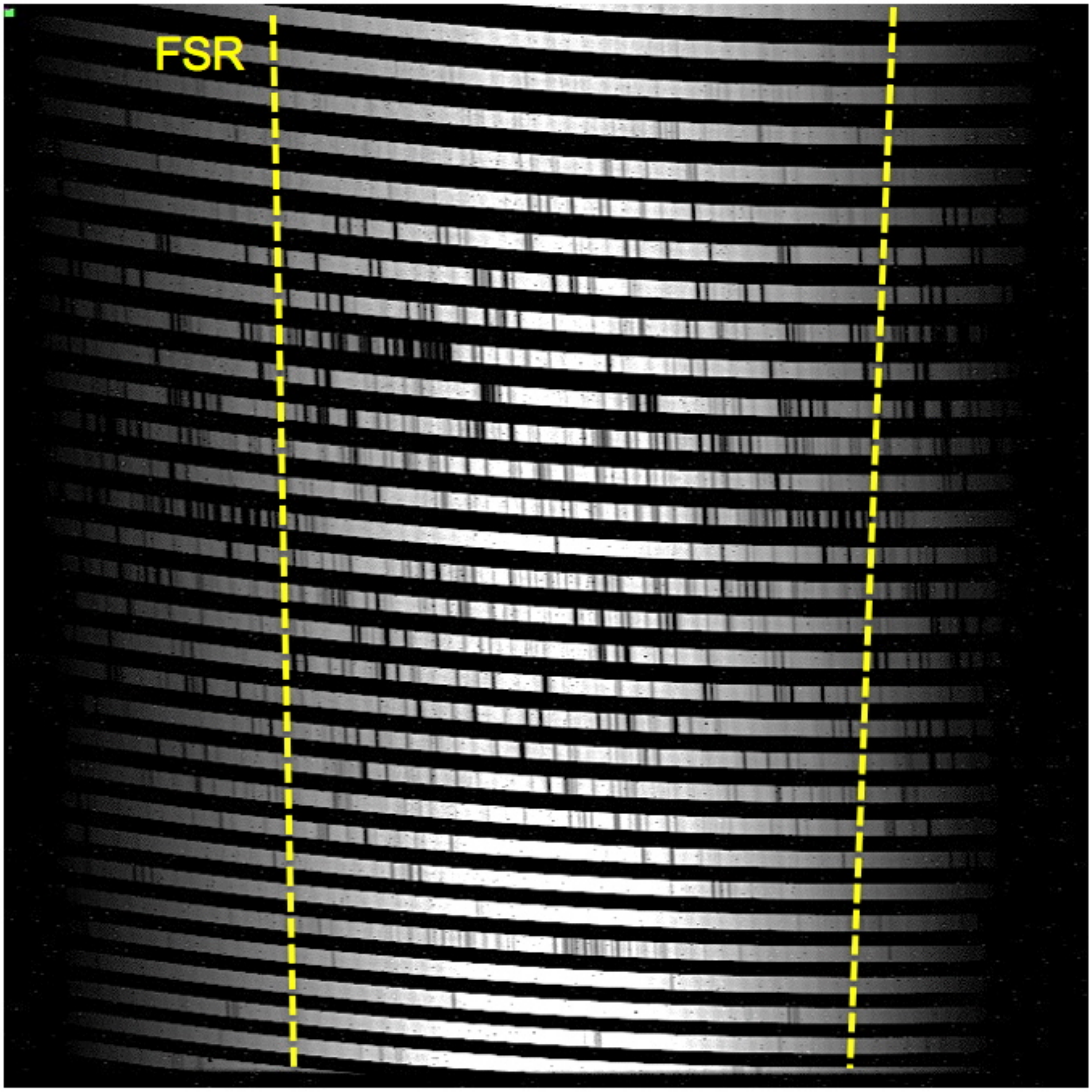

Figure 5. The K_{gas} exposure (2.18-2.47 µm, mid-way between K2 and K3), slit length 5″, 497 line per mm grating. In this exposure the $^{13}CH_4$ gas cell is placed over the cryostat window and backlit by the QTH lamp. The free spectral range (FSR) is shown (yellow).

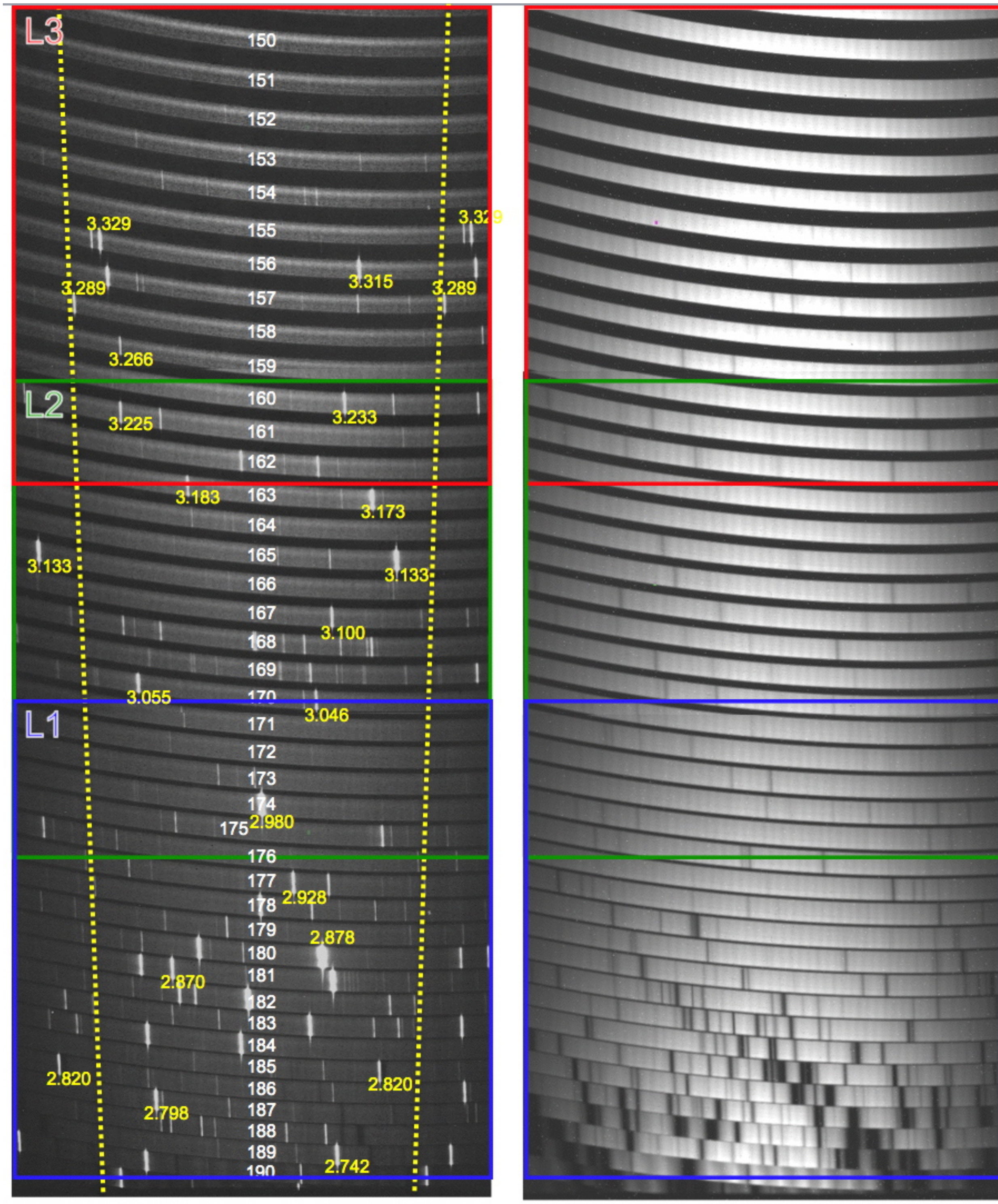

Figure 6. The L1 (blue), L2 (green) and L3 (red) exposures (see Table 5), slit length 15″, 450 line per mm grating. ThAr lamp (left) and black body lamp (1100K) flat fields (right). The free spectral range (FSR) is shown (yellow).

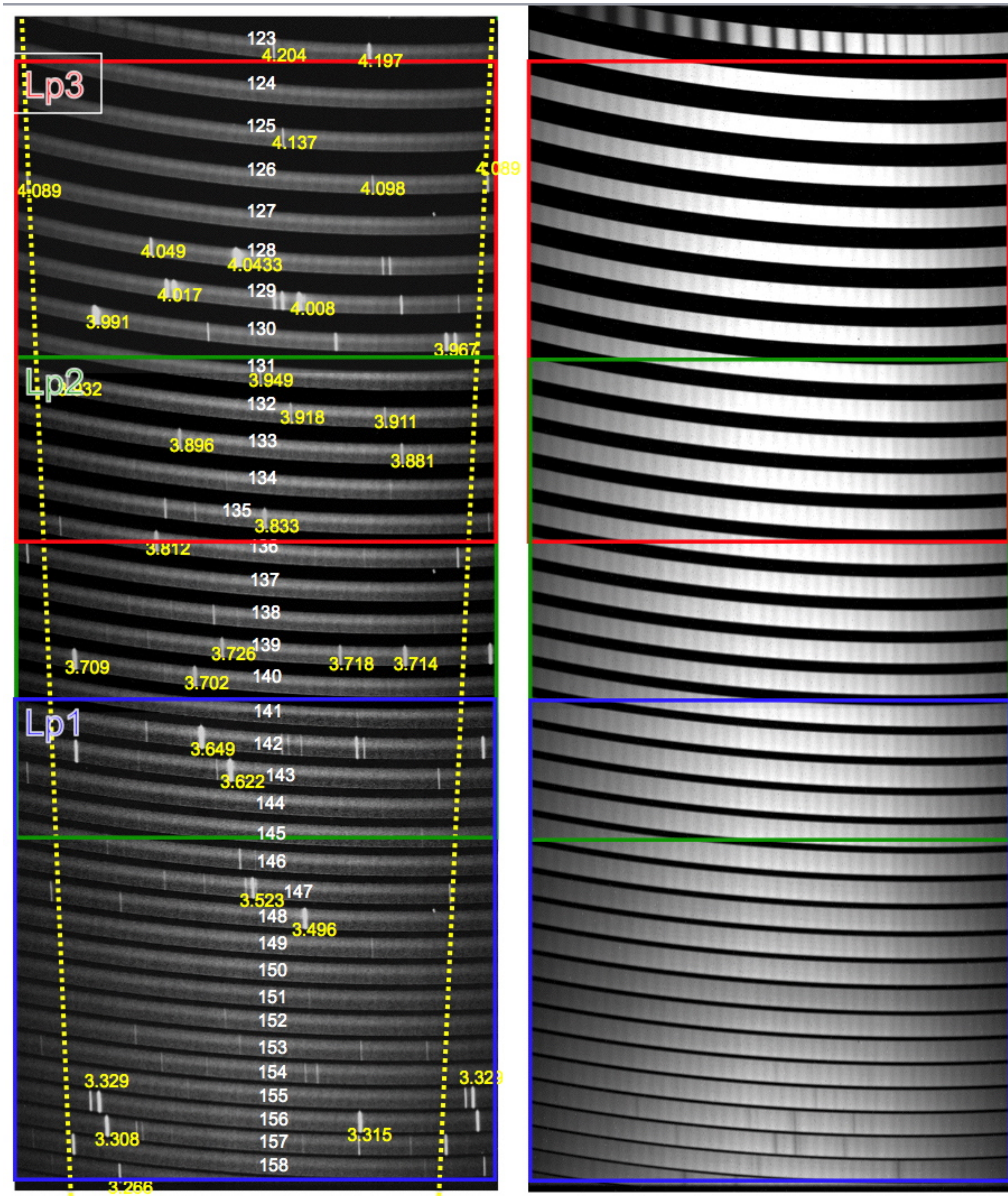

Figure 7. The Lp1 (blue), Lp2 (green) and Lp3 (red) exposures (see Table 5), slit length 15″, 360 line per mm grating. ThAr lamp (left) and black body lamp (1100K) flat fields (right). The free spectral range (FSR) is shown (yellow).

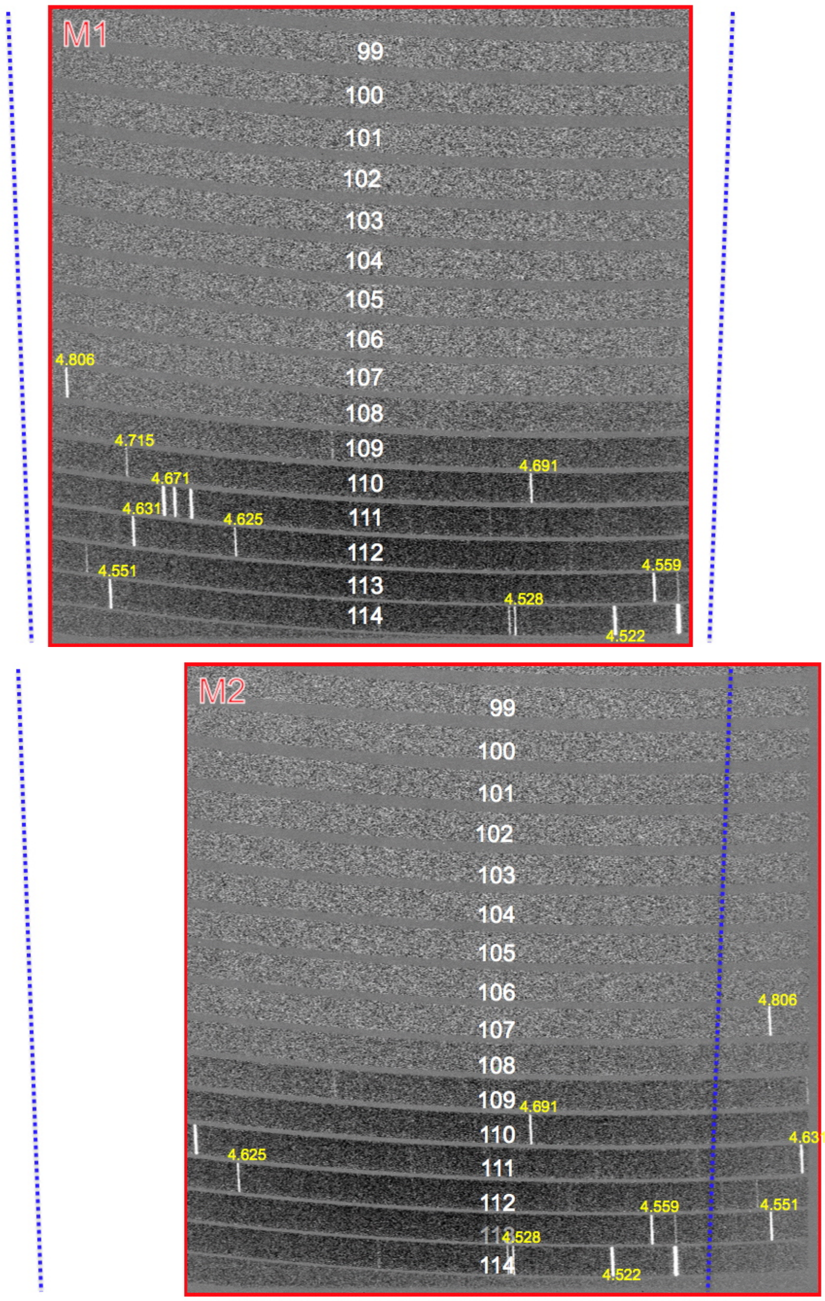

Figure 8. The M1 and M2 settings, slit length 15″, 210 line per mm grating. ThAr lamp (left) and black body lamp (1100K) flat fields (right). The free spectral range (FSR) is shown (blue).

4 Spectrograph Array

Performance parameters of the H2RG array in the spectrograph are given in Table 6.

Table 6. Spectrograph H2RG array

Parameter	***H2RG design***	***H2RG measured***	***Note***
Format	2048x2048		
Wavelength range	1.15-5.3 μm	1.1-5.3 μm	Short wavelength is limited by absorption in Si immersion grating
Slit width	0.375″, 0.75″, 1.50″, 4.00″		3 pixel slit width for 0.375″
Slit length *J , H, K* *L, Lp, M* *Lp*4	5″ 15″ 25″		
Gain	1.5 e/DN	1.8 e/DN	Varies slightly with individual array gain (TIG)
Read Noise NDRs =1 NDRs=32	12 e RMS 5 e RMS	10 e RMS (30 ch.) 23 e RMS (2 ch.) 4 e RMS (30 ch.) 8 e RMS (2 ch.)	The array is read out in 32 channels (stripes) each 64 pixels wide
Dark current + Instrument background	<0.1 e/s	0.05 e/s median	At 0.312 V bias when stable
Total Well depth	>50,000 e	71,000 e	At 0.312 V bias
Throughput 1.25 μm 1.65 μm 2.20 μm 3.60 μm 4.80 μm	0.08 0.16 0.18 0.17 0.16	0.05 0.15 0.18 0.22	A0V star measured through 4.0″ wide slit in photometric conditions

4.1 Testing for correct exposure level

An important feature of array operation is the need to keep exposure levels below the intensity level that can be reasonably corrected (to 1% or better) for non-linearity. This level is about 30,000 DN (three-quarters full well, gain 1.8 e/DN). When multiple non-destructive reads are done to reduce read noise, as is the default, DV displays the average of the NDRs and so half the NDRs will be above the average intensity level by an amount depending upon photon rate from the object. **We therefore recommend that observers measure the maximum signal rate with a short integration (≤10 s) with NDR=1 and then use the following formula to set the '*itime*' (in seconds):**

$$itime = \frac{30{,}000}{2 \times rate} - 0.5$$

Where *itime* is in seconds and *rate* is in DN/s. To measure the *rate* set the *itime* manually and then click the '*Test Go*' button. This will turn save off, put the telescope beam in position A, set NDRs to one, take an image and then restore the original set up. Finally, measure the *rate* using the maximum level reported in DV (avoiding hot pixels and scaling to one second), and adjust the *itime*. Observers can always use shorter *itimes* appropriate to their S/N requirements. For faint objects we do not recommend *itimes* longer than about 600 seconds even if the *rate* measurement allows it. Also, due array clocking *itimes* round down to the nearest multiple of 0.463 s (the minimum full array read out time).

The full array read out time of 0.463 s is the time required for one NDR. By default the array does as many NDRs as possible up to a maximum of 32. For example, for an *itime* of 9.26 s ten NDRs will be done (9.26/0.463 = 10), reducing the read noise by about $10^{1/2}$. Since there is little improvement in read noise above 32 NDRs *itimes* longer than 14.82 s default to 32 NDRs. The penalty paid for doing multiple NDRs is an increase in the time required by *0.461 s × the number of NDRs*. To increase observing efficiency observers can choose to reduce NDRs manually. Using shorter exposures and coadding (e.g. for M-band observations) can significantly increase read out overheads.

4.2 Observing efficiency

Tables 9-12 estimate the integration time required to reach a desired S/N but do not estimate the clock time, which includes a number of observing overheads. By default iSHELL does the maximum number of NDRs that it can fit into a given on-chip integration time (*itime*) up to a maximum of 32, to minimize read noise. Each NDR takes an additional 0.464 s. The total number of reads per *itime* is NDRs × coadds. NDRs × coadds is defined as the DIVISOR keyword in the header. (Note that in DV the displayed flux is scaled to the itime by dividing the summed flux by the DIVISOR. This is not done automatically when displaying stored fits data in IDL or IRAF, for example. To reproduce the DV display the data must first be divided by the DIVISOR). For example, 21 NDRs can be done in an on-chip integration time of 9.7 s and so with the default number of NDRs selected a 9.7 s on-chip integration time actually takes about 9.744 s + 21x0.464 s or 19.488 s in clock time. If the user chooses to do only one NDR then the same integration times takes 9.744 s but with higher read noise. Coadding images is also less efficient than one long integration time but is often required when short on-chip integration times are required to avoid saturation or to reduce the number of nods. Additional overhead is also needed to display and store data. Table 7 is a guide to observing with different combinations of integration times, NDRs and coadds.

Table 7. Measured clock time for typical combinations of itime, NDRs and coadds.

itime (s)	*coadds*	*NDRs*	*Total itime (s)*	*Clock time (s)*
Default number of NDRs				
1	30	2	30	71
3	10	3	30	63
10	3	21	30	62
15	2	32	30	62
30	1	32	30	47
60	1	32	60	77
120	1	32	120	137
NDRs manually set to 1				
1	30	1	30	58
3	10	1	30	39
10	3	1	30	34
15	2	1	30	33
30	1	1	30	33
60	1	1	60	63
120	1	1	120	123

Clearly, executing the default number of NDRs can sometimes double the effective integration time. Other overheads included in Table 6 are the times taken to display and store data. One overhead not included is the beam switch dead time (*Beam DTime* in the XUI). This is the wait time between nodding the telescope and restarting spectrograph integrations when performing cycles. This wait time allows time for the telescope to nod and for the guider to then lock onto the guide star before resuming spectrograph integrations. The default is five seconds but can be set by an observer.

A particular example is observing at M1 and M2 with iSHELL and a 0.375″ slit. In good sky conditions the *itime* needs to limited to a maximum of about 15 s to keep signal (which is typically dominated by sky background) within the linear correctable range. For good sky subtraction the telescope needs to be nodded roughly every 30 s. A typical observing sequence might be *itime*=15.0 s, coadds=2, AB *cycles*=15. Other overheads in include the time required to nod the telescope and settle (beam switch dead-time *DTime*=5.0 s) and the time required to display the data and write to disk (about 5 s). Using the default number of NDRs (32 for 15 s) the clock time required for this observation sequence is about 34 minutes. However, observations in the M-band are strongly background limited so NDRs can be manually set to one without any read noise penalty. In this case the clock time required is about 19 minutes, saving 15 minutes of clock time.

4.3 Spectrograph S/N widget in DV

The S/N widget estimates the S/N per resolution element (i.e slit width). The S/N per pixel column is roughly S/N / (slit width in pixels)$^{1/2}$ when sky background or signal limited, or S/N / (slit width in pixels) when read noise limited.

4.3.1 L, Lp and M modes

In these modes the star is nodded along the 15″-long slit and the A-B beam is displayed in DV buffer C. The cursor *Pointer* is displayed in buffer C and the cursor moved over the desired location of the spectrum in buffer C. The S/N is then displayed in buffer D along with the location of the pseudo box placement (see Figure 9). Signal is measured in an object box 14 pixels long (1.75″) and the same width as the slit. The signal in a skybox is measured at the same location in the B beam. To allow for variations in the sky background level affecting the A-B subtraction the summed signal in two boxes each 7 pixels long and the same width as the slit on either side of the object box are subtracted from the summed object box signal.

The signal-to-noise is given by:

$$\frac{S}{N} = \frac{G(objectbox - sidebox)}{(G\times(objectbox - sidebox) + G\times skybox\ + 14 \times slitwidth \times RN)^{1/2}}$$

Where the gain G=1.8 e/DN and read noise RN=7 e RMS (conservative estimate).

4.3.2 J, H and K modes

In these modes the slit length of 5″ is too short for nodding. However, nodding is not required since at iSHELL resolving powers the sky background is almost negligible. The cursor *Pointer* is displayed in buffer A and the cursor moved over the desired location of the spectrum in buffer A. The S/N is then displayed in buffer D along with the location of the pseudo box placement (see Figure 9). Signal is measured in an object box 14 pixels long (1.75″) and the same width as the slit. To allow for small variations in the sky background level affecting the A frame (e.g. unsubtracted sky lines) the summed signal in two boxes each 7 pixels long and the same width as the slit on either side of the object box are subtracted from the summed object box signal.

The signal-to-noise is given by:

$$\frac{S}{N} = \frac{G(objectbox - sidebox)}{(G\times(objectbox - sidebox) + 14 \times slitwidth \times RN)^{1/2}}$$

Where the gain G=1.8 e/DN and read noise RN=7 e RMS (conservative estimate).

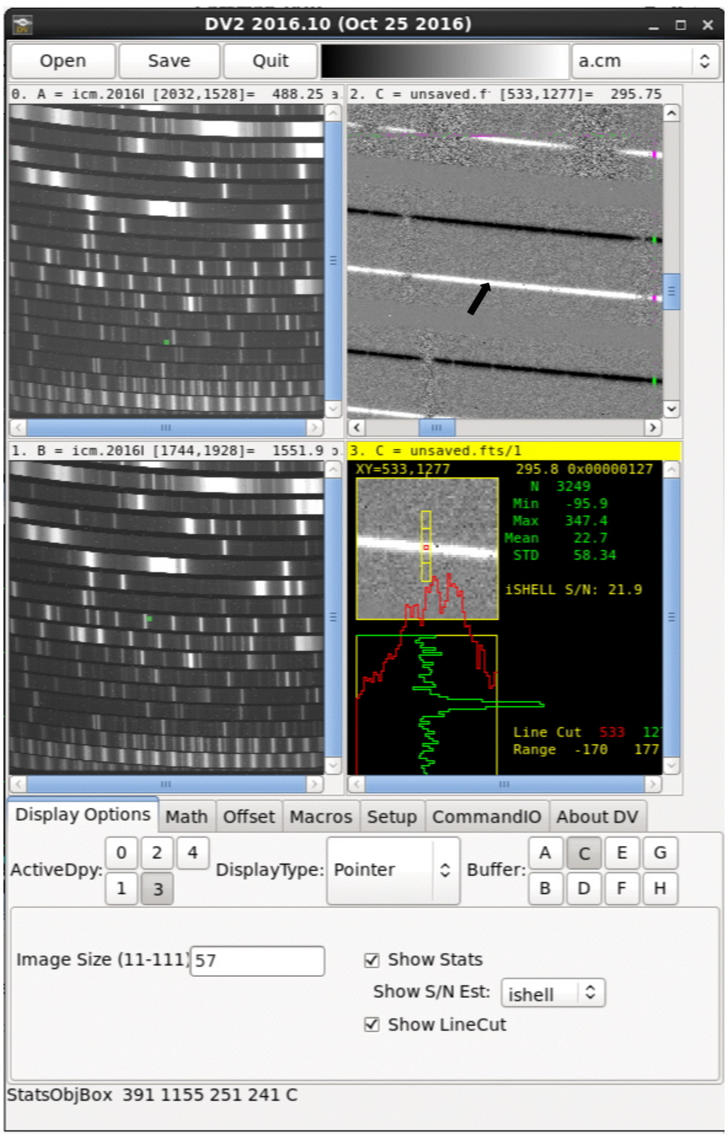

Figure 9. Signal-to-noise widget in DV. The pointer is selected in display 3 and moved over the spectrum in buffer C (A-B) (*LLpM* modes) or buffer A (*JHK* modes). The widget only works for point sources. Select for iSHELL in the lower right of DV. A zoomed section of buffer C (*M*1 spectral mode) is displayed in this view

5 Infrared Guider Array

Performance parameters of the Aladdin 2 InSb array in the guider are given in Table 8.

Table 8.

Parameter	***SpeX***	***iSHELL***	***Note***
Format	512x512	512x512	SpeX uses one quadrant of a 1024x1024 four quadrant Aladdin 3 array
Wavelength range	0.9-5.5 μm	0.9-5.5 μm	
FOV	60x60″	42″ diameter	iSHELL FOV underfills array
Sub-array read out	pending	pending	2017
Image scale	0.1185″/pixel	0.1040±0.007″/pixel	Measured
Gain	17 e/DN	17 e/DN	
Read Noise NDRs=1 NDRs=16	94 e RMS 34e RMS	110 e RMS 45 e RMS	At 7μs/pixel (0.241 s min. itime)
Dark current + instrument background	6 e/s	10 e/s	At 0.400 V bias when stable
Well depth	90,000 e	90,000 e	At 0.400 V bias
Throughput J K	0.18 0.25	0.17 0.33	UKIRT FS 151 *K*=11.87 *J-H*=0.274 *H-K*=0.061

5.1 Testing for correct exposure level

The full well depth on the 512x512 InSb Aladdin 2 array in the guider is 6000 DN (gain 15 e/DN). To keep in the linear range counts should be kept below about 3000 DN. Since fewer NDRs are done with the imaging array (the maximum is 8 NDRs) than the spectrograph array the signal level can be measured directly from the image in DV without the need for a test exposure. Guiding also works well on saturated images.

The full array read out time of 0.241 s is the time required for one NDR. *itimes* round down to the nearest multiple of 0.241 s (the minimum full array read out time). By default the array does as many NDRs as possible up to a maximum of 8. For example, for an *itime* of 1.205 s five NDRs will be done (1.205/0.241 = 5), reducing the read noise by about $10^{1/2}$. Since there is little improvement in read noise above 8 NDRs *itimes* longer than 1.928 s default to 8 NDRs. We plan to implement sub-array readouts by 2017.

5.2 Observing efficiency

The penalty paid for doing multiple NDRs is an increase in the time required by *0.241 s × the number of NDRs*. To increase observing efficiency observers can choose to reduce NDRs manually. For example an itime of 1.928 s with default NDRs (8) is only 50% efficient.

6 Data size, transfer and storage

For the 2048x2048 H2RG array in the spectrograph the individual file size is 16.8MB. However, we store three files per image: pedestal minus signal, pedestal, and signal, for a of total image size of 50MB. The reason for the extra files, which are stored as extensions to each image, is to more accurately compute corrections for non-linearity using the absolute pedestal and signal levels rather than the relative pedestal minus signal level. For the active 512x512 quadrant of the InSb Aladdin 3 array in the infrared guider the individual file size is 1 MB. Only the pedestal minus read is stored.

The best way get your data is to download it to your home machine from the IRTF data disk by sftp (rsync is also available). Ask your support astronomer for details. Long-time observers should also note that spectrograph images require ten times more disk space to store and take about ten times longer to ftp than with the old SpeX 1024x1024 array images. iSHELL data is also archived.

7 Example Observing Sequence

The setup procedure for iSHELL is very similar to that for SpeX. A significant difference is that the slit length in iSHELL is only 5.0″ in the *JHK* modes compared to 15.0″ in SpeX and so point sources are not nodded along the slit. Instead a dark exposure of the same integration time is subtracted from the target exposure made in the center of the slit. The small sky background along the slit in these modes is fitted and subtracted in data reduction. At *LL′M* where the sky background is higher a 15.0″ slit allows point source to be nodded along the slit. Extended sources are nodded out of the slit if a sky exposure needs to be subtracted. A 25″ slit can be used at 3.8-4.2 μm (*Lp4*, see Table 5).

The details of spectral calibration are still being worked out, however, it is very likely that an A0V standard star will be required for telluric removal and for accurate wavelength calibration using telluric features. A tool to locate A0V stars can be found on the SpeX webpage. A Thorium-Argon lamp is used for first-order wavelength calibration but accurate wavelength calibration requires many more lines than are available (particularly at 3-5 μm). Telluric features provide these wavelength fiducials.

7.1 Set up spectrograph

The spectrograph GUI is shown in Figure 10.

1. Set wavelength range by selecting exposure setting (see Table 5) in the ***XD Tilt*** icon. This automatically sets the following mechanisms:
    a. ***Dekker*** (slit length)
    b. ***Order Sorter Filter Wheel*** (order sorting filter)
    c. ***XD Rotate*** (XD grating)
    d. ***XD Tilt*** (tilt of XD grating)
    e. ***Afocus*** (spectrograph focus)
2. Select the ***Slit*** width (this sets the spectrograph resolving power)

7.2 Set up slit viewer for target

This procedure is very similar to acquisition and guiding with SpeX (see SpeX manual on the IRTF website). The FOV and image scale of iSHELL are 42″ (circular) and 0.10″ per pixel. The FOV slightly under fills the array. The slit-viewer GUI is shown in Figure 11.

1. Slew telescope to target
2. Select guide filter in slit-viewer filter wheel ***Gflt***
3. Move ***Rotator*** to set desired position angle of slit on the sky. For point sources setting the position angle to the parallactic angle is optimum.
4. Take acquisition image and focus if required
5. If guiding on a point source target select ***Autoguidebox setup***
6. Move target into *Guidebox A* drawn in DV. Otherwise set up to guide on object in the FOV or with the telescope's off-axis guider (see SpeX manual). (Point sources can only be nodded along the slit in the *LLpM* modes (15.0″slit). In the *JHK* modes the target is positioned in the center of the slit (5.0″ slit)

7. Set integration time of guider and start guiding. Guiding is done by offsetting the telescope and so guide corrections more frequent than once per second are not possible; so don't set the integration time short.

7.3 Take spectra of target

1. Set integration time of spectrograph (see section 4.1) and start integrating
2. At end of integration stop guiding
3. Run calibration macro (arcs and flats). **This should be done at the target position**

7.4 Set up slit viewer for A0V standard star

1. Slew telescope to standard star
2. Select guide filter in slit-viewer filter wheel ***Gflt***
3. Move ***Rotator*** to the parallactic angle
4. Take acquisition image and focus if required
5. If guiding on a point source target select ***Autoguidebox setup***
6. Move target into *Guidebox A* drawn in DV. Otherwise set up to guide on object in the FOV or with the telescope's off-axis guider (see SpeX manual). (Point sources can only be nodded along the slit in the *LL′M* modes (15.0″slit). In the *JHK* modes the target is positioned in the center of the slit (5.0″ slit)
8. Set integration time of guider and start guiding. Guiding is done by offsetting the telescope and so guide corrections more frequent than once per second are not possible; so don't set the integration time short.

7.5 Take spectra of A0V standard star

1. Set integration time of spectrograph (see Section 4.1) and start integrating
2. At end of integration stop guiding

7.6 Take darks for JHK spectra

At a suitable time during the observing shift take dark/bias frames needed to subtract from *JHK* spectra.

1. Set integration time
2. Run dark macro
3. Repeat for different integration times

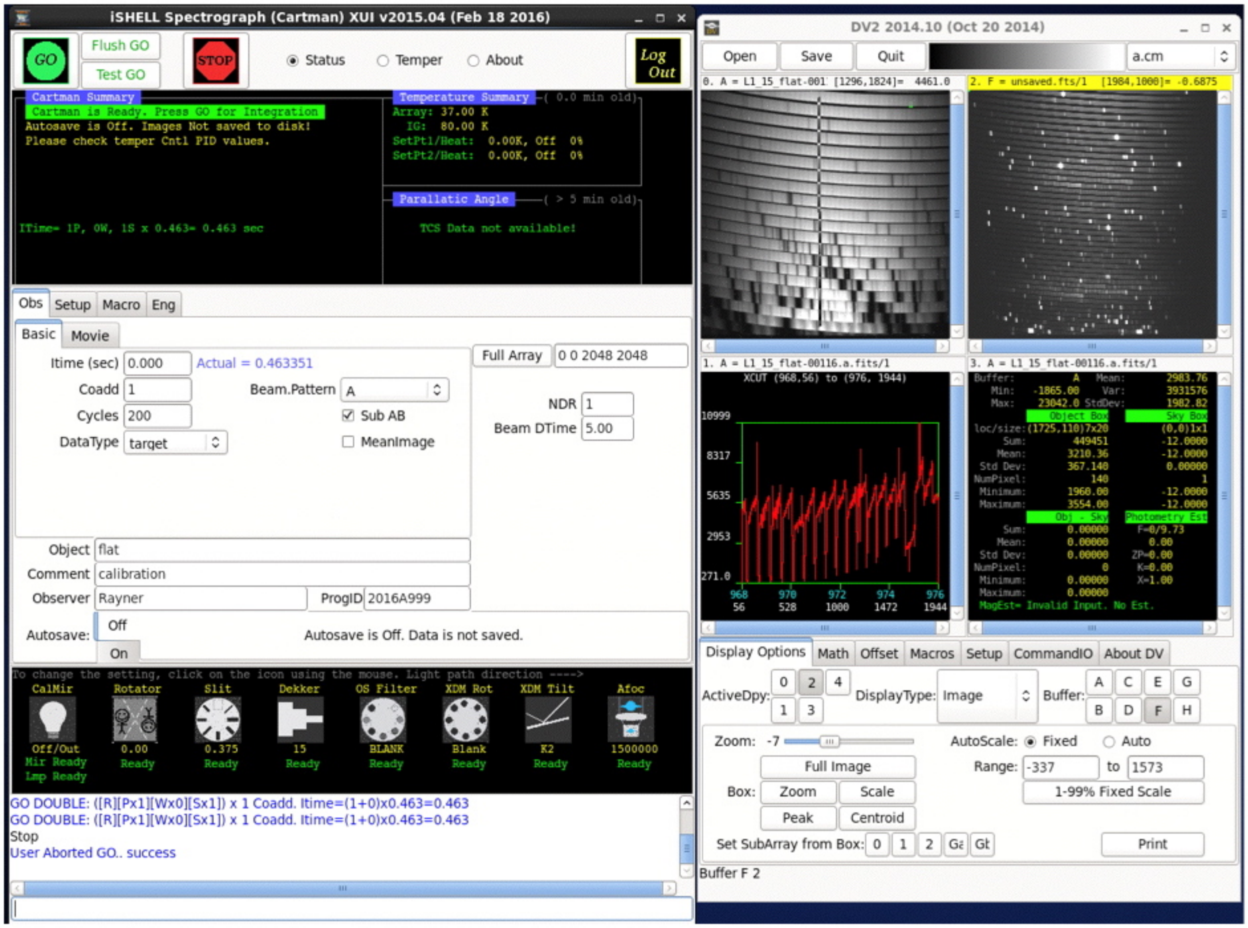

Figure 10. iSHELL spectrograph GUI.

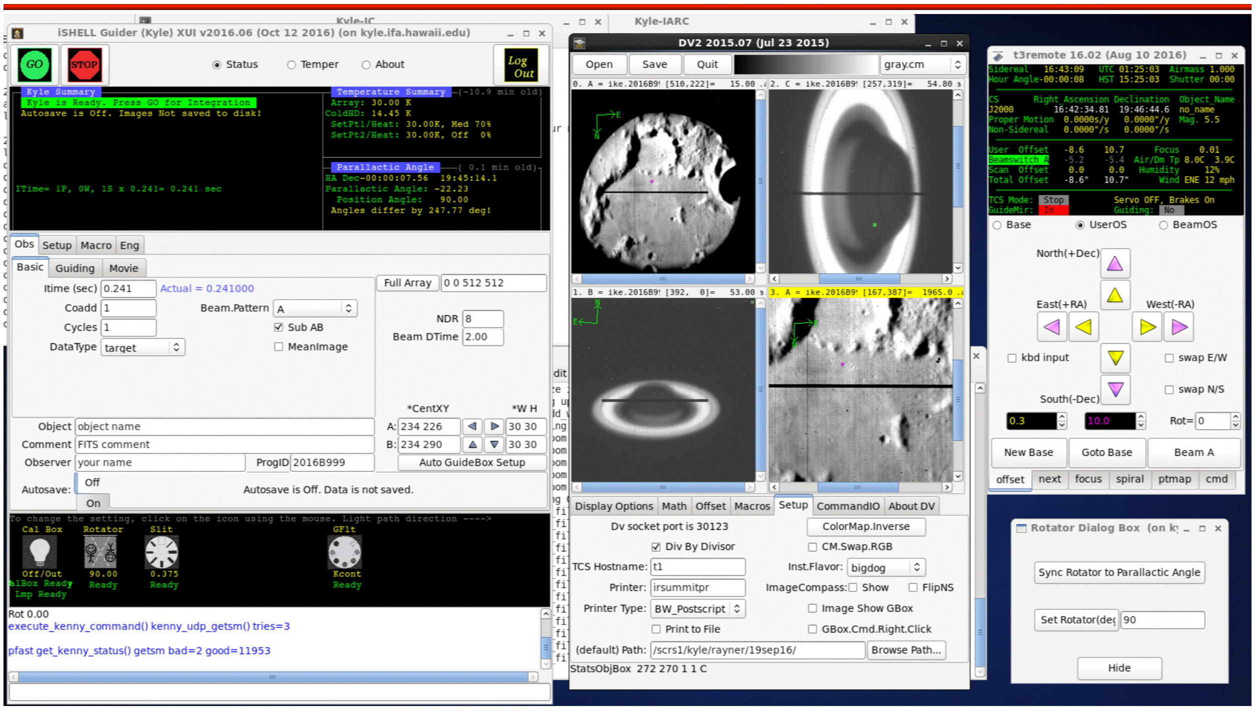

Figure 11. iSHELL infrared guider/slit viewer GUI. Real data is displayed (the moon in K_{cont} and Saturn in *K*). The 't3remote' panel to the right displays telescope information. Within t3remote the 'offset' panel can be used to offset the telescope and guide on objects too extended for auto-guiding.

7.7 *Sensitivity*

The instrument parameters used to estimate spectral sensitivity are given Table 9. Array performance and instrument throughput should be slightly better than used in the sensitivity model (discussed below).

Table 9. Instrument sensitivity parameters: spectrograph

Parameter	*iSHELL*
Resolving power (R)	70,000
Spectral sampling	3 pixels per slit width
Wavelength coverage	1.1-5.3 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 7)

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 (seeing plus diffraction) is about 0.7″ (see Figure 12).

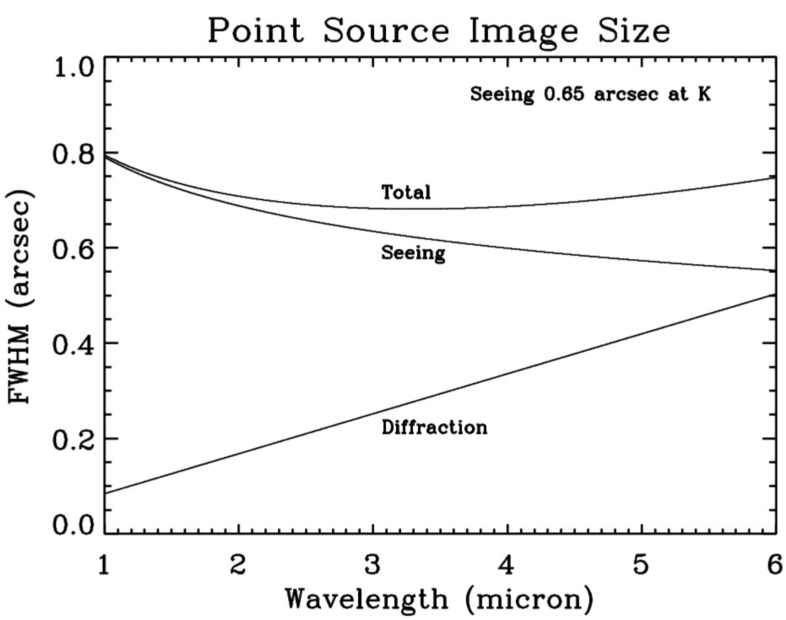

Figure 12. Point source image size

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=35,000) wide slits (see Figure 13). Imperfect guiding and focus will further reduce slit efficiency.

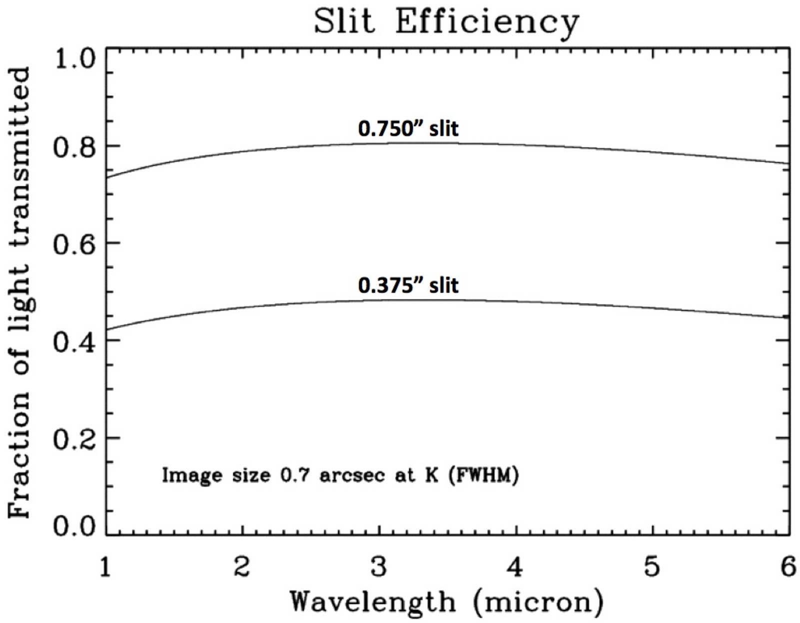

Figure 13. Slit efficiency

A conservative estimate of instrument throughput is used in the sensitivity calculation (see Table 10). The efficiency of the slit is not included in throughput estimates since it is dependent on image size (seeing etc.).

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).

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. The Hawaii-2RG detector in iSHELL sees an instrument background (including dark current) of about 0.1 e/s and achieves a read noise of about 5 e RMS with multiple non-destructive reads (NDRs). The quantum efficiency of the array averages about 85%. See Table 7 for details of H2RG array performance.

Table 10. iSHELL throughput estimates.

Element	*Efficiency*					*Notes*
	1.25μm	**1.65μm**	**2.20μm**	**3.60μm**	**4.80μm**	
Telescope						
Primary	0.98	0.98	0.98	0.98	0.98	Total measured emissivity 4%
Secondary	0.98	0.98	0.98	0.98	0.98	See above
Foreoptics						
CaF_2 window	0.94	0.95	0.95	0.95	0.95	BBAR witness sample
Fold mirror 1	0.96	0.96	0.96	0.96	0.98	Protected-silver, fold
Collimating mirror	0.98	0.98	0.98	0.98	0.98	Protected-silver
Fold mirror 2	0.96	0.96	0.96	0.96	0.98	Protected-silver, fold
Cold stop	0.95	0.95	0.95	0.95	0.95	Undersized to mask telescope
Rotator mirror 1	0.96	0.96	0.96	0.96	0.98	Protected-silver, fold
Rotator mirror 1	0.96	0.96	0.96	0.96	0.98	Protected-silver, fold
Rotator mirror 1	0.96	0.96	0.96	0.96	0.98	Protected-silver, fold
Fold mirror 3	0.96	0.96	0.96	0.96	0.98	Protected-silver, fold
Lens 1 (BaF_2)	0.93	0.95	0.96	0.96	0.95	BBAR witness sample
Lens 2 (LiF)	0.94	0.95	0.95	0.95	0.95	BBAR witness sample
Fold mirror 4	0.96	0.96	0.96	0.96	0.96	Protected-silver, fold
Total Foreoptics	**0.55**	**0.58**	**0.58**	**0.58**	**0.58**	
Slit viewer						
Slit mirror	0.97	0.97	0.97	0.97	0.97	Gold-coated CaF_2, fold
Fold mirror 5	0.96	0.96	0.96	0.96	0.96	Protected-silver, fold
Lens 3 (BaF_2)	0.93	0.95	0.96	0.96	0.95	BBAR coat est.
Lens 4 (LiF)	0.94	0.95	0.95	0.95	0.95	BBAR coat est.
Cold stop	1.00	1.00	1.00	1.00	1.00	Oversized
Filter	0.85	0.90	0.85	0.95	0.91	Measured average across range
Lens 5 (LiF)	0.94	0.95	0.95	0.95	0.95	BBAR witness sample
Lens 6 (BaF_2)	0.93	0.95	0.96	0.96	0.95	BBAR coat est.
Aladdin 2 array	0.85	0.85	0.85	0.85	0.85	Eng. array from SpeX est.
Total Slit Viewer	**0.48**	**0.52**	**0.53**	**0.53**	**0.53**	
Total FO + SV	**0.26**	**0.30**	**0.31**	**0.31**	**0.31**	
Spectrograph						
Slit substrate (CaF_2)	0.94	0.95	0.95	0.95	0.95	BBAR coat est.
Order sorting filter	0.85	0.90	0.90	0.95	0.91	Measured average across range
Fold mirror	0.96	0.96	0.96	0.96	0.96	Protected-silver, fold
OAP 1	0.98	0.98	0.98	0.98	0.98	Gold-coated aluminum
SIG - grating	0.75	0.75	0.75	0.75	0.75	Est. peak (measured at *H* and *K*)
SIG - substrate	0.75	0.95	0.96	0.95	0.98	BBAR coating (two surface transmission)
OAP 1	0.98	0.98	0.98	0.98	0.98	Gold-coated aluminum
Spectrum mirror	0.98	0.98	0.98	0.98	0.98	Protected-silver
OAP 2	0.98	0.98	0.98	0.98	0.98	Gold-coated aluminum
XD grating	0.60	0.65	0.70	0.65	0.65	Off-the-shelf replica gratings
Lens 1 (BaF_2)	0.93	0.95	0.96	0.96	0.95	BBAR witness sample
Lens 2 (ZnS)	0.96	0.98	0.98	0.99	0.99	BBAR witness sample
Lens 3 (LiF)	0.94	0.95	0.95	0.95	0.95	BBAR witness sample
H2RG QE	0.70	0.90	0.90	0.90	0.85	Teledyne measurements for iSHELL array
Total Spectrograph	0.14	0.28	0.31	0.30	0.28	At blaze peak/average across blaze
Total FO + Spectr.	**0.08**	**0.16**	**0.18**	**0.17**	**0.16**	**Predicted at blaze peak**
Total FO + Spectr.	**0.05**	**0.15**	**0.18**	**0.22**		**Measured on-sky at blaze peak**

7.7.1 Spectroscopy

The results of the sensitivity model for the spectrograph discussed above are tabulated in Table 11 (point source) and Table 12 (extended source). The sensitivity is per spectral resolution element (i.e. not per pixel).

Table 11. iSHELL one-hour (600 sec x 6 coadds) point-source sensitivity (read noise 5 e RMS, dark 0.1 e/s, seeing 0.7″, throughput 0.1 except 0.05 at *J*), sum rows 1.5 x seeing FWHM (arcsec) along slit.

R	S/N	Magnitude (Vega)					Line flux (erg s^{-1} cm^{-2})				
		J	*H*	*K*	*L*	M	*J*	*H*	*K*	*L*	*M*
75,000	**100**	9.7	9.9	9.5	7.4	5.0	7.3×10^{-15}	2.5×10^{-15}	1.8×10^{-15}	2.6×10^{-15}	1.2×10^{-14}
75,000	**10**	12.5	12.7	12.3	10.0	7.5	5.5×10^{-16}	1.9×10^{-16}	1.4×10^{-16}	2.4×10^{-16}	1.2×10^{-15}
37,500	**100**	10.5	10.9	10.5	8.3	5.9	7.3×10^{-15}	1.9×10^{-15}	1.4×10^{-15}	2.2×10^{-15}	1.0×10^{-14}
37,500	**10**	13.2	13.7	13.2	10.9	8.4	5.5×10^{-16}	1.6×10^{-16}	1.1×10^{-16}	2.0×10^{-16}	1.0×10^{-15}

Table 12. iSHELL one-hour (600 sec x 6 coadds) extended source sensitivity (read noise 5 e RMS, dark 0.1 e/s, seeing 0.7″, throughput 0.1 except 0.05 at *J*), sum rows 1.0″ along slit.

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*
75,000	**100**	9.7	9.8	9.4	7.2	4.9	6.9×10^{-15}	2.7×10^{-15}	2.0×10^{-15}	3.0×10^{-15}	1.4×10^{-14}
75,000	**10**	12.5	12.6	12.2	9.8	7.4	5.3×10^{-16}	2.1×10^{-16}	1.5×10^{-16}	2.7×10^{-16}	1.3×10^{-15}
37,500	**100**	10.5	11.0	10.6	8.4	6.0	6.9×10^{-15}	1.8×10^{-15}	1.3×10^{-15}	2.1×10^{-15}	9.7×10^{-15}
37,500	**10**	13.3	13.7	13.3	10.9	8.5	5.3×10^{-16}	1.5×10^{-16}	1.1×10^{-16}	2.0×10^{-16}	9.6×10^{-16}

Table 11 gives point-source sensitivity over a range of exposure times for R=70,000 (0.375″ slit) in mediocre seeing (1.0″ at *K*).

Table 11. Estimated point-source sensitivity for R=75,000 (0.375″ slit) at 100σ in mediocre seeing (1.0″ at K). To remove hot or noisy pixels requires about six or more median-combined spectral images. The ETC assumes a conservative throughput of 0.1 except 0.05 at *J*

Total exp. (sec)	*itime (sec)*	*number of coadds*	*Magnitude (Vega)*				
			J	*H*	*K*	*L*	*M*
0.5	0.5	1	0.4	0.7	0.4	-0.8	-1.5
10.0	10.0	1	3.6	4.0	3.6	2.4	1.1
60.0	10.0	6	5.2	5.5	5.1	3.9	2.2
60.0	60.0	1	5.6	5.9	5.5	4.1	2.3
300.0	60.0	5	6.9	7.3	6.9	5.3	3.2
300.0	300.0	1	7.2	7.5	7.1	5.4	3.2
600.0	120.0	5	7.6	8.0	7.6	5.8	3.6
600.0	600.0	1	7.9	8.2	7.8	5.8	3.6
1800.0	300.0	6	8.6	9.0	8.6	6.6	4.2
1800.0	1800.0	1	8.8	9.1	8.7	6.6	4.2
3600.0	600.0	6	9.2	9.5	9.2	7.0	4.6
3600.0	3600.0	1	9.3	9.7	9.3	7.0	4.6
7200.0	600.0	12	9.6	10.0	9.6	7.4	5.0
7200.0	7200.0	1	9.8	10.1	9.7	7.4	5.0

Table 14 gives point-source sensitivity over a range of exposure times for R=35,000 in (0.75″ slit) mediocre seeing (1.0″ at *K*).

Table 14. Estimated point-source sensitivity for R=35,000 (0.75″ slit) at 100σ in mediocre seeing (1.0″ at K). To remove hot or noisy pixels requires about six or more median-combined spectral images. The ETC assumes a conservative average throughput of 0.1 except 0.05 at *J*

Total exp. (sec)	*itime (sec)*	*number of coadds*	*Magnitude (Vega)*				
			J	*H*	*K*	*L*	*M*
0.5	0.5	1	1.1	2.0	1.6	0.5	-0.2
10.0	10.0	1	4.4	5.3	4.9	3.6	2.2
60.0	10.0	6	5.9	6.7	6.3	5.0	3.3
60.0	60.0	1	6.3	7.2	6.8	5.3	3.3
300.0	60.0	5	7.7	7.3	6.9	5.3	3.2
300.0	300.0	1	8.0	7.5	7.1	5.4	3.2
600.0	120.0	5	8.4	9.1	8.7	6.9	4.6
600.0	600.0	1	8.6	9.4	9.0	7.0	4.6
1800.0	300.0	6	9.4	10.1	9.7	7.6	5.2
1800.0	1800.0	1	9.5	10.3	9.9	7.6	5.2
3600.0	600.0	6	10.0	10.6	10.2	8.0	5.6
3600.0	3600.0	1	10.1	10.8	10.4	8.0	5.6
7200.0	600.0	12	10.4	11.1	10.7	8.4	6.0
7200.0	7200.0	1	10.6	11.2	10.8	8.4	6.0

Initial commissioning data indicates that sensitivity is roughly as predicted, except at J, where the absorptivity of the silicon substrate of the immersion grating increases and where the efficiency of the BBAR coat on the immersion grating could not be optimized.

7.7.2 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 uses the Aladdin 2 512x512 InSb array that was used in SpeX prior to its upgrade in 2014. 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 15.

Table 15. Slit viewer sensitivity 60s 10σ

Magnitude (Vega)		
J_{OS}	*K*	*L′*
18.0	16.6	11.7