SpeX OBSERVING MANUAL

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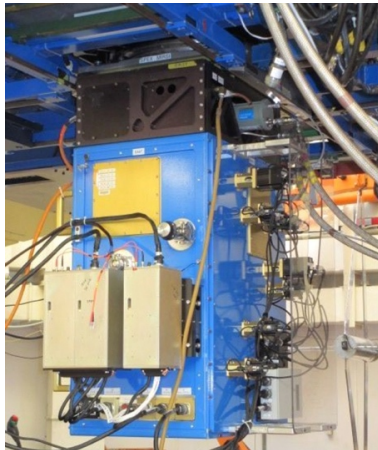
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Revision History

Revision No.	Author	Date	Description
Revision 1	John Rayner	29 Sept. 2014	First release
Revision 2	John Rayner	06 March 2015	Second release
Revision 3	Mike Connelley	30 Aug. 2017	Third release
Revision 4	Mike Connelley, John Rayner	20 Aug. 2020	Fourth release

Contents

1 INTRODUCTION

SpeX is a medium-resolution infrared spectrograph built at the Institute for Astronomy (IfA), for the NASA Infrared Telescope Facility (IRTF) on Mauna Kea. The National Science Foundation (NSF) originally funded SpeX in 1996 with additional funding from NASA for the detector arrays in 1998. SpeX saw first light in May 2000. NSF funded an instrument upgrade in 2008 but delays in procurement of a science grade H2RG array delayed completion until 2014. The primary reason for the upgrade was to replace obsolete array control and instrument control electronics although the opportunity was also taken to upgrade the arrays as well. The Raytheon Aladdin 3 1024x1024 InSb array in the spectrograph was replaced by a Teledyne 2048x2048 Hawaii-2RG array and the engineering grade Aladdin 2 512x512 InSb array in the IR slit viewer was replaced by the science grade Aladdin 3 array from the spectrograph (only a 512x512 quadrant is used). Astronomical Research Cameras, Inc. controllers run both arrays. Most of the warm electronic hardware was also replaced: motors, motor controllers, Hall effect sensor control, power supplies, computers and GUIs.

For most observing programs guiding is done with the IR slit viewer on spillover flux from the object in the slit. However, for optically visible objects selectable IR transmitting and visible reflecting dichroics in SpeX feed the MORIS CCD camera attached to the side of SpeX to enable guiding in the visible. MORIS is a collaboration between MIT and IRTF. It became an IRTF facility instrument in 2012. MORIS is also used as a scientific CCD imager and for simultaneous optical and IR observations in conjunction with SpeX. A schematic layout of the instrument is shown in Figure 1-1.

The upgrade has resulted in increased simultaneous (one shot) wavelength coverage in all spectral modes and improved spectral sensitivity (0.25-0.5 magnitudes depending on wavelength). Due to faster computers instrument control is more robust and there are fewer software problems.

The purpose of this document is to provide users with an operating manual for SpeX.

1.1 Abbreviations

|	
AR	Anti-reflection (coat)
ARC	Astronomical Research Cameras (array controller vendor)
BDV	Bigdog data viewer screen
BXUI	Bigdog X-windows user interface
DN	Data number (intensity display unit in DV)
DV	Data viewer display
FITS	Flexible Image Transport System
FOV	Field of view
FWHM	Full width half maximum
GDV	Guidedog data viewer screen
GUI	Graphical user interface
GXUI	Guidedog X-windows user interface
H2RG	Hawaii-2RG detector array
IfA	Institute for Astronomy, University of Hawaii
IRTF	Infrared Telescope Facility
itime	On-chip integration time
LXD	Long wavelength cross-dispersed mode
MDV	MORIS data viewer
MORIS	MIT Optical Rapid Imaging System
MXUI	MORIS X-windows user interface
NDR	Non-destructive read
QE	Quantum efficiency
R	Resolving power ($\lambda/\Delta\lambda$)
RMS	Root mean squared
S/N	Signal (S) to noise (N) ratio
SV	Slit viewer
SXD	Short wavelength cross-dispersed mode
TCS	Telescope control system at IRTF
TO	Telescope operator
XD	Cross-dispersed/disperser
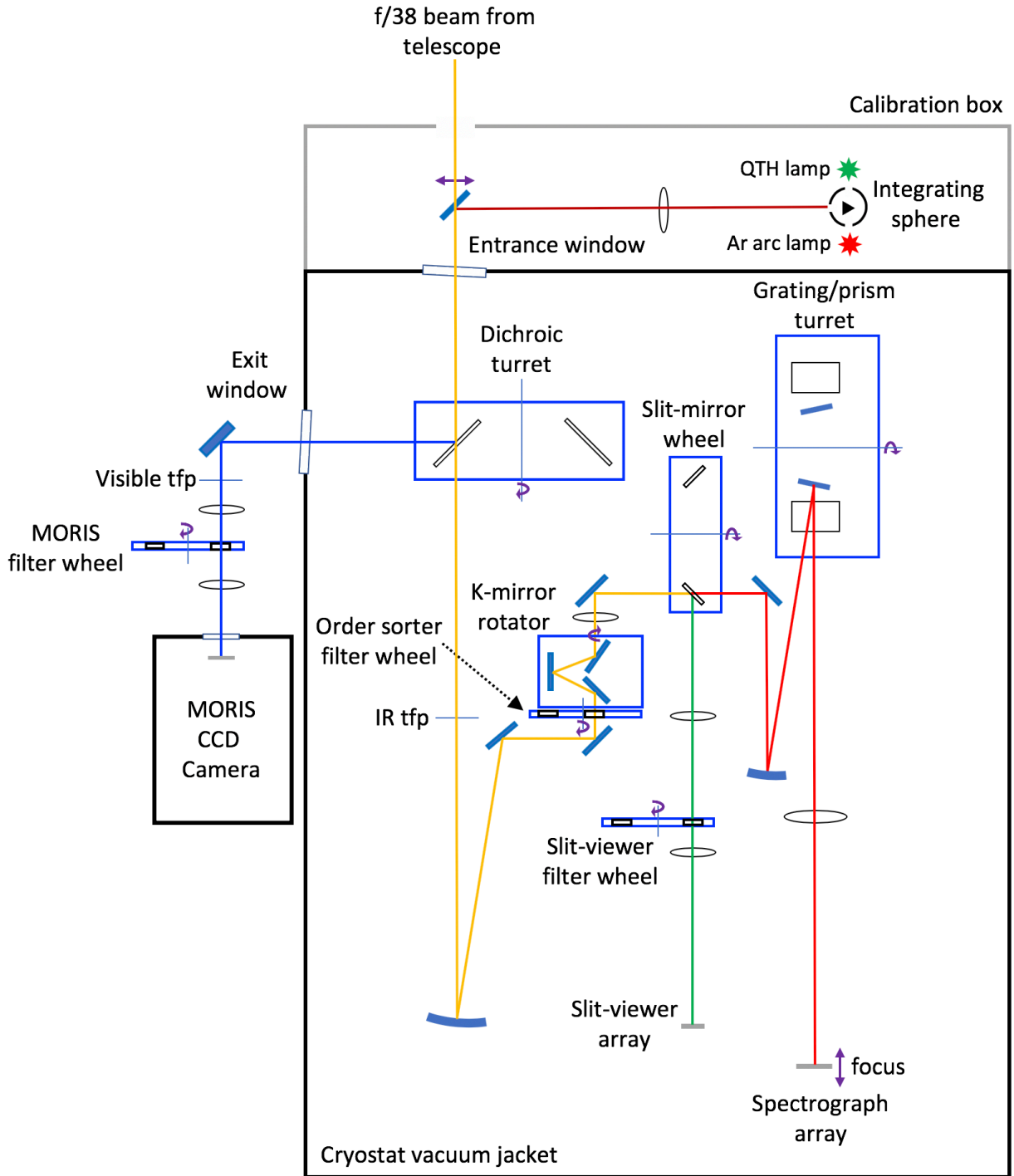
Figure 1-1. Instrument schematic layout
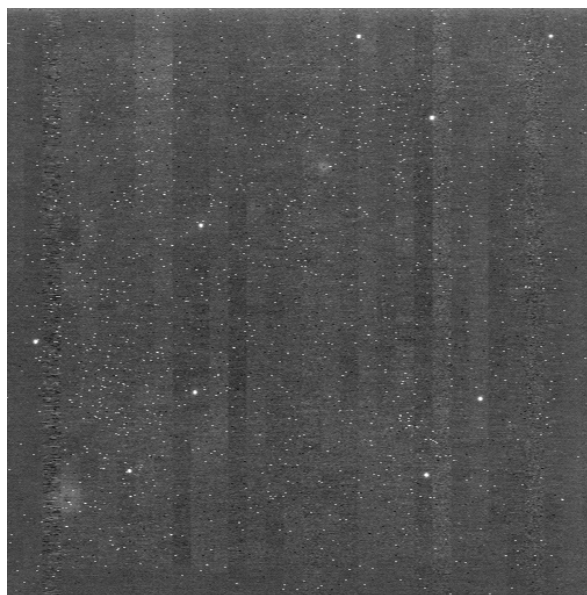
2 UPGRADE CHANGES

2.1 Spectrograph

The Aladdin 3 1024x1024 InSb array in the spectrograph was replaced by a 2048x2048 Hawaii-2RG array. Performance of these two arrays is compared in Table 1. The most significant differences between the old and new arrays are the greater wavelength coverage of the H2RG due to its larger format and better near-optical response, and improved faint object sensitivity due to its significantly lower read noise, dark current and persistence.

The different readout architectures of the Aladdin 3 and H2RG arrays result in observable effects. All 32 channels of the 1024x1024 Aladdin InSb spectrograph array are read out simultaneously. There are eight channels per array quadrant (i.e. per 512x512 sub-arrays). Channel one reads out column one, channel two reads out column two etc. repeating every eight columns across the array quadrant. Given slight variations in channel gain and 'burst' noise on read out this results in a distinctive array read out pattern at very low signal levels: slight offsets between the four quadrants and 'saw tooth' column to column signal variations. The one quadrant of the 1024x1024 Aladdin array in the guider that is read out has the same eight-column structure as before.

Figure 2-1. Dark exposure (60 s) showing a 64-pixel wide readout channel pattern on the H2RG array. The star-like features are alpha-particle hits from a ThF$_4$ AR coat on the surface of the lens facing the detector. The hit rate is about once every five seconds.

Similarly, all 32 channels of the 2024x2048 H2RG spectrograph array are read out simultaneously. In contrast, however, each channel reads out blocks of 64-pixel wide columns. Given slight variations in channel gain and 'burst' noise on read out this results in a distinctive array read out pattern at very low signal levels: a vertically striped pattern with slight offsets of a few DN between neighboring channels (see Figure 2-1). Offsets are typically several DN (the CDS read noise is about 8 DN) and are easily removed in data reduction.

Overall the QEs (and therefore relative throughputs) of the two devices are similar. The differences are probably due to the performance of the anti-reflection (AR) coat on the H2RG required to get good performance in the near optical (< 1 μm, see Figure 2-2).

Table 1. Spectrograph Array

Parameter	Aladdin 3	Hawaii-2RG	Comment
Format	1024 x 1024	2048 x 2048 2040 x 2040 light sensitive	
Number of readouts	32	32	
Sub-array?	Yes, any box	Yes, between rows only	
Pixel size	27 μm	18 μm	
Pixel operability	99%	99%	
Useful wavelength range	0.8-5.5 μm	0.7-5.35 μm	
Average QE	≈80%	≈80%	See plot below
Operating rev. bias	0.400 V	0.312 V	
Pixel rate	15 μs/pixel (20 slowcnts) 3.5 μs/pixel (3 slowcnts)	3 μs/pixel	
Min. full array read out time	0.51 s (15 μs/pixel) 0.12 s (3.5 μs/pixel)	0.463 s (3 μs/pixel)	
Read noise: single CDS	40 e RMS (15 μs/pixel)	12 e RMS (3 μs/pixel)	
Read noise: 32 NDRs	12 e RMS (15 μs/pixel)	5 e RMS (3 μs/pixel)	
Dark current	0.2 e/s	0.05 e/s	Median
Dark current + persistence	>1.0 e/s	0.10 e/s	
Gain	12 e/DN	1.5 e/DN	
Full well depth	7,000 DN 84,000 e	43,000 DN 65,000 e	To saturation
Linear well depth	4,000 DN 48,000 e	30,000 DN 45,000 e	Correctable to < 1%
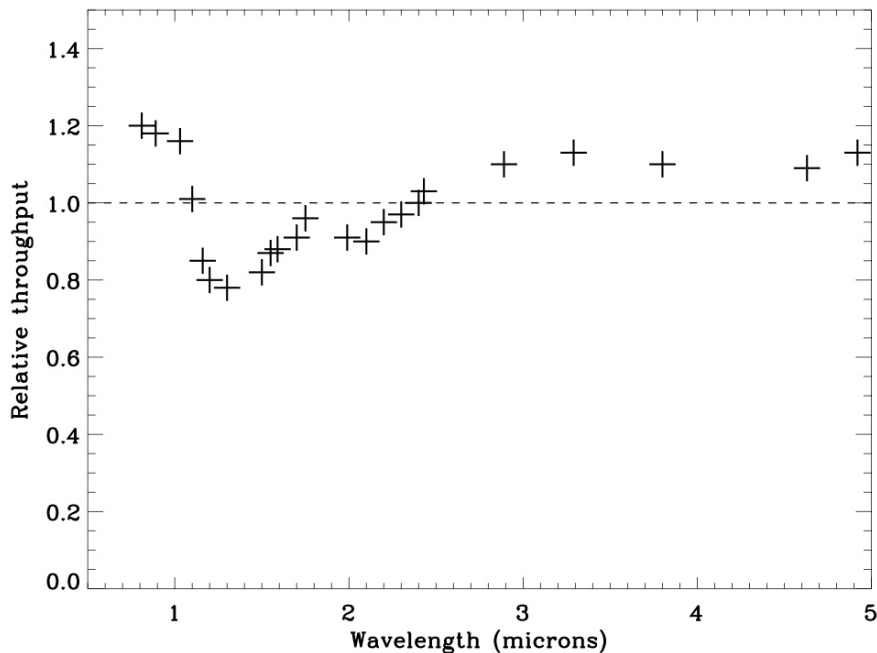
Figure 2-2. Spectroscopic throughput of post-upgrade SpeX relative to pre-upgrade SpeX. Throughput was measured by comparing flux of the same standard star through the 3.0″ slit width (no slit loss). Since the optics are the same this is a direct comparison of the QEs of the H2RG and Aladdin 3 arrays.

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). An approximate way to do this is simply to adjust the on-chip integration time by measuring the maximum counts in DV. However, 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 200 seconds even if the *rate* measurement allows it. Also, due to changes in 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 4.64 s ten NDRs will be done (4.64/0.463 = 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 *0.463 s × the number of NDRs*. To increase observing efficiency observers can choose to reduce NDRs manually.

When the array is idling between exposure sequences it is read out destructively and frequently using 'global resets' to prevent it saturating on any signal. Saturation needs to be avoided to prevent residual image effects. On switching from global resets to the slower pixel-to-pixel resets needed for low noise integrations the first frame in a sequence shows a 'picture frame' offset effect at an intensity level of 10-20 DN as shown in Figure 2-3. To minimize this offset in faint object exposures the '*Flush Go*' button takes a 15 second un-stored exposure to flush the array before immediately executing the commanded exposure sequence (i.e. before global resets resume).
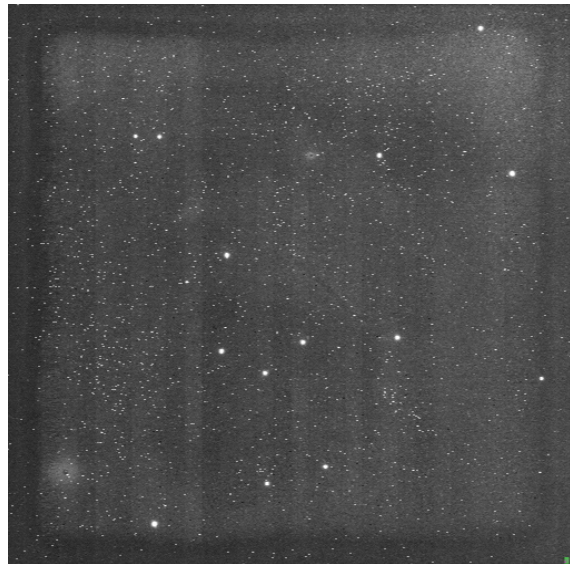
Figure 2-3. The 'picture frame' effect that occurs in the first frame of a series of exposures when the read out switches from global resets to pixel-to-pixel resets. Shown is an 'un-flushed' 60 s dark exposure.

We also strongly recommend that observers acquire <u>at least</u> three AB cycles (six spectra) of their targets whatever the brightness. This allows any systematic effects in the data to be removed by applying a median combination to the spectra. The most prominent of these effects are the star-like features that are randomly distributed on the array due to alpha-particle decays from Thorium used in the AR coats (see Figure 2-1). (The AR coats were applied in 1999 when the potential problem was not recognized.) These features were also present at the same frequency in the original Aladdin 3 data but the smaller pixels and better sampling of the new H2RG makes the features appear star-like rather than 'blocky'. **Also, due to seeing and guiding variations we strongly recommend that observers acquire <u>at least</u> three AB cycles to accurately measure spectral slope (J-K < ± 0.03). If this is not done spectral slope cannot be measured accurately (J-K ~ ± 0.1 for a single AB pair).**

The spectrograph modes before and after the upgrade are listed in Table 2. In PRISM mode the short wavelength limit of 0.70 µm is set by strong absorption in the AR coats, which were originally optimized for 0.8-5.5 µm, while the effective long wavelength limit of 2.52 µm is set by sky background noise at the low resolving power of the prism. The long wavelength limit in LXD_long mode is set by the cut-off wavelength of the H2RG array. All the other wavelength limits are set by the size of the array. Spectra are also better sampled because of the smaller pixel size (e.g. there are now three pixels across the 0.3″ slit instead of two previously).

Table 2. Spectrograph modes before and after upgrade. The given resolving power (R) is matched to the 0.3″ slit width but wider slits are available (0.3″, 0.5″, 0.8″, 1.6″ and 3.0″)

Spectrograph mode	Wavelength Range	R (0.3″ slit)
Pre-upgrade		
PRISM	0.80-2.5 µm	200
SXD	0.80-2.4 µm	2000
LXD1.9	1.95-4.2 µm	2500
LXD2.1	2.15-5.0 µm	2500
LXD2.3	2.25-5.5 µm	2500
Single order short	0.90-2.4 µm	2000
Single order long	3.10-5.4 µm	2500
Post-upgrade		
PRISM	0.70-2.52 µm	200
SXD	0.70-2.55 µm	2000
LXD_short	1.67-4.2 µm	2500
LXD_long	1.98-5.3 µm	2500
Single order short	0.90-2.4 µm	2000
Single order long	3.10-5.3 µm	2500

With the 1024x1024 Aladdin 3 array originally in SpeX the file size was 4.2MB (and sometimes 2.1 MB at low flux). Now, with the 2048x2048 H2RG array in the spectrograph the individual file size is 16.8MB. However, we now store three files per image: pedestal minus signal, pedestal, and signal, for a total image size of 50MB. The reason for the extra files, which are stored as extensions to each image, is to accurately compute corrections for non-linearity. Consequently, **observers should note that spectrograph images take about ten times longer to ftp and require ten times more disk space to store than with the old SpeX.**

2.2 Slit Viewer

The Aladdin 2 512x512 InSb engineering grade array in the slit viewer was replaced by the Aladdin 3 1024x1024 InSb array originally in the spectrograph, although one 512x512 quadrant of this array is used. Performance of these two arrays when in the slit viewer is compared in Table 3. The most significant differences between the old and new arrays are the better cosmetics and reduced odd-even fixed pattern noise of the Aladdin 3 array. However, when switching from idle into long integrations the first frame in a sequence shows a slight gradient in the bias level, decreasing from top-left (pixel 0, 0) to bottom-right (pixel 511, 511) in the data viewer. Successive frames in a sequence do not show the effect since they are not preceded by global resets (see Section 2.1). Sensitivity is not significantly improved with the new array.

Table 3. Slit Viewer Array

Parameter	Aladdin 2	Aladdin 3	Comment
Format	512 x 512	512 x 512 (only one quadrant is used)	
Number of readouts	8	8	
Sub-array?	Yes, any box	Yes, any box	
Pixel size	27 μm	27 μm	
Pixel operability	98%	99%	A3 has a diagonal crack 500 x1 pixels
Useful wavelength range	0.8-5.5 μm	0.8-5.5 μm	
Average QE	≈80%	≈80%	
Operating rev. bias	0.400 V	0.400 V	
Pixel rate	10 μs/pixel (20 slowcnts) 3 μs/pixel (3 slowcnts)	7 μs/pixel 15 μs/pixel	TBC
Min. full array read out time	0.34 s (10 μs/pixel) 0.10 s (3 μs/pixel)	0.24 s (7 μs/pixel) 0.48 s (15 μs/pixel)	TBC
Read noise: single CDS	60 e RMS (10 μs/pixel)	45 e RMS (15 μs/pixel)	TBC
Read noise: 32 NDRs	20 e RMS (10 μs/pixel)	12 e RMS (15 μs/pixel)	TBC
Dark current	2 e/s	2 e/s	Median (long - short itime)
Dark current + persistence		>3 e/s	TBC
Gain	15 e/DN	17 e/DN	TBC
Full well depth	8,000 DN 120,000 e	7,100 DN 120,000 e	To saturation
Linear well depth	3,000 DN 45,000 e	3,000 DN 51,000 e	Correctable to < 1%

2.3 Spectrograph sensitivity

The sensitivity of the spectrograph is given in Table 4. It is calculated using an instrument model and the measured array performance from Table 1. Perfect telluric removal has been assumed.

Table 4. Spectrograph one-hour 50σ sensitivity with the 0.3″ slit and seeing of 0.7″. On-chip integration times are SXD 200 seconds, LXD 5 seconds, PRISM 200 seconds. Observing overheads are not included.

λ (μm)	SXD (0.3″ slit) R=2000		LXD (0.3″ slit) R=2500		PRISM (0.3″ slit) R~200	
	Aladdin 3	H2RG	Aladdin3	H2RG	Aladdin 3	H2RG
1.02	14.47	15.12			17.55	17.98
1.25	14.45	14.98			17.61	18.00
1.30	14.60	15.17			17.29	17.52
1.65	13.71	14.01			16.16	16.37
1.67	13.78	14.09	12.25	12.82	15.80	15.98
2.20	13.62	14.29	11.76	12.46	15.64	16.09
2.25	13.50	14.02	11.77	12.47	15.46	15.83
3.65			9.61	9.96		
4.77			7.23	7.46		

A seeing of 0.7″ FWHM measured in the *K* band has been assumed. It is convolved with a guide error of ± 0.125″ (effectively broadening the seeing profile by 0.25″). In SXD mode (R=2000, 0.3″ slit) in between OH lines observations are typically read noise and dark current limited and sensitivity is improved by about 0.5 magnitudes due to the better read noise and dark current performance of the new H2RG array. The lower resolving power of PRISM mode (R~200 see Figure 2-4, 0.3″ slit) means that the OH background is more evenly distributed and so the improvement is slightly less (0.25-0.5 magnitudes). In LXD mode (R=2500, 0.3″ slit) on-chip integration times are limited to a few seconds to prevent saturation on the sky at 4-5 μm. At these wavelengths the 0.2 magnitude improvement is sensitivity is mostly due to the slightly better throughput (see Figure 2-2). The necessarily short on-chip integration times in LXD mode mean that the 1.67-2.4 μm region, where sky background is much reduced, is read noise limited, and sensitivity is improved by about 0.5 magnitudes due to the lower read noise of the new H2RG array.

The limiting flux calculator on the SpeX webpage is more conservative than the instrument model used for Table 4 and although the exact sensitivities may differ the same improvements are predicted.

2.4 Spectrograph S/N widget in DV

A simple signal-to-noise widget is now incorporated into DV. It works on point sources only. The widget assumes that the star is nodded along the slit and that 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 2-4). Signal is measured in an object box 14 pixels long (1.4″) and the same width as the slit. The signal in a sky box 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 either side of the object box are subtracted from the summed object box signal.

The signal-to-noise is given by:

$$\frac{S}{N} = \frac{G(objectbox - sidebox)}{(G \times (objectbox - sidebox) + G \times skybox)^{1/2}}$$
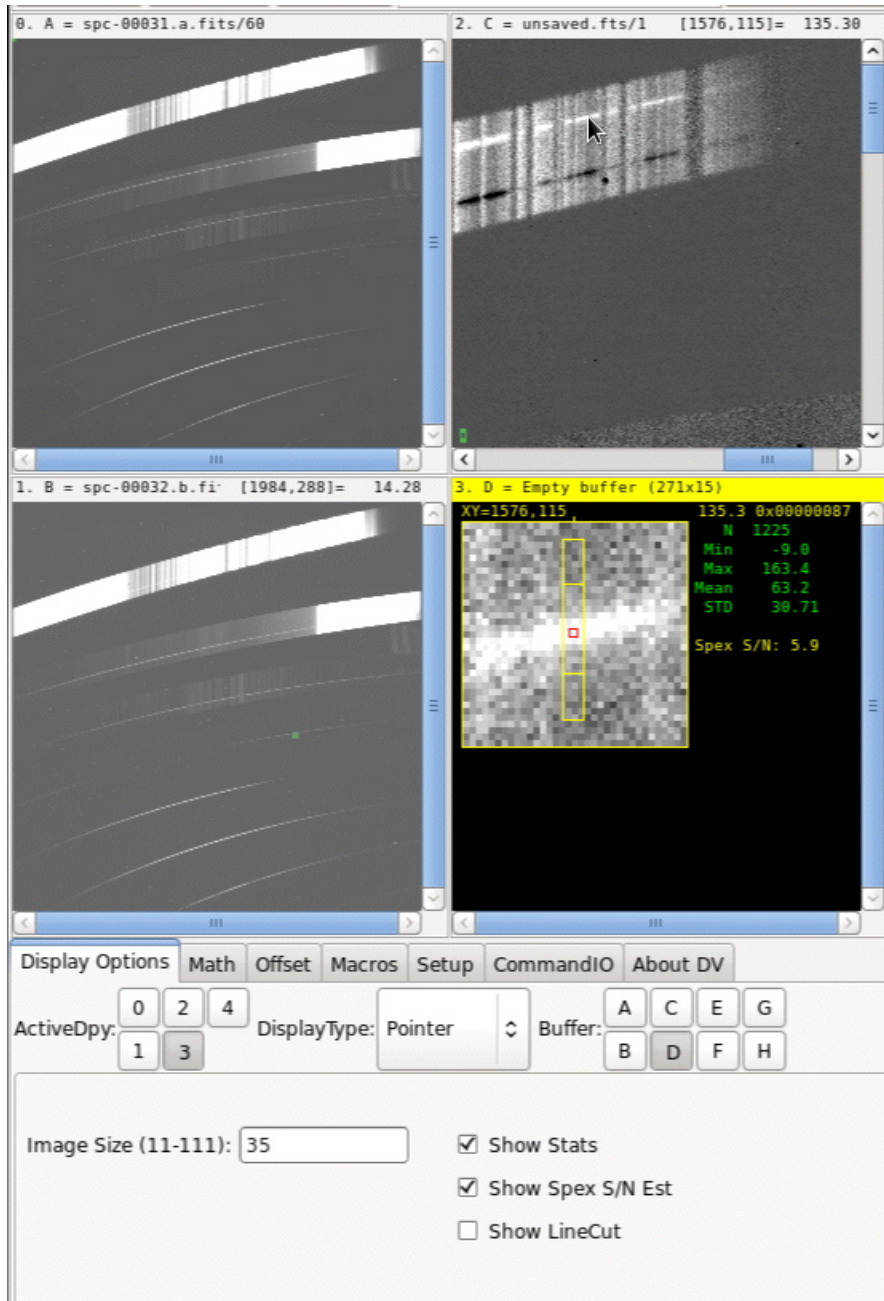
Where the gain G=1.5 e/DN.

Figure 2-4. Signal-to-noise widget in DV. The pointer is selected in buffer D and moved over the spectrum in buffer.

2.5 S/N measured in 'QuickLook' spectral extraction

During observing sessions, spectra are automatically extracted and displayed in DV (see Figure 2-5). This "Quicklook" data reduction enables observers to assess the quality of their data in (near-)real-time. All SpeX observing modes (except the single order modes) observed with beam pattern A-B are supported. The software determines from the FITS headers if sufficient data are available to run a scripted version of Spextool. It then automatically extracts spectra, using a fixed aperture (i.e., the optimal extraction method is not used). For off-slit nodding, it is assumed the target is extended and the inner 30% of the slit length is extracted. Currently, the spectra are not divided over a standard star, and hence they display atmospheric absorption lines, as well as the typical curved response shape for echelle gratings or the transmission curve for the
prism mode.

The reduced spectra and signal-to-noise values as a function of wavelength are automatically displayed in DV. The result of the latest cycle is sent to DV buffer F, and the average for a given target and observing mode is sent to buffer G. To view these, one needs to select Display Type "QuickLook". At present, only one of the nods is sent to DV (the nod pair is not averaged), and the signal-to-noise values are per spectral pixel. The signal-to-noise values will be square root 2 higher if the A and B nod spectra are averaged. The signal-to-noise values can be converted from per pixel to per resolution element by multiplication with the square root of the slit width in pixels.

Flat field and wavelength calibration files are also automatically reduced after the calibration macro is executed. The best matching calibration files will be used for the data reduction. If no calibrations were taken yet during the observing session, they will be selected (closest in time) from a calibration database. If such calibrations are not available, the data reduction will only start once the calibration macro has been executed.

To check the status of the Quicklook data reduction, see the messages in the dedicated x-terminal in the observing session. For further information, visit <http://irtfweb.ifa.hawaii.edu/~quicklook/>.
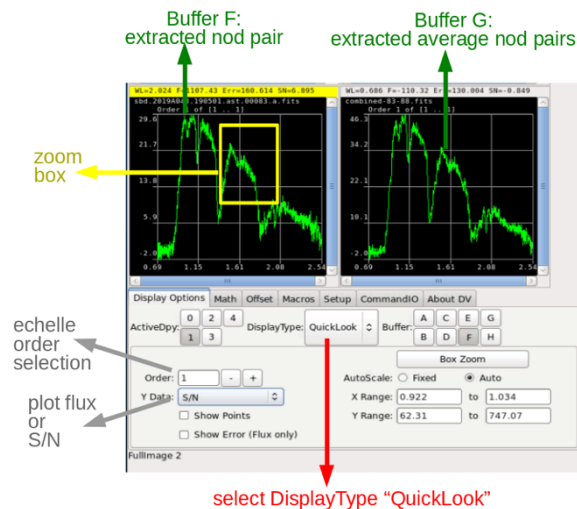

Figure 2-5. QuickLook real-time spectral extraction

2.6 Spectrograph observing efficiency

The limiting flux calculator on the SpeX calculator estimates the integration time required to reach a desired S/N but it does not estimate the clock time, which includes a number of observing overheads. By default, SpeX 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. 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. Additional overhead is also needed to display and store data. Table 5 is a guide to observing with different combinations of integration times, NDRs and coadds.

Table 5. 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
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
30	1	1	30	33
60	1	1	60	63
120	1	1	120	123

Clearly, coadding can sometimes double the effective integration time but is unavoidable in some LXD modes to avoid saturation on the sky. Other overheads included in Table 5 are the times taken to display and store data. One overhead not included is the beam switch dead time (*Beam DTime* in BXUI). 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.

## 2.7 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 to 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 are also archived.

The total number of reads per *itime* is NDRs × coadds. NDRs × coadds is defined as the DIVISOR keyword in the header. 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.

3 ACQUISITION AND GUIDING

Acquisition and guiding are done with the slit viewer/IR guider, which is known colloquially as Guidedog. Users operate Guidedog from the Guidedog X-windows User Interface (GXUI) and display data in the Guidedog Data Viewer (GDV). The SpeX foreoptics reimage the telescope focal plane onto gold-coated slit mirrors (see Table 6). The slit mirrors reflect a 60″x60″ FOV through the guider filter wheel (see Table 7) and onto the slit-viewer array (see Table 3). The field on the slit mirror and array can be rotated using a K-mirror image rotator in the foreoptics.
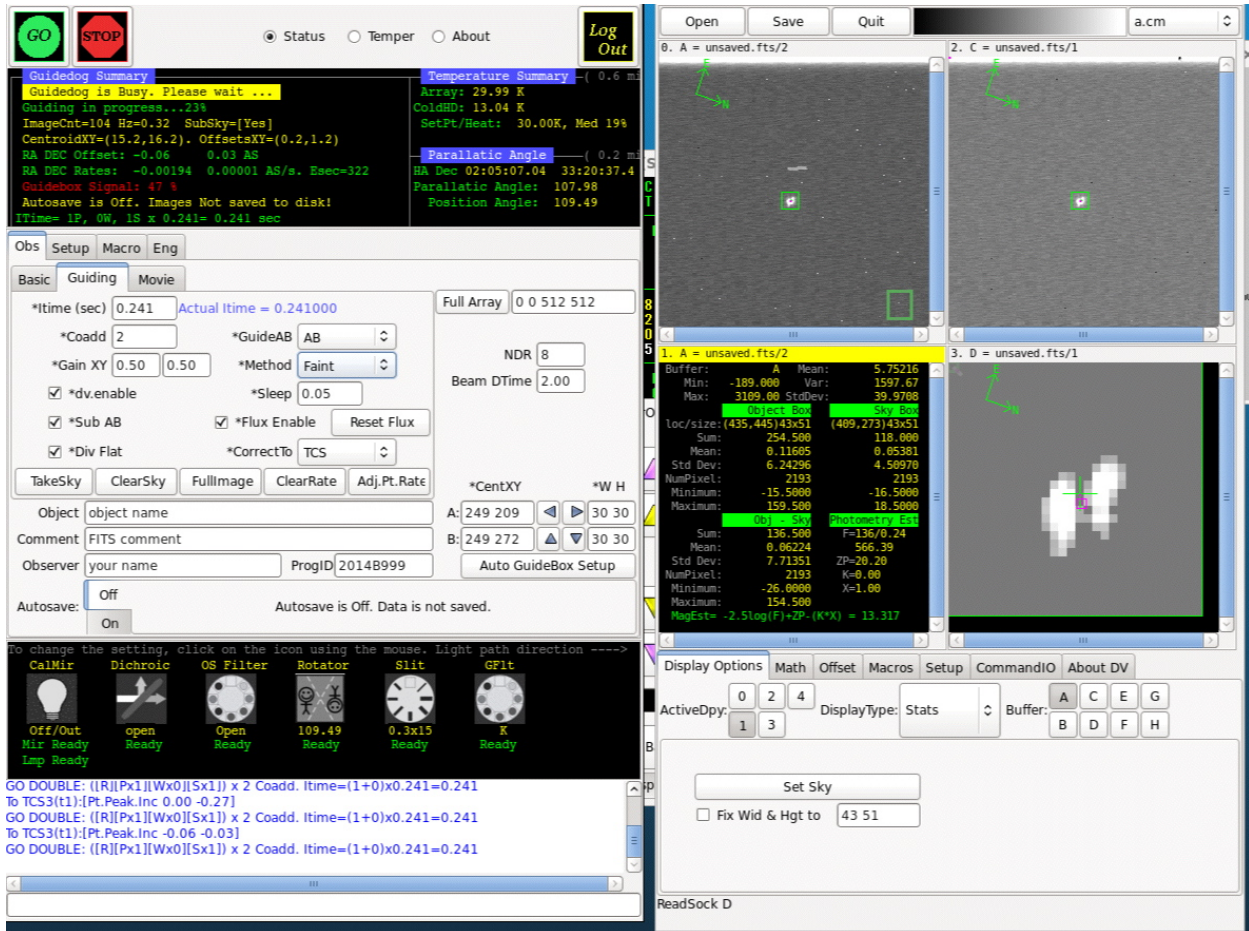
Figure 3-1. Guidedog user interface showing the GXUI on the left and the GDV on the right. Mechanisms are moved by clicking on the icons at the bottom of GXUI and then selecting positions from a pull-down menu.

The image rotator is used to align the slit with some preferred direction in the object (e.g. binary star position angle) or with the parallactic angle so that any atmospheric dispersion is along the slit to minimize light loss (see Figure 3-2). Setting the slit to the parallactic angle is also very important in measuring the correct spectral shape of point sources. Even though dividing by a telluric standard star of know shape corrects the measured shape to first order we have found that the slope variation is much reduced when both the target and standard are observed at the parallactic angle.
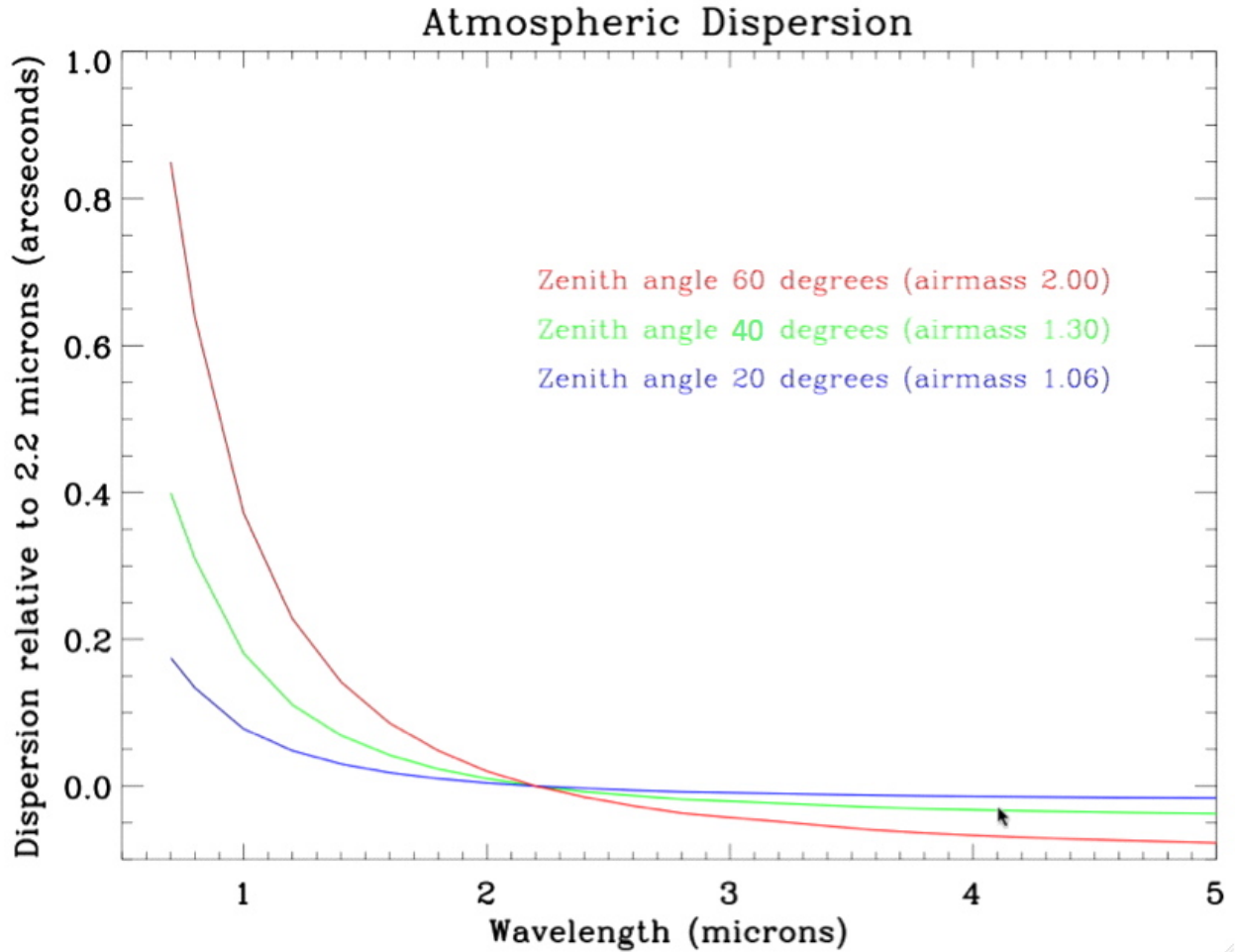
Figure 3-2. Atmospheric dispersion as a function of wavelength and zenith distance (airmass) relative to 2.2 μm for Maunakea.

Table 6. Slit wheel.

| Position	Slit	Comment
0	Mirror/blank	Mirror to guider, blank-off to spectrograph
1	0.3″ x 15″	
2	0.5″ x 15″	
3	0.8″ x 15″	
4	1.6″ x 15″	
5	3.0″ x 15″	For spectro-photometry
6	0.3″ x 60″	
7	0.5″ x 60″	
8	0.8″ x 60″	
9	1.6″ x 60″	
10	3.0″ x 60″	For spectro-photometry

Table 7. Guider filter wheel

Position	Filter	Comment
0	Open	
1	Z 0.95-1.11 µm	
2	J_{MK} 1.164-1.326 µm	
3	H_{MK} 1.487-1.783 µm	
4	K_{MK} 2.027-2.363 µm	
5	L'_{MK} 3.424-4.124 µm	
6	5.1 µm 0.5%	Cross with Long 4 in OSF
7	FeII 1.644 µm 1.5%	Cross with PK50 blocker in OSF
8	H_2 2.122 µm v=1-0 s(1)	
9	Brγ 2.166 µm 1.5%	
10	cont-K 2.26 µm 1.5%	
11	CO 2.294 µm 1.5% (2-0bh) + ND 2.0 (1%)	
12	$H+K$ notch	Optimized for faint object guiding
13	L_{nb} 3.454 µm 0.5%	
14	1.74 µm 1.5%	

3.1 Imaging and acquisition

Images are taken with Guidedog in *Basic* mode. The Guidedog XUI and DV are found the VNC session #2 (Stefan.ifa.hawaii.edu:2). The *Basic* mode window (see Figure 3-3) is selected by clicking on *Obs* in GXUI (see Figure 3-1). Parameters include *itime, coadd, cycles* and *Beam.Pattern* (A, B or AB). The default number of NDRs is 8 but observers can manually select any number up to 32. The user saves images to the directory *path*. *Autosave* can be turned on or off. Images are taken by clicking the [GO] button at the top of the GXUI window. Imaging can be stopped at any time by clicking the [STOP] button.
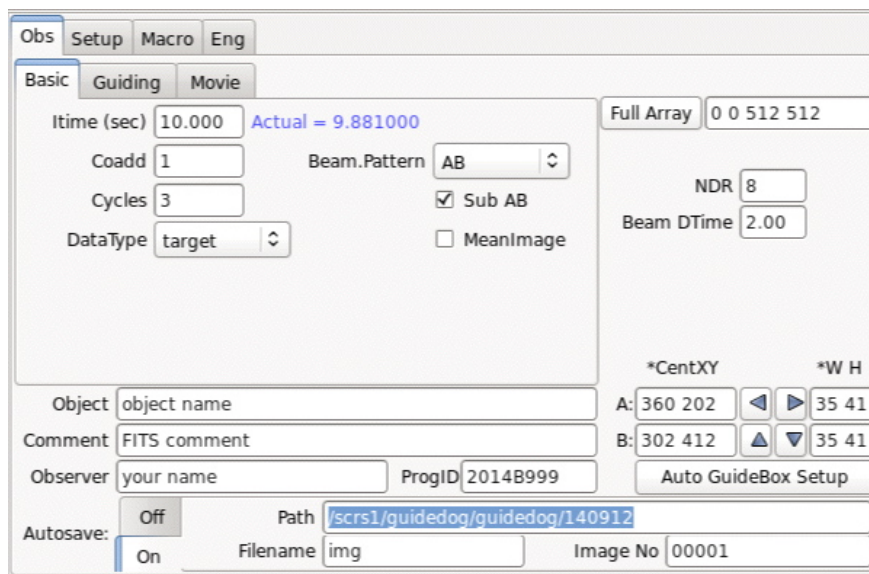
Figure 3-3. Basic imaging mode window.

Target acquisition proceeds as follows:

1. Send target coordinates to the telescope operator (TO). Coordinates can be sent to the TO by using *StarCat* or the *next* button in *t3remote* (see Figure 3-4).
2. TO slews the telescope to the target.
3. If optically visible the TO will move the telescope on-axis mirror in (obscuring Guidedog) and find the target with the on-axis TV. If the target is very faint or red the TO can find a nearby SAO star and then slew to a bore-sighted position in the Guidedog FOV. The TO removes the telescope on-axis mirror. Make sure the SpeX calibration mirror (*CalMir*) is out of the beam.
4. Check target coordinates in *t3remote*.
5. Select an appropriate guider filter and image the field. Normally the order sorter filter should be open.
6. In the *J*, *H* and *K* filters target magnitude can be measured in DV to help with identification. Select *Stats* in *DisplayType*. Draw a box over a nearby area sky in the selected image, click *Set Sky*, and move the box over the star. In good conditions magnitudes are accurate to about 0.1 mag.

Figure 3-4. T3 remote TCS widget. Left - *next* **panel to send object coordinates to the TO. Right - *offset* paddle panel for manual guiding. Set *Rot* to the position angle of the SpeX rotator to turn east-west and north-south on the paddle to horizontal and vertical in GDV.**

3.2 Guiding

SpeX is optimized to use slit widths about the same size as the seeing. Normal telescope tracking is not accurate enough to keep targets in the narrow slits for more than about one minute and so active guiding is a critical feature of SpeX operation. There are several guiding options with SpeX:

1. IR guiding with SpeX guider/slit viewer
2. Visible guiding with the MORIS CCD camera fed from SpeX
3. Visible guiding with the telescope off-axis guider

All these methods rely on small corrections to telescope pointing, limiting correction to longer than once per second. Consequently, guider integration times shorter than about one second are not needed. Faster correction for tip-tilt seeing a variation requires use of the tip-tilt secondary mirror and this is not currently available.

3.2.1 IR guiding with SpeX

In this mode auto-guiding is done on spillover flux from the star in the slit or on a star in the 60″x60″ FOV of the guider. The approximate limits for auto-guiding in median seeing are given in Table 8. Magnitude limits for manual guiding on spillover using the guide buttons in *t3remote* are about one magnitude fainter.

Filter	Star in 0.5 ″slit (spill-over)	Star in field
J	16	18
K	15	17

Table 8. Approximate magnitude limits for auto-guiding: 0.5″ slit, *itime* 30 s with stored sky subtraction, and median seeing (about 0.7″). TBC

Auto-guiding also works well on extended objects such as galaxy nuclei and small disks (e.g. 4″ diameter disk of Uranus) so long as the objects are bright enough and guiding on the peak or centroid is acceptable (the guide box size can be manually adjusted). Positioning a slit at a particular location on Jupiter or Saturn, for example, must be done using non-sidereal telescope tracking with manual guide corrections done by observing the slit location in the slit viewer.

Procedure Overview:
1. Select slit and guide filter
2. Slew to target
3. Set rotator angle
4. Take an image with the guider.
5. Click on *Auto GuideBox Setup*.
6. Offset telescope to put the star onto the slit
7. Start guiding

Detailed procedure:

1. Select desired slit and guider filter (see Figure 3-5).
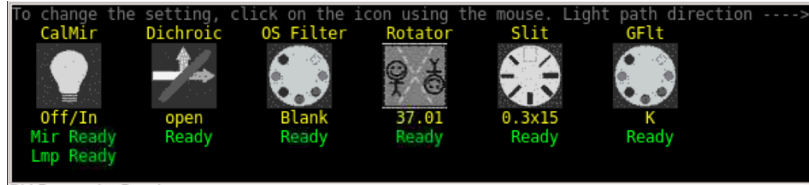
Figure 3-5: Click on the Slit and GFlt icons to get pull down menus to select the slit and guider filter, respectively.

2. Slew to object and acquire (Section 3.1 above)
3. Set desired position angle on the sky. Click on rotator icon (see Figure 3-5) and either *Sync Rotator to Parallactic Angle*, or enter position angle and click on *Set Rotator (deg)*.
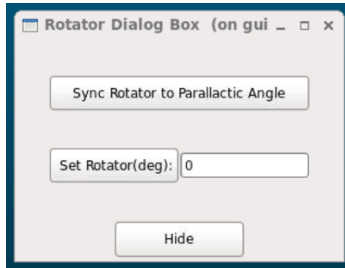

Figure 3-6: In the Rotator dialog box, click on the 'Sync Rotator to Parallactic Angle' button to do that, or enter a discrete angle and click on 'Set Rotator'.

4. Take an image of the field:
   a. In GUI select *Basic* (see Figure 3-3).
   b. Set desired *itime, coadds* and *cycles*.
   c. Click on to take an image

   An image compass showing the position angle on the sky is displayed in the image. The field rotates clockwise on the screen for positive angles.

5. In the GXUI *Obs* panel click on *Auto GuideBox Setup* (see Figure 3-1). This will display the default A and B guide boxes for the selected slit in the active display in Guidedog DV (GDV). The guide boxes are positioned for optimum nodding of point sources along the slit. It will also set the correct telescope nod direction by reading the current SpeX rotator angle in the latest Guidedog image. **Clicking *Auto GuideBox* Setup must follow changing the rotator and taking an image otherwise the telescope will nod in the wrong direction**.

6. Move the target star into the telescope A beam box:

   a. In GDV, draw a line from the star to the approximate center of the A box. With a three-button mouse this is done by placing the cursor over the star, holding down the keyboard shift key and the middle mouse button at the same time, and dragging a line from the star to the box (see Figure 3-7).

   b. Move the star into the A box by offsetting the telescope. In GDV select the *Offset* panel and click *Offset Telescope* (see Figure 3.8).

   c. Check that the star is in the box by taking another image and redisplaying the guide boxes (*Auto GuideBox Setup*).
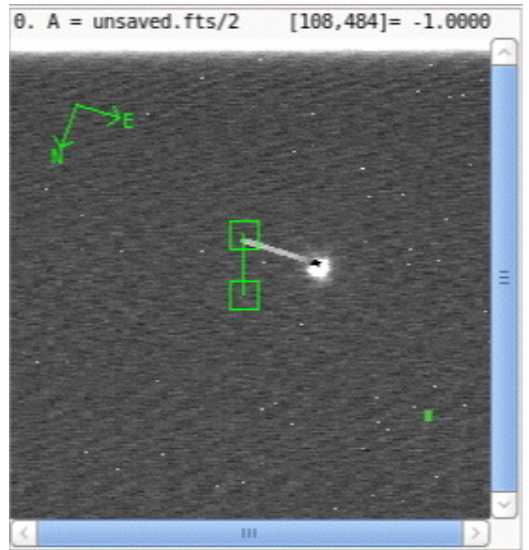
Figure 3-7. Move target star in A box by drawing a line from the star to the box and offsetting the telescope.
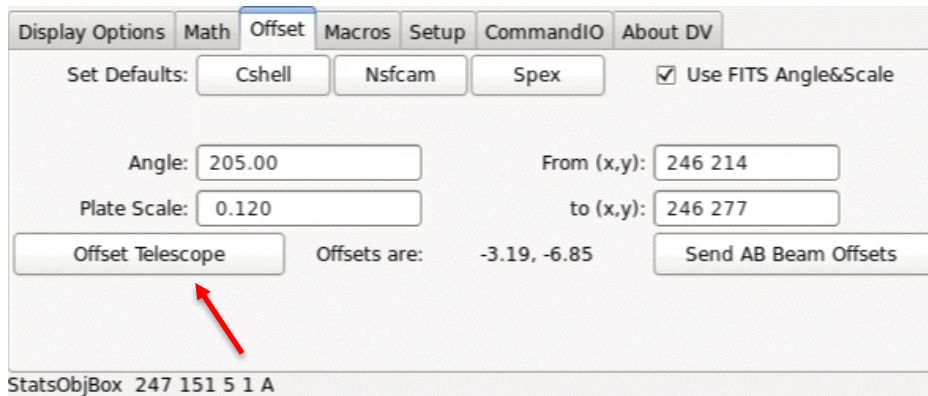

Figure 3-8. Offset panel. Click on *Offset Telescope* to move the star into the slit (A box).

Without a three-button mouse there are alternative ways to move the star:

   d. Type the coordinates of the star and center of A box, read from the cursor positions in GDV, into the *From* and *to* boxes respectively in the *Offset* panel.

   e. Or move the cursor over the star and hold down the *shift* and *F* keys to read the *From* position, and hold down the *shift* and *T* keys to read the *to* position. The coordinates will appear in the *From* and *to* boxes.

   f. Click *Offset Telescope* (see Figure 3-8).

7. Start guiding on the star in slit:
   a. In the GXUI *Obs* panel select the *Guiding* panel (see Figure 3-9).
   b. Set *itime* and *coadds*.
   c. To guide in the A and B beams choose *AB* from the *GuideAB* pull-down menu.
   d. For auto-guiding set *CorrectTo* to *TCS* from the pull-down menu. For manual guiding using the paddle buttons in *t3remote* set *CorrectTo* to *Off* (see Figure 3-9).
   e. Choose the guiding method from the *Method* pull-down menu. *Faint* works well for most point sources.
   f. If desired *Autosave* can be turned on in GXUI but this is not necessary to guide.
   g. Click [GO] in GXUI to start guiding. By default, the zoomed guide image will appear in *ActiveDpy 3* buffer *D* in GDV.
   h. To check that the correct telescope nod has been set click on *Beam A* in the *offset* panel of *t3remote*. This should move the into the B box in GDV. Switch back by clicking on *Beam B*. If not click on *Auto GuideBox Setup* and reposition the star.
   i. Sometimes the guide star will oscillate about the slit in the X direction (horizontal axis in GDV). Reducing the default gain of 0.5 in *Gain XY* can minimize this.
   j. At longer integrations (*itime* > 10 s) the guide star sometimes favors one side of the slit. This can indicate a problem with the telescope sidereal tracking rate. To adjust the tracking rate click on *ClearRate* and then wait several *itimes* before selecting *Adj.Pt.Rate*.
   k. To stop guiding, click on the [STOP] button.
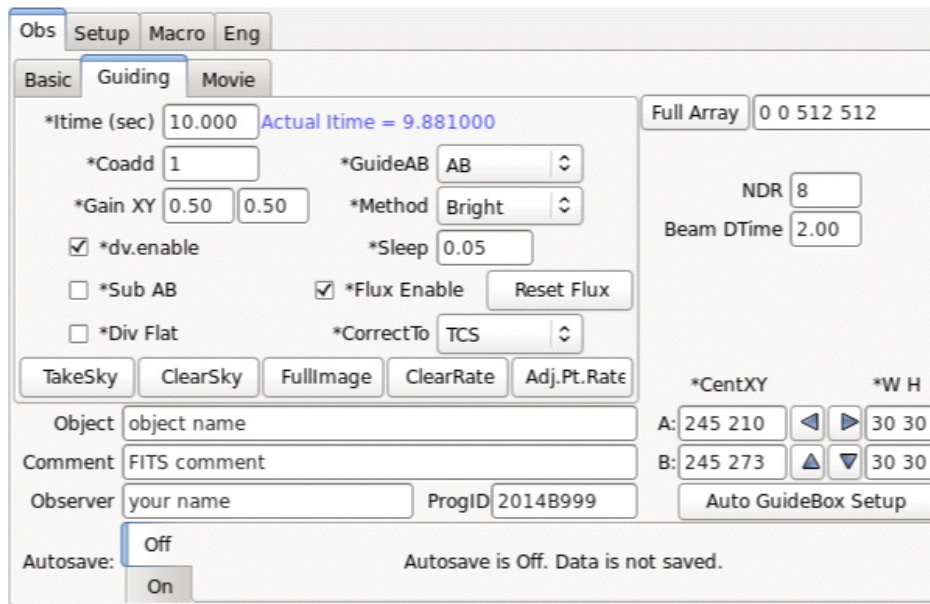
Figure 3-9. Guiding panel. All items preceded by an asterisk (*) can be changed while guiding is in progress.

8. Start guiding on star in field (for sidereal rates only). This is usually more precise than guiding on an object in the slit since the image centroid is more stable:

Figure 3-10. Setting guide boxes for an offset guide star in the Guidedog FOV.

   a. Place target star in the center of A box (see item 6).
   b. In *Display Options* panel select the appropriate *ActiveDpy* in GDV and draw a box over the selected guide star in the field. (Use middle mouse button; move box around by clicking on left or right mouse buttons).
   c. With *DisplayType* set to *Image* click *Ga* in *Display Options* panel (see Figure 3-1). The A and B guide boxes will be redrawn in GDV (see Figure 3-10). If desired the guide box width and height can be manually changed in the *W H* widget.
   d. In the GXUI *Obs* panel select the *Guiding* panel (see Figure 3-7).
   e. Set *itime* and *coadds*.
   f. To guide in the A and B beams choose *AB* from the *GuideAB* pull-down menu.
   g. For auto-guiding set *CorrectTo* to *TCS* from the pull-down menu. For manual guiding using the paddle buttons in *t3remote* set *CorrectTo* to *Off*.
   h. Choose the guiding method from the *Method* pull-down menu. *Faint* works well for most point sources.
   i. If desired *Autosave* can be turned on in GXUI but this is not necessary to guide.
   j. Click [GO] in GXUI to start guiding. By default, the zoomed guide image will appear in *ActiveDpy 3* buffer *D* in GDV.
   k. Once guiding has been started it is sometimes necessary to fine time the position of the target star in the slit. This is done by changing the coordinates of the off-slit guide boxes by using the arrows in the *Guiding* panel (see Figure 3-9 and 3-11).

Figure 3-11. Arrows are used to fine-tune the position of the off-slit guide boxes.

   l. To check that the correct telescope nod has been set click on *Beam A* in the *offset* panel of *t3remote*. This should move the into the B box in GDV. Switch back by clicking on *Beam B*. If not click on *Auto GuideBox Setup* and reposition the star.
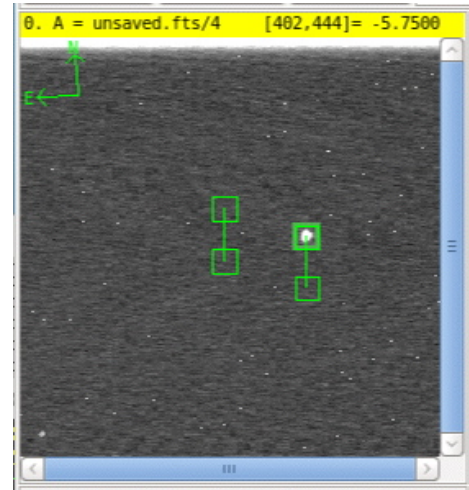
9. To guide on faint stars (about J>14, K>13) it is usually necessary to subtract a stored sky image of the same *itime* from the consecutively taken guide star images:
   a. In the *Guiding* panel click *ClearSky*.
   b. Move the guide star out of the guide box. Using the offset buttons in t3remote is a good way to do this.
   c. Click *TakeSky*. This needs to be taken at the same *itime* as intended for guiding.
   d. Move guide star back into guide box.
   e. Click *Sub AB*.

f. Start guiding (see item 7). The sky-subtracted image is used to guide on. It is displayed in the guide window (by default *ActiveDpy 3* buffer *D* in GDV).

g. Since sky level changes with time and observing conditions the quality of the sky subtraction will degrade with time and it may be necessary to change the stored sky occasionally depending on the length of the observing sequence.

10. To guide on extended objects, it is necessary to increase the size of the A beam guide box and nod out of the slit for the B beam position:

a. Do not click *Auto GuideBox Setup* since this loads the default guide box parameters.

b. Change coordinates *CenXY* of guide box A to the center of the slit and increase width and height of box *W* and *H* as necessary (see Figure 3-11).

c. Change *GuideAB* to *A* (no guiding in sky-only B beam position)

d. Tell the TO the required B beam offset position in arcseconds RA and Dec.

e. Move target into box A position

f. The other guiding options are the same as described in 7 and 8 above.

g. Click in GXUI to start guiding.

11. Set up the spectrograph and start science integrations.

3.2.2 Visible guiding with MORIS

MORIS is the CCD camera attached to the side of SpeX (see Figure 1-1). Users operate MORIS from the MORIS X-windows User Interface (MXUI) and display data in the MORIS Data Viewer (MDV) (see Figure 3-12). The MORIS XUI and DV are found in VNC session #12 (Stefan.ifa.hawaii.edu:12). Its primary use is to provide simultaneous optical and infrared photometry in conjunction with SpeX. However, it is also a very efficient visible guider for SpeX. In this mode visible reflecting and IR transmitting dichroics in SpeX feed MORIS. Since the two dichroics cut-on at 0.7 μm and 0.9 μm (see Figures 3-13 and 3-14) using MORIS limits the spectral range of SpeX (see Table 9). Without the dichroics SpeX can reach about 0.7 μm. Users operate MORIS from the MORIS X-windows User Interface (MXUI – see Figure 3-12), which is similar to GXUI. The dichroics reflect a 60″x60″ FOV onto the E2V 512x 512 CCD in MORIS. This is the same size and pixel scale (0.12″/pixel) as Guidedog. MORIS has its own filter wheel (see Table 10). Since the dichroics are in front of the internal SpeX rotator the orientation of the image in MORIS is fixed (north up and east to the left in DV).
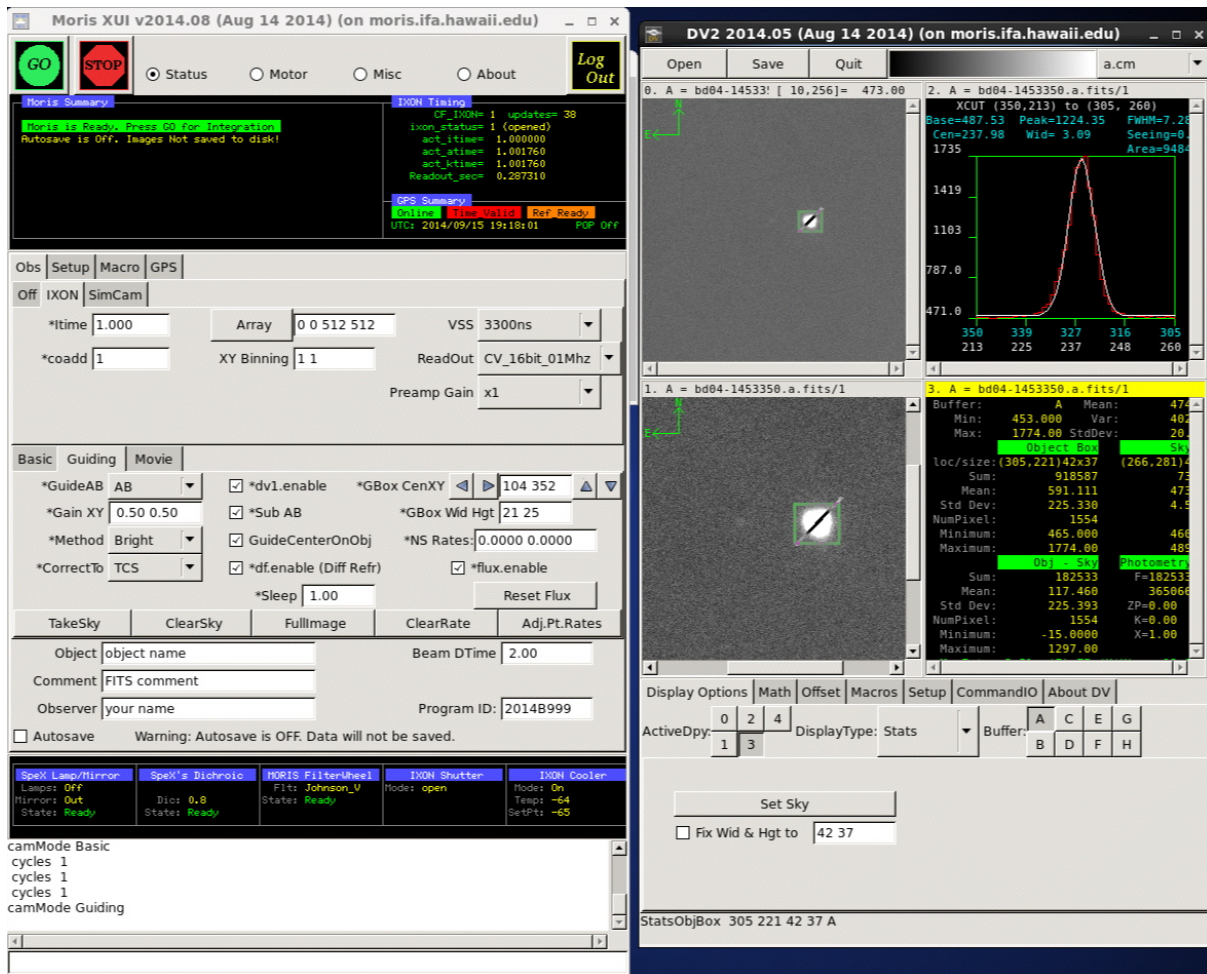

Figure 3-12. MORIS user interface showing MXUI on the left and the MDV on the right. Mechanisms are moved by clicking on the icons at the bottom of GXUI and then selecting positions from a pull-down menu. However, the *SpeX Lamp/Mirror* and *SpeX Dichroic* can only be moved from Bigdog or Guidedog.

Table 9. Dichroic turret

Position	Dichroic	Comment
0	*Pupil viewer lens*	Used to image secondary mirror and measure system emissivity
1	*0.9 μm*	MORIS (visible) guiding Rf: 0.42-0.92 μm, Tx: 0.92-6.0 μm
2	*Open*	Guidedog (IR) guiding only
3	*0.7 μm*	MORIS (visible) guiding Rf: 0.40-0.68 μm, Tx: 0.70-6.0 μm
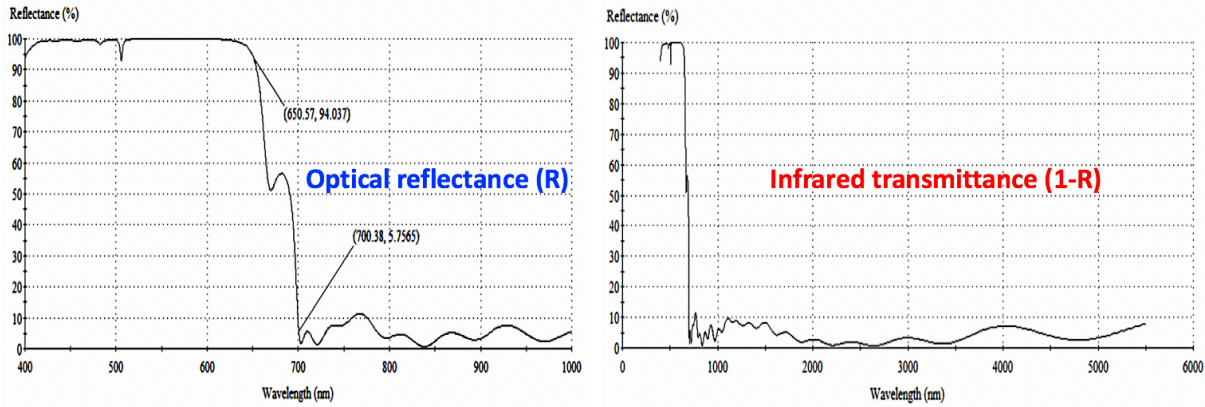
Figure 3-13. Reflectance/transmittance vs. wavelength for '0.7 μm' cut-on dichroic
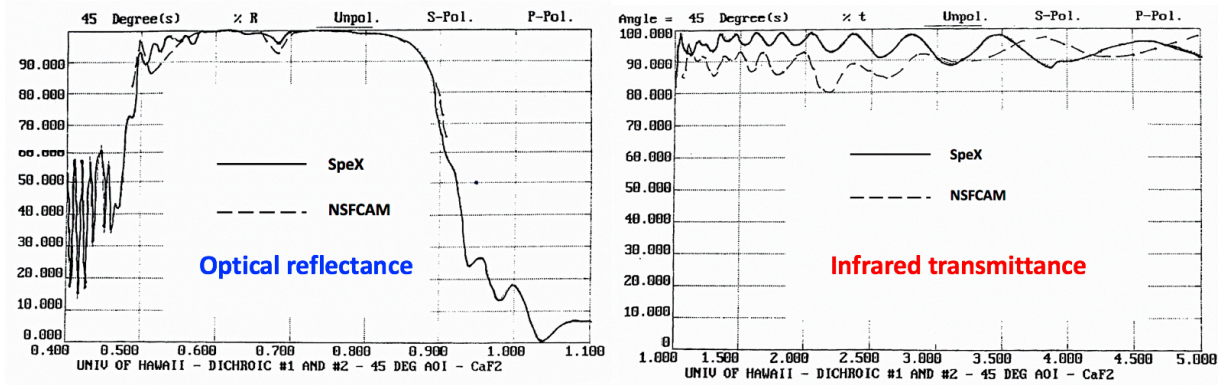
Figure 3.14. Reflectance/transmittance vs. wavelength for '0.9 μm' cut-on dichroic

Table 10. MORIS filter wheel

Position	Filter	Comment
0	*Open*	
1	*SDSS g'*	
2	*SDSS r'*	
3	*SDSS i'*	
4	*SDSS z'*	
5	*Johnson V*	
6	*VR*	
7	*LPR_600*	Long-pass red filter, from 0.60 μm
8	*LPR_700*	Long-pass red filter, from 0.70 μm
9	*890_19nm_CH$_4$*	

Guiding with MORIS is usually more precise than guiding on an object in the slit since the image centroid is more stable. If the target is visible MORIS is able to guide on much fainter objects than Guidedog (see Table 11). **Despite the slight throughput loss due to the dichroic (transmission about 0.9), the more accurate visible guiding with MORIS can significantly improve spectral sensitivity (better than one magnitude compared to IR guiding due to reduced slit losses).**

Table 11. MORIS sensitivity

Magnitude limit (no moon)	Filter	Guider itime (s)
V=20.5	*LPR_600*	10.0

The detailed procedure is similar to the Guidedog set up (see Section 3.2.1). It involves first placing the target star in the slit using Guidedog and then guiding using MORIS:

In Guidedog: Follow steps 1-7 in section 3.2.1. Rather than having *Correct To* set to *TCS*, set *Correct To* to *Off*. Guidedog will then take images continuously until told to stop, but will not send guide corrections to the TCS.

In MORIS:
1. Select MORIS guider filter (see Table 10).

2. Take an image of the field:
    a. In MXUI select *Basic* (see Figure 3-12).
    b. Set desired *itime,* and *cycles.*
    c. *Click on* [GO].
    The field in MORIS is always oriented with north at the top and east to the left.

3. Select the guide star. This is usually the science object in the slit:
    a. In *Display Options* panel select the appropriate *ActiveDpy* in MDV and draw a box over the selected guide star in the field. (Use middle mouse button; move box around by clicking on left or right mouse buttons).
    b. With *DisplayType* set to *Image* click *Ga* in *Display Options* panel. This sets the A guide box location in MORIS. (The B guide box location is queried from the TCS, which gets the information from step 5 above.) If desired the guide box width and height can be manually changed in the *W H* widget (cover the star while making the box as small as possible).
    c. For auto-guiding set *CorrectTo* to *TCS* from the pull-down menu. For manual guiding using the paddle buttons in *t3remote*, set *CorrectTo* to *Off.*
    d. Choose the guiding method from the *Method* pull-down menu. *Faint* works well for most point sources.
    e. If desired *Autosave* can be turned on in MXUI but this is not necessary to guide.
    f. Click [GO] in MXUI to start guiding. By default, the zoomed guide image will appear in *ActiveDpy 3* buffer *D* in MDV.
    g. Once guiding has been started it is usually necessary to fine tune the position of the target star in the slit (MDV). This is done by changing the coordinates of the off-slit guide boxes by using the arrows in the *Guiding* panel (see Figure 3-15). Note the arrows to the left and right of the *CenXY* coordinates move the guide box east-west and north-south respectively.

This moves the science object in the slit east-west and north-south as seen in GDV (i.e. not left-right and up-down).

4. Set up the spectrograph and start science integrations.
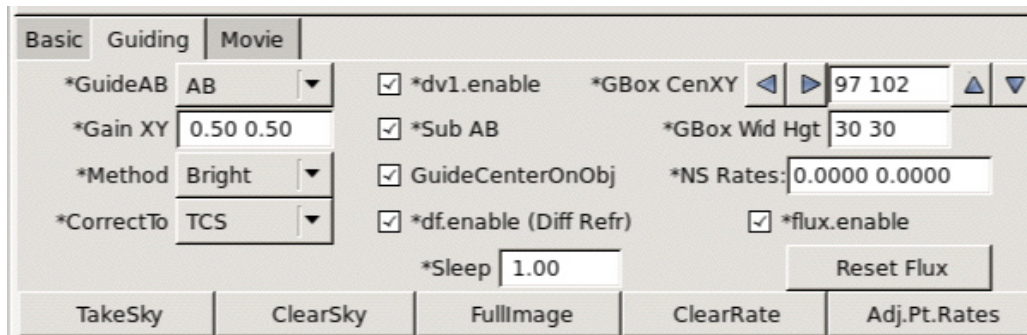
Figure 3-15. MORIS Guiding panel. All items preceded by an asterisk (*) can be changed while guiding is in progress.

3.2.3 Using the MORIS Widget

Based on accurate pixel scales and orientations of the Guidedog and MORIS detectors, we have developed a widget that streamlines the setup of MORIS as a guider for SpeX. This new procedure involves first starting the MORIS guider, then using images taken with Guidedog to identify the science target, determine a precise pixel location of the target centroid, and calculate the offset needed to move the target onto the SpeX slit. This offset is applied as a simultaneous telescope move and a shift in the MORIS guidebox position, producing a quick positioning of the science target on the slit while the telescope is being actively guided.

Procedure Overview:
7. Take an image of the field with MORIS
8. Choose the guide star in MORIS DV, and then…
9. Start guiding with MORIS. Once MORIS is guiding…
10. Go to Guidedog. Take an A-B image pair.
11. Find the star in GDV's buffer C
12. Calculate and apply offsets using the MORIS widget
13. Take another Guidedog A-B pair to check that the target is on the slit. MORIS will still be guiding
14. Take science data with Bigdog.

Detailed Procedure:

Follow "In Guidedog:" steps 1-5 listed in section 3.2.1. Steps 3 – 5 must be followed each time the SpeX rotator angle is changed, so that the telescope nod direction is correctly aligned with the slit direction. Once this procedure is complete, follow these steps:

In MORIS: Start guiding on a star with MORIS
6. Select the *MORIS Filter Wheel* filter (see Table 10). Make sure the MORIS *IXON Shutter* is *Open*. See Figure 3-12.
7. Take an image of the field:

a. In MXUI, select *Basic* (see Figure 3-12), and set *Beam.Pattern* to *A*.
b. Select *Itime* and *coadds*, and set *Cycles* to 1.

c. Press ![GO] in MXUI

The MORIS field is always oriented with north at the top and east to the left.

8. Select the guide star. If the science target is a small Solar System body with non-sidereal rates (i.e.: asteroid, comet or planetary satellite), guide on the science target.

    a. In the *Display Options* panel select the appropriate *ActiveDpy* in MDV (corresponding to the A buffer), set the mouse on the guide target, and click the *left* mouse button to put the guidebox onto the guide star.

    b. With *DisplayType* set to *Image* click *Ga* in *Display Options* panel (see Figure 3-16). This sets the A guide box location in the MDV. (While guiding, the B guide box location is queried from the TCS). If desired, the MORIS guide box width and height can be manually changed in the *W H* fields in MXUI.

9. Start guiding with MORIS.

    a. In MXUI, select *Guiding* to display guide control options.

    b. Set *CorrectTo* to *TCS* and *GuideAB* to *AB* in the pull-down menus.

    c. Choose the guiding method from the *Method* pull-down menu (*Bright*, *Faint*, or *Very Faint*) based on the brightness of the guide star. This can be changed once the guider is started to improve the guiding.

    d. Default *Gain XY* values are 1.0 and 1.0. Because MORIS does not see the spectrograph slit, these values for gain should work well under most circumstances.

    e. If desired, *AutoSave* can be turned on in MXUI, but this is not necessary to guide.
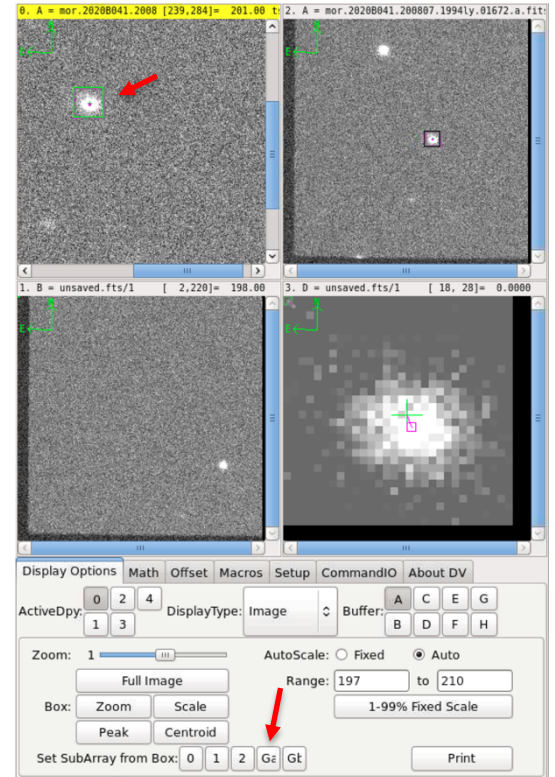
Figure 3-16. The guide box has been placed on the star in display 0 (top left). Click on Ga (bottom center) to set this box to be the A guide box location.

    f. Click ![GO] in MXUI to start guiding. By default, the zoomed guide image will appear in *ActiveDpy* 3 buffer D in MDV.

In Guidedog: See where the star is in Guidedog, use the widget to offset to the slit.

10. Take a single A-B image pair of target field.

    a. Choose *Basic* in GXUI.

    b. Choose appropriate *Itime* and *coadds*. Set *Cycles* to 1.

    c. Set *Beam.Pattern* to *AB*.

    d. Confirm that *SubAB* is checked on. This will automatically place the A – B difference image in buffer C.

    e. Click ![GO] in GXUI

11. Identify the science target in the C buffer image (the A-B image) in GDV. If target is not visible, try repeating step 10 with a longer itime.

12. Calculate and apply offsets to move science target onto the slit.

    a. In the *Display Options* panel select the appropriate *ActiveDpy* in GDV (corresponding to the C buffer). Using the *middle* mouse button, draw a small box that surrounds the positive (A-beam) image of the science target, as shown in Figure 3-16.

    b. Under *Offset* in GDV, **click the MORIS GuideBox Adj button** to bring up the MORIS offset window (see Figure 3-17).
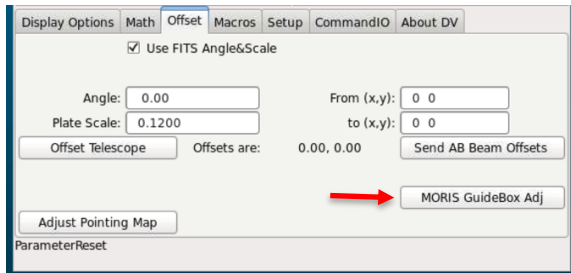
Figure 3-17. In the Guidedog DV, in the *Offset* tab, you will find the *MORIS Guidebox Adj* button at the lower right corner.
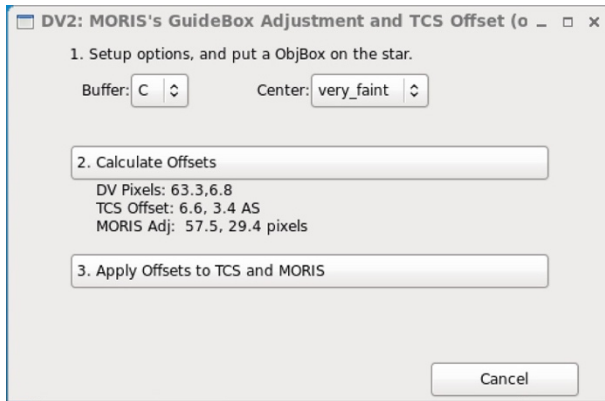

Figure 3-18. The MORIS Guidebox Adjustment and TCS Offset window. After clicking on button 2, the calculated offsets are displayed

      c. In this widget, set *Buffer* to *C*, and choose a proper *Center* method (usually *faint* or *very_faint*).

      d. Click on button "*2. Calculate Offsets*". This will result in calculated offsets for TCS and MORIS being displayed (See Figure 3-18). The offset is drawn in the C-buffer image in GDV (See Figure 3-19).
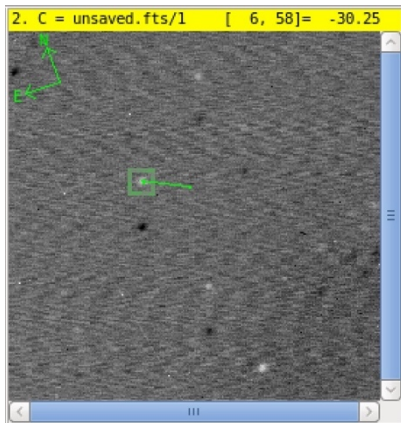

Figure 3-19. This C-buffer image from Guidedog shows the first pair taken to acquire the science target. A box was manually drawn (middle mouse button) around the positive (A-beam) image of the target, and after button 2 was pressed on the MORIS widget, the offset is drawn (green line).

e. Click button "*3. Apply Offsets to TCS and MORIS*" to simultaneously move the telescope and offset the MORIS guidebox.

13. Take confirmation A-B image pair with Guidedog (optional). If the science target is bright enough that spillover light from the slit might be detected, an A-B pair can be taken to confirm the location of the target on the SpeX slit.

      a. Choose *itime*. Set *coadds* and *Cycles* to 1 in GXUI.

      b. Confirm *Beam.Pattern* is still set to *AB*, and that *SubAB* is checked on.

      c. Click in GXUI.

      d. Inspect resulting image to confirm location of the A and B images of the target. Click *Auto GuideBox*

Setup in GXUI to show the nominal locations on the slit (see example in Figure 3-20).
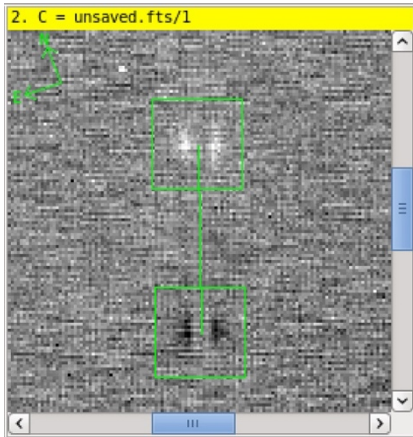
Figure 3-20. Example Guidedog confirmation image (difference of A-B image pair) showing the position of the science target on the slit after offsets have been applied using the *MORIS Guidebox Adjustment and TCS Offset* widget.

In BigDog:

5. Set up the spectrograph and start science integrations.

3.2.4 Visible guiding with the off-axis guider

The off-axis guider can be used if there are no suitable guide stars in the 60″x60″ FOV of SpeX or MORIS. Unlike the IR guider and MORIS the telescope off-axis guider is not mounted to the SpeX cryostat and so there can be relative flexure between the target in the slit and the off-axis guide star. The practical limit is about 30 minutes of integration time after which the target star will need to be reentered. This can be done on the fly if it is visible in the slit. The telescope guider has a horseshoe-shaped field-of-view with an inner radius of 100″ and an outer radius of 200″. Place the target in the slit and ask the TO to start guiding on a suitable off-axis star. Make sure that the target does not move out of the slit when guiding is started (it should not). If it does then ask the TO to tweak the position of the guide box. The sensitivity of the visible off-axis guider is given in Table 12.

Table 12. Visible off-axis guider sensitivity.

Magnitude limit (no moon)	Guider itime (s)
V=10.0	0.7
V=12.7	3.5
V=14.0	6.5
V=15.0	8.0

3.2.5 Subarrays with Guidedog

It is now possible to use subarrays with Guidedog. The subarray is defined as [X Y W H]. X is the number of columns to skip over, and must be a multiple of 8. Y is the number of rows to skip over, and must be in a multiple of 4. W is the number of column reads, or in other words W is the width of the subarray, and must be a multiple of 8. H is the number of row reads, or in other words H is the height of the subarray, and must be a multiple of 4.

4 SPECTROSCOPY

The spectrograph is known colloquially as Bigdog. Users operate Bigdog from the Bigdog X-windows User Interface (BXUI) and display data in the Bigdog Data Viewer (BDV) (see Figure 4-1). The Bigdog XUI and DV are found the VNC session #1 (Stefan.ifa.hawaii.edu:1). There are six spectroscopy modes in SpeX:

1. **SXD** 0.7-2.55 μm, R~2000 matched to 0.3x15" slit
2. **Prism** 0.7-2.52 μm, R~200 matched to 0.3x15" slit or 0.3x60" slit
3. **LXD_short** wavelength 1.67-4.2 μm, R~2500 matched to 0.3x15" slit
4. **LXD_long** wavelength 1.98-5.3 μm, R~2500 matched to 0.3x15" slit
5. **Single-order short** wavelength 0.9-2.4 μm, R~2000 matched to a 0.3x60" slit
6. **Single-order long** wavelength 3.1-5.3 μm, R~2500 matched to a 0.3x60" slit

These are selected by clicking on the grating turret icon in BXUI. The cross-dispersed modes require a slit length of 15″ while the prism and single-order modes can use slit lengths of either 15″ or 60″. The available slit widths are 0.3″, 0.5″, 0.8″, 1.6″ and 3.0″. Moving between modes takes about one minute. The spectrograph focus is automatically adjusted for each mode and requires no action by the observer. Spectrograph focus is independent of the telescope focus on the slit, which is done by the TO and requires focusing the telescope using Guidedog (the slit viewer).

It is very important to set the slit at the parallactic angle when observing point sources in the SXD and Prism modes (see Figure 3-2). This is optimum for overall efficiency and for the accurate measurement spectral shapes.

The data reduction program for SpeX, 'Spextool', is designed to produce fully calibrated data from the cross-dispersed modes and the prism. Spextool is not designed to reduce data form the single-order modes since these can be reduced with standard packages such as IRAF.

Once the slit is selected and guiding is started, the next step is to set up the spectrograph:
1. Select slit and spectrograph mode (the grating turret can be moved before or after guiding is started).
2. Acquire science target, set rotator angle and start guiding (see Section 3).
3. Take a test exposure with Bigdog (the spectrograph) to establish the correct on-chip integration time (*itime* in BXUI).
   a. Set *itime* to 10 s or less depending on object brightness
   b. Click *Test Go* in BXUI
   c. In BDV measure maximum signal *rate* in DN/s (e.g. draw a line across the spectral orders as shown in Figure 4.1). Calculate the maximum *itime* allowed to operate in the linear range of the array: $itime = \frac{30,000}{2 \times rate} - 0.5$
      The *itime* can be less than this to satisfy the required S/N. We recommend *itimes* no longer than 200 s even if allowed (see section 2.1).
   d. Set desired *itime*, *coadds*, *cycles* and *beam.pattern*.
   e. Click *Go* for bright objects or *Flush Go* for fainter objects (*itime* > 60 s). *Flush Go* takes a 15 s unstored integration in the A beam to minimize the picture frame effect (see Section 2.1) and then immediately executes the previously set *itime*, *coadds*, *cycles*, *beam.pattern* sequence.

4. Follow the same procedure for the telluric standard star. Spextool uses A0V or G2V stars selected to be nearby the object in air mass and angle. Find A0V and G2V stars using the star locator on the SpeX webpage.

5. Run the calibration macro corresponding to the spectroscopy mode and slit width:
   a. Select *Macro* button in BDV
   b. Select macro (left or right mouse button) e.g. *ucal_sxd_0.3* for SXD mode and 0.3″ slit. The macros store the current configuration and restore it at completion.
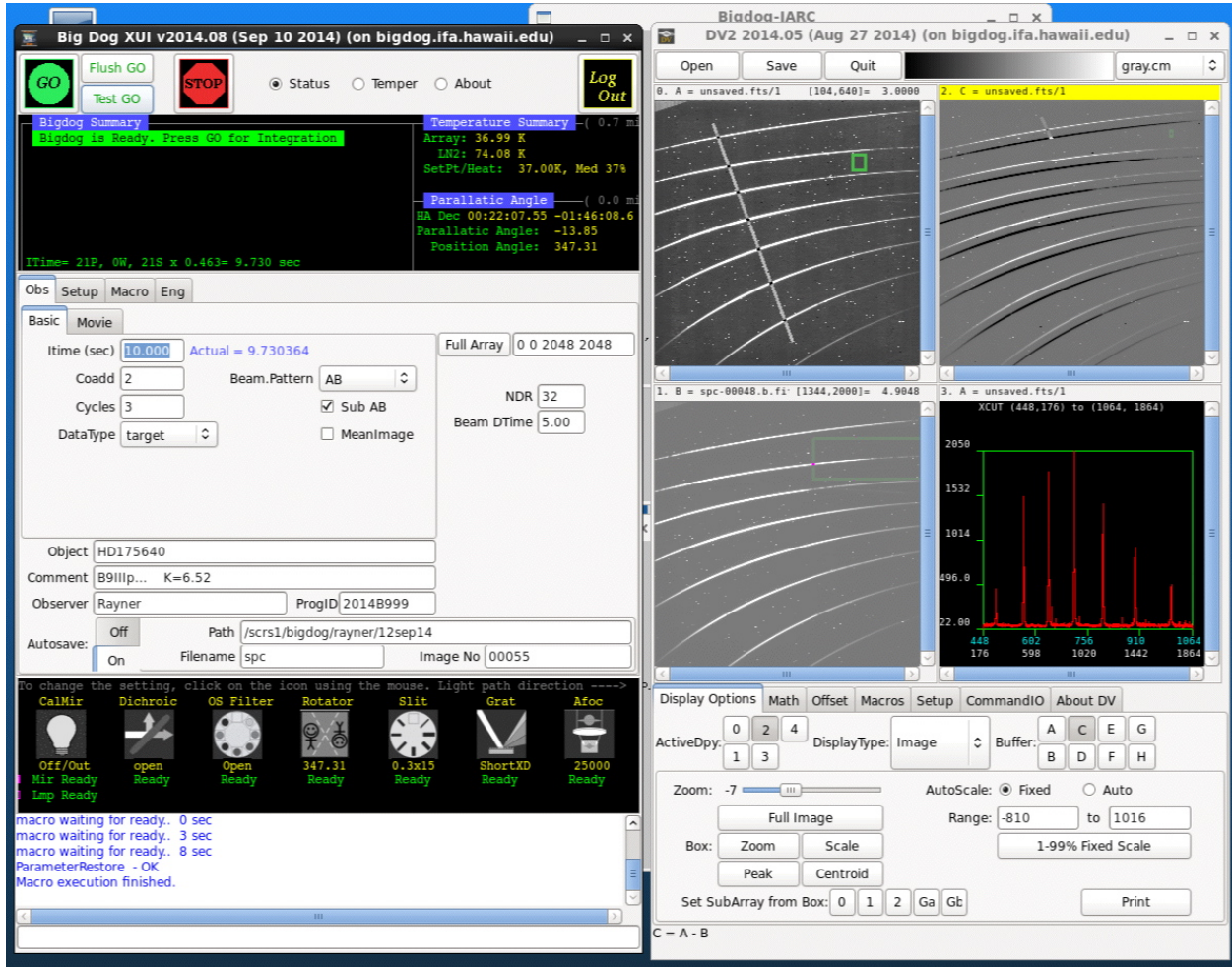   c. Click *Execute*

Figure 4-1. Bigdog user interface showing BXUI on the left and the Bigdog Data Viewer (BDV) on the right. Mechanisms are moved by clicking on the icons at the bottom of BXUI and then selecting positions from a pull-down menu. An SXD point-source spectrum is shown in BDV. A line is drawn across the spectra in the top-left DV pane and an *XLineCut* plotted in the bottom-right pane to find the maximum signal rate and to set the *itime*. By default beam A goes into buffer A and is display in panel zero (top-left), beam B (nodded 7.5″ within the 15″ long slit) goes into buffer B and is displayed in panel one (bottom-left), and the A-B beam goes into buffer C and is displayed in panel two (top-right). Counting from the top SXD mode covers orders 3-10 although order 10 is not extracted in Spextool since it completely overlaps with order 9 and is fainter.

4.1 SXD mode

The short wavelength cross-dispersed (SXD) mode covers spectral orders 3-10. The grating blaze peak is designed to be at about 6.6 μm in first order and so the blaze in order three is at 2.2 μm, in order four at 1.65 μm, in order five at 1.32 μm etc., although in practice the peaks are slightly shifted to shorter wavelengths. Figures 4-2 (orders 9-6) and 4-3 (orders 5-3) show spectral extractions for each order out to the edge of the array for an A0V telluric standard star. The intrinsic A0V stellar spectrum is multiplied by the grating blaze function, instrument throughput (optics and array QE), and telluric spectrum.
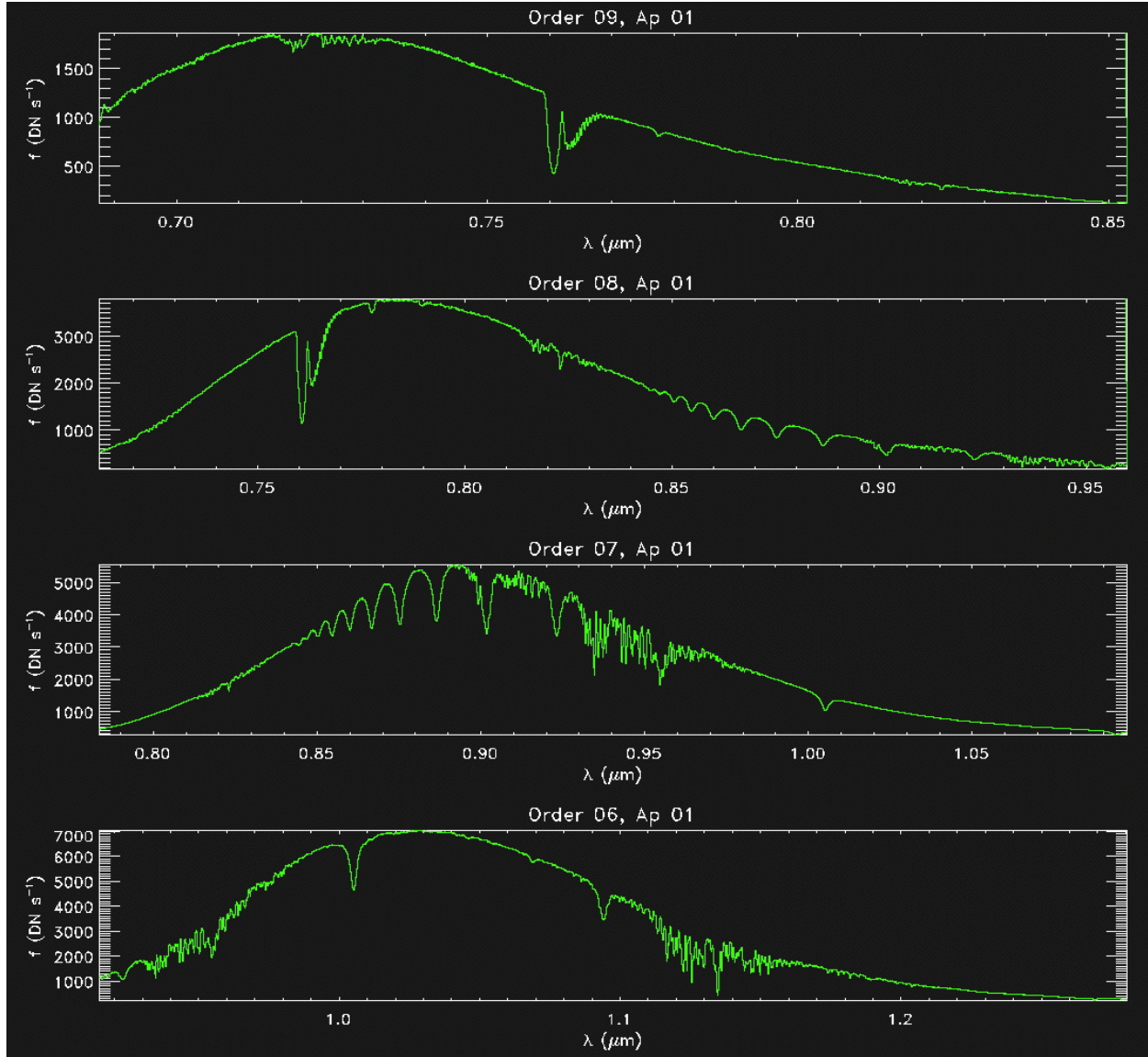

Figure 4-2. SXD mode spectral extractions, orders 9-6, for an A0V star. The intrinsic A0V spectrum is multiplied by the grating blaze function, instrument throughput, and telluric spectrum. The extractions for each order go all the way to the edge of the array (i.e. where any part of the 15″ slit contacts the edge of the array).

In SXD mode on-chip integration times are limited by object brightness and not by nighttime sky brightness, even in the wider slits. The brightest features in the sky are OH emissions lines. Even so we do not recommend on-chip integration times (*itime*) longer than about 200 s since at least three cycles (six images) are needed to remove random noisy pixels and to mitigate against OH emission line variability.
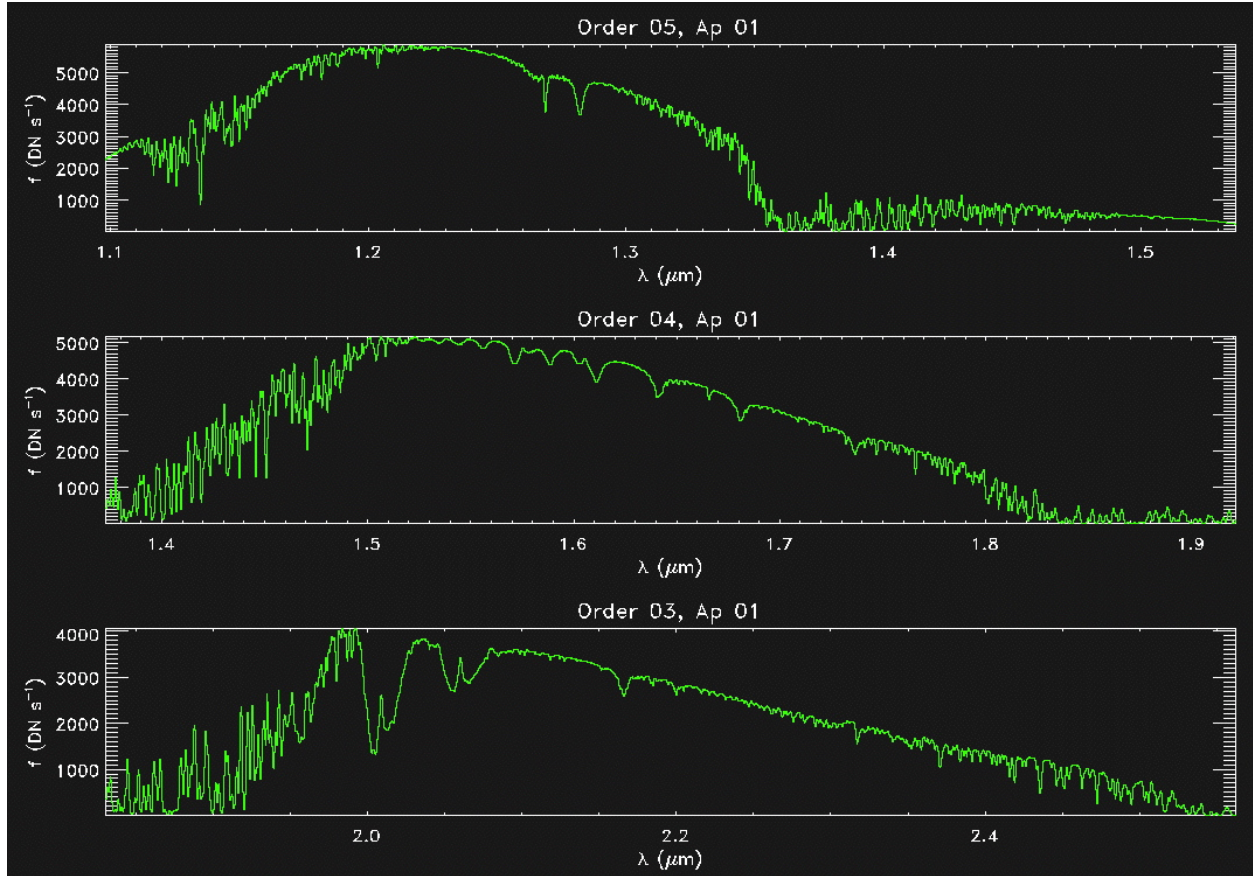

Figure 4-3. SXD mode spectral extractions, orders 5-3, for an A0V star.

A resolving power of $R=2000$ is matched to the 0.3″ slit width in SXD mode. However, as expected from the standard grating equation R varies slightly with diffraction angle and therefore with wavelength as shown for order three in Figure 4-4. The other orders show similar trends. R also scales with slit width.
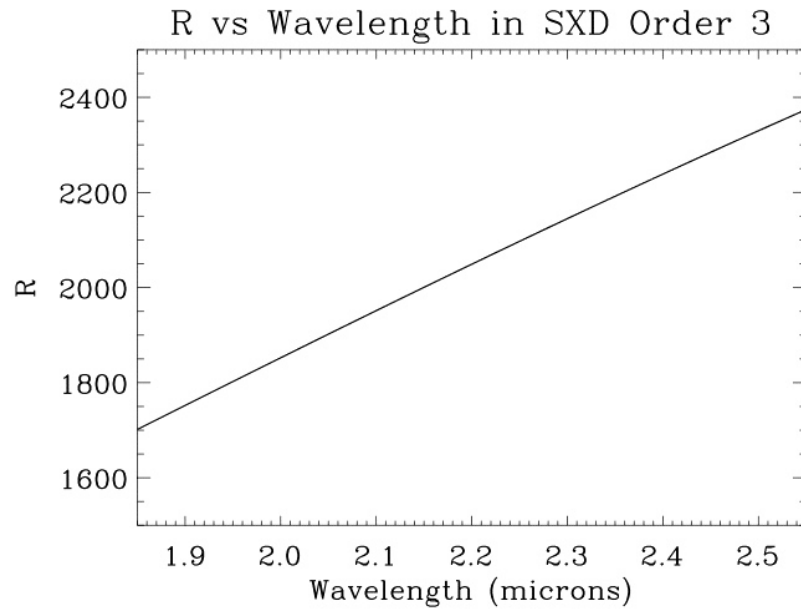
Figure 4-4. Variation of resolving power R with wavelength in order three.

4.2 Prism mode

In prism mode spectral dispersion is done with a fused silica prism and so there are no spectral orders. Figure 4-5 shows prism spectra of an A0V telluric standard star in BDV: the A beam in panel zero (top-left), the B beam nodded 7.5″ within the 15″ long slit in panel one (bottom-left), and A-B beam in panel two (top-right). The slit width was 0.3″. Note the rising sky continuum level at $\lambda > 2.5$ μm (towards the right in BDV. This together with telluric absorption at $\lambda > 2.5$ μm limits the long wavelength limit to about 2.52 μm. The effective cut-off at about 0.7 μm is due to absorption in the AR coatings of the ZnS lenses used in the foreoptics and spectrograph.
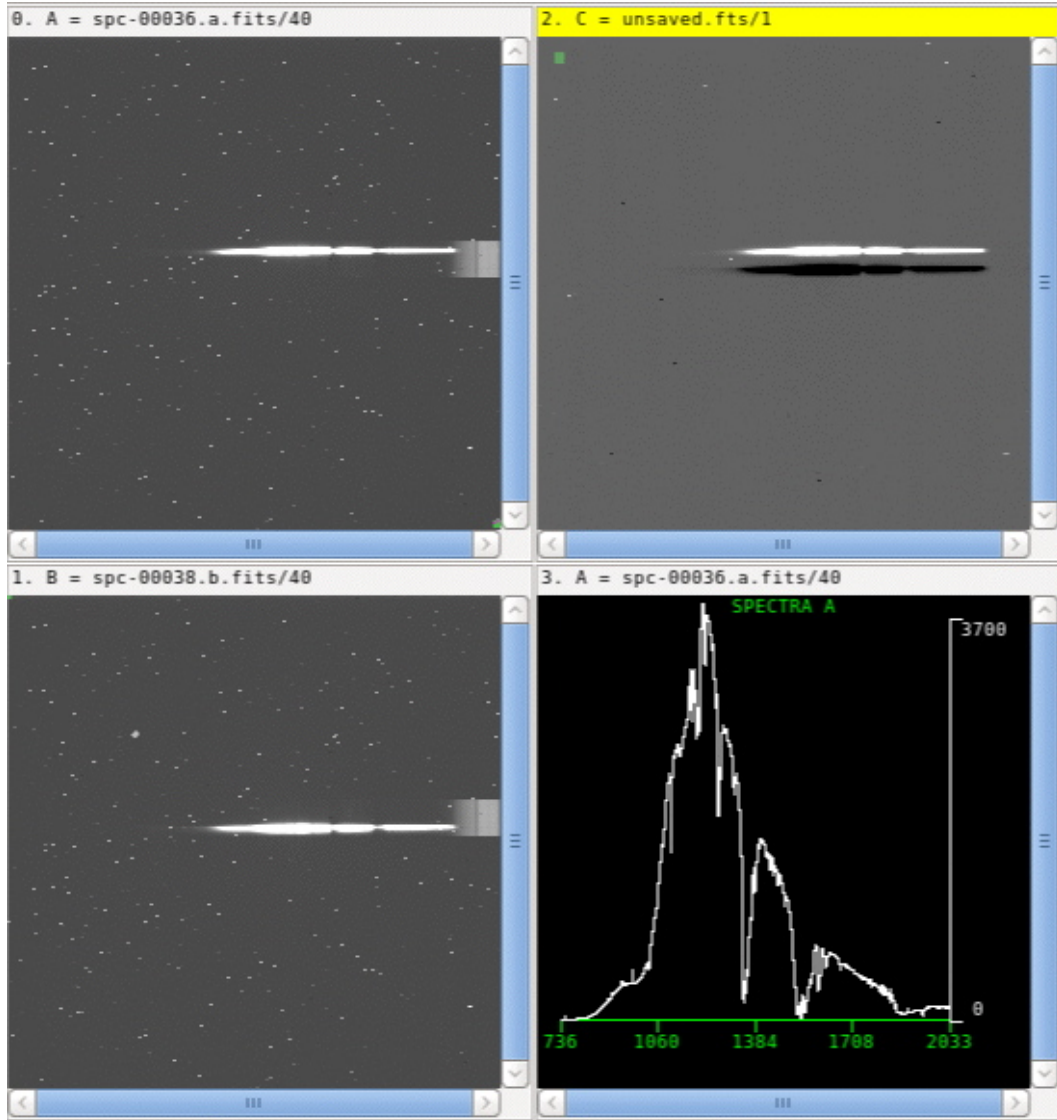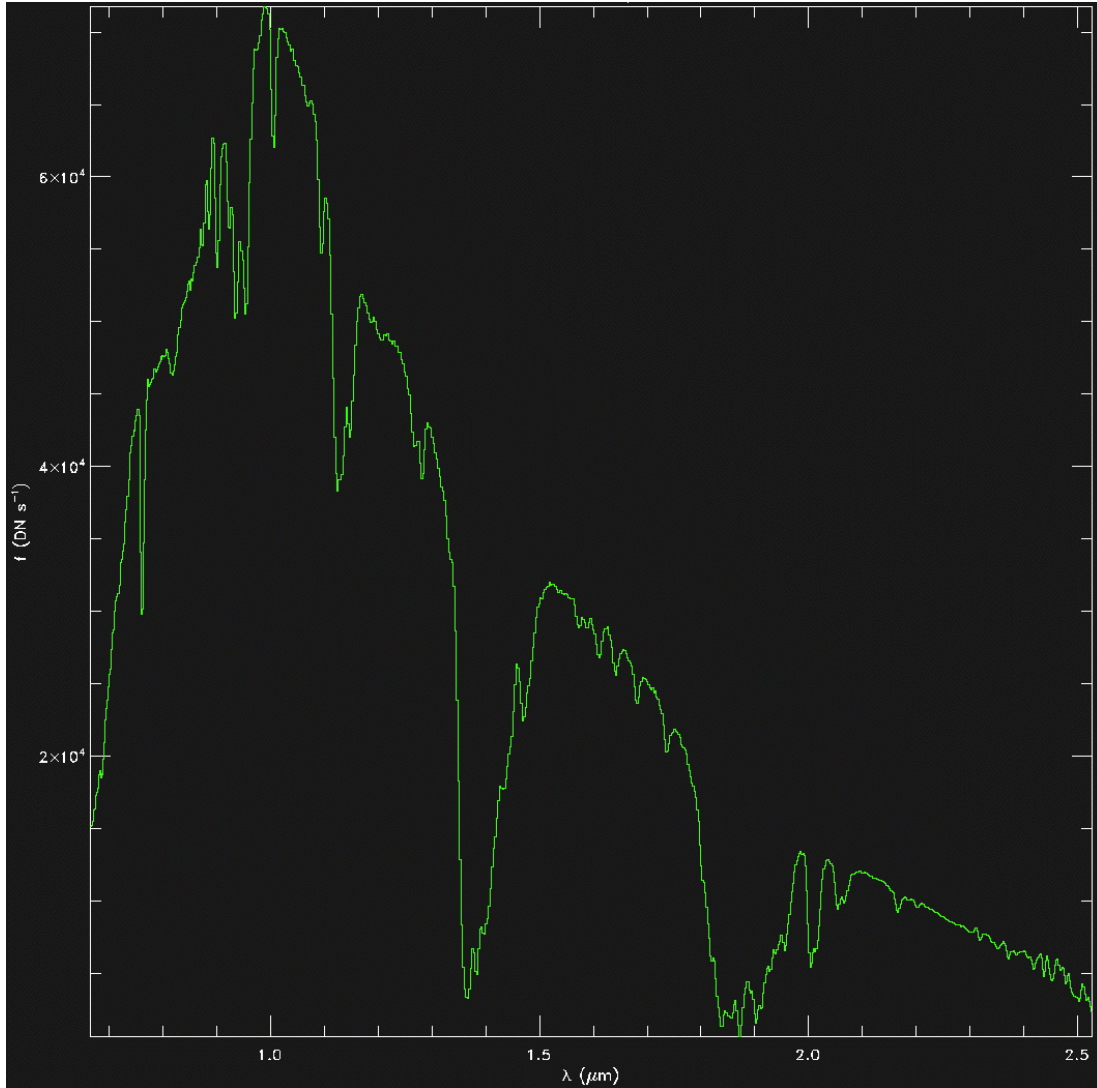

Figure 4-5. An A0V telluric standard star prism spectrum as it appears in BDV: A beam in panel zero (top-left), B beam in panel one (bottom left), and A-B beam in panel two (top-right). Panel three shows an intensity plot versus pixel number for the raw A beam (in DV select *Spectra A* in *DisplayType* and draw a box over the spectrum).

Figure 4-6. Prism mode spectral extraction for an A0V telluric standard star with a slit width of 0.3″. The intrinsic A0V spectrum is multiplied by the instrument throughput and telluric spectrum.

Figure 4-6 shows a spectral extraction of an A0V telluric standard star in prism mode with a slit width of 0.3″. The intrinsic A0V stellar spectrum is multiplied by the grating blaze function, instrument throughput (optics and array QE), and telluric spectrum. The decrease in signal towards longer wavelength is due to the decreasing intrinsic flux from the star while the decreasing signal at short wavelengths is due to decreasing efficiency of the AR coats (optimized for 0.9-5 μm) and array QE.

In prism mode on-chip integration times are limited by object brightness and not by nighttime sky brightness, even in the wider slits. The brightest features in the sky are OH emissions lines. Even so we do not recommend on-chip integration time (*itime*) longer than about 200 s due to OH variability and the desire for accurate sky subtraction.

The resolving power *R* changes by over a factor of two across the 0.7-2.5 μm wavelength range due to the change in refractive index of the fused-silica prism material (see Figure 4-7). The average is about *R*=200

matched to a slit width of 0.3″. R also scales with slit width. With no grating blaze function and the reduced number of optical surfaces the throughput of prism mode is about twice that of the cross-dispersed instrument modes.
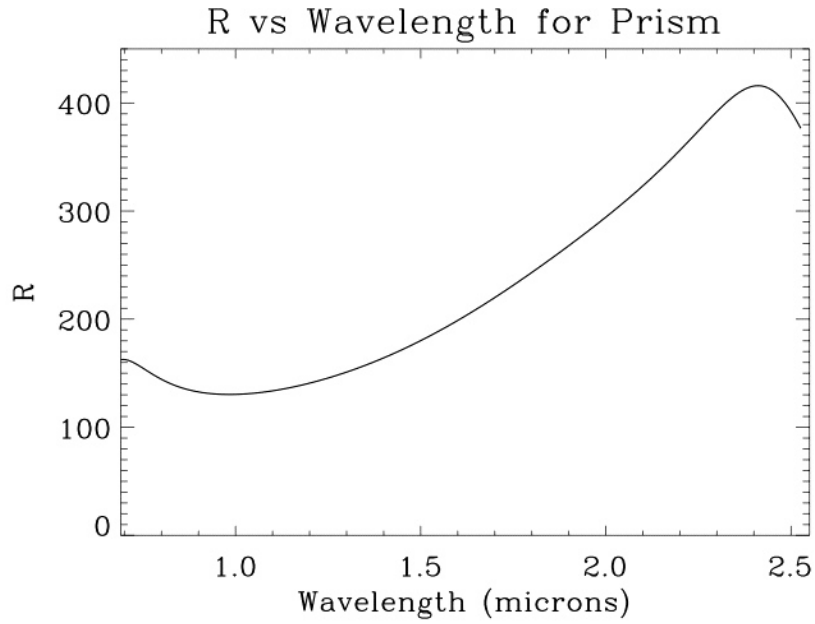
Figure 4-7. Variation of prism resolving power *R* with wavelength for a slit width of 0.3″.

4.3 LXD_short mode

The long wavelength cross-dispersed mode (LXD) has one grating-prism combination that can be tilted slightly by rotating the grating turret (0.9 degrees) to get two slightly different wavelength ranges. The long wavelength short cut-off cross-dispersed mode (LXD_short) covers wavelengths 1.67-4.2 μm in spectral orders 5-12 and the long wavelength long cut-off cross-dispersed mode (LXD_long) covers wavelengths 1.98-5.3 μm in spectral orders 4-10. The grating blaze peak is designed to be at about 20 μm in first order and so the blaze peak in order four is at 5.0 μm, in order five at 4.0 μm, in order six at 3.3 μm etc., although in practice the peaks are slightly shifted to shorter wavelengths. Given the high sky background and relatively poor telluric transmission in order four at 4.5-5.3 μm the LXD_long mode is only useful for bright objects ($M' < 7$ magnitudes).

Figure 4-8 shows LXD_short spectra of an A0V telluric standard star in BDV: the A beam in panel zero (top-left), the B beam nodded 7.5″ within the 15″ long slit in panel one (bottom-left), and A-B in panel two (top-right). The slit width was 0.3″. Note the increasing sky background at longer wavelengths. This causes some scattered light in the raw spectra but this is successfully removed in the A-B subtraction.

Figures 4-9 (orders 12-9) and 4-10 (orders 8-5) show spectral extractions for each order out to the edge of the array for an A0V telluric standard star. The intrinsic A0V stellar spectrum is multiplied by the grating blaze function, instrument throughput (optics and array QE), and telluric spectrum.

Except for very bright sources (point sources $L' < 6$) on-chip integration times in LXD_short mode are limited by sky brightness at 4 μm. In good sky conditions on-chip integration times are limited to about 30 s in the 0.3″ slit width (and proportionately shorter in wider slits). Nods to the sky should be done no longer than every minute (including any overhead).

A resolving power of $R=2500$ is matched to the 0.3″ slit width in LXD mode. However, as expected from the standard grating equation varies slightly with diffraction angle and therefore with wavelength as shown for order four in Figure 4-11. The other orders show similar trends. R also scales with slit width.

Wavelength calibration in SpeXtool for LXD_short mode uses both the arc lamps and sky lines. Arc and flat lamp data are taken using the calibration macros, as described on page 34 in Section 4. Additionally, the observer should take a spectral image of blank sky, with the target off of the slit, for each target. This exposure only needs to be long enough to clearly show the sky lines.
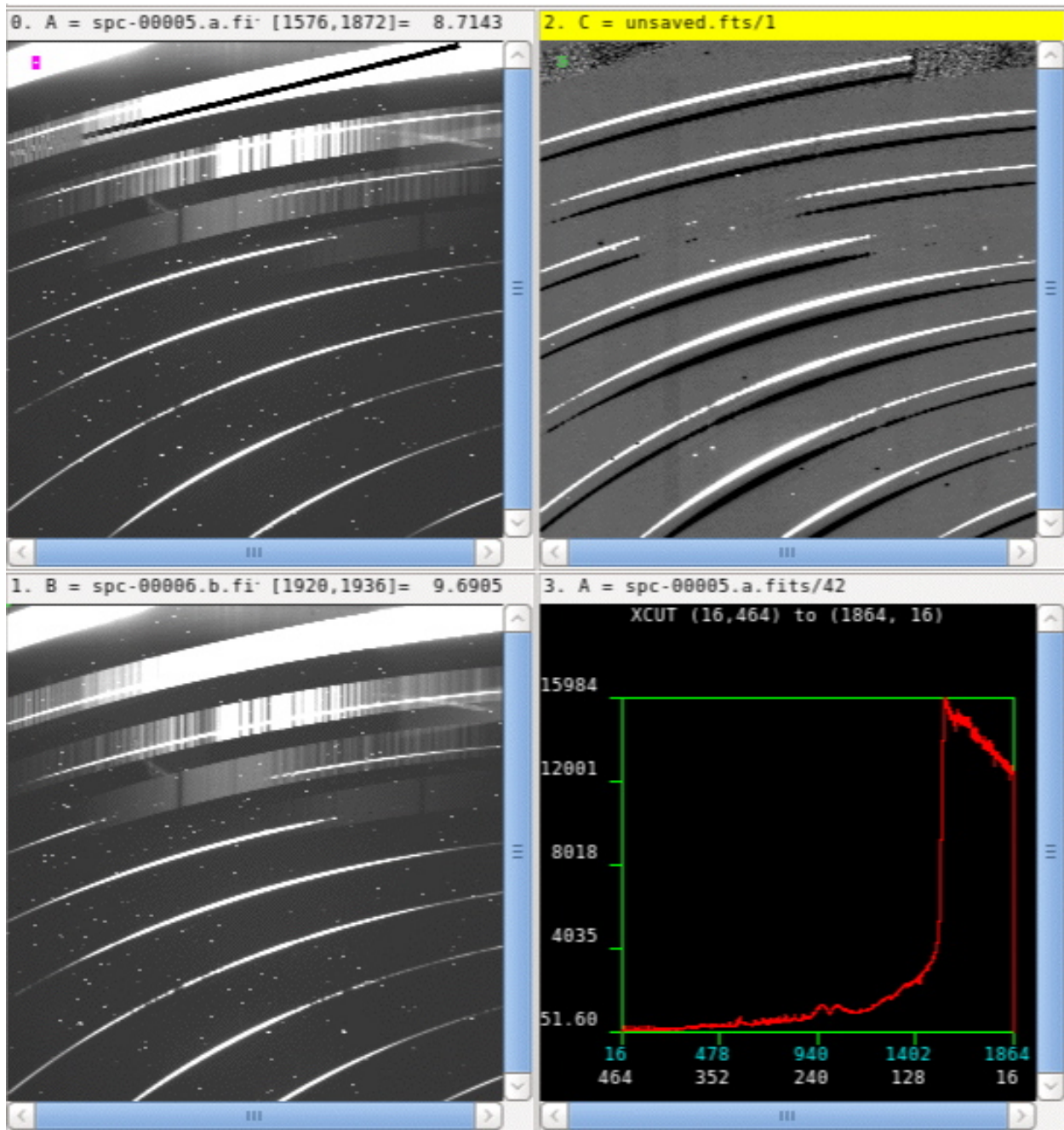
Figure 4-8. An A0V telluric standard star spectrum in LXD_short mode as it appears in BDV: A beam in panel zero (top-left), B beam in panel one (bottom left), and A-B beam in panel two (top-right). Panel three shows an intensity plot versus pixel number for the *xlinecut* drawn in panel one (in DV select *xlinecut* in *DisplayType*). The background increases exponentially toward the atmospheric cut off at 4.2 μm.
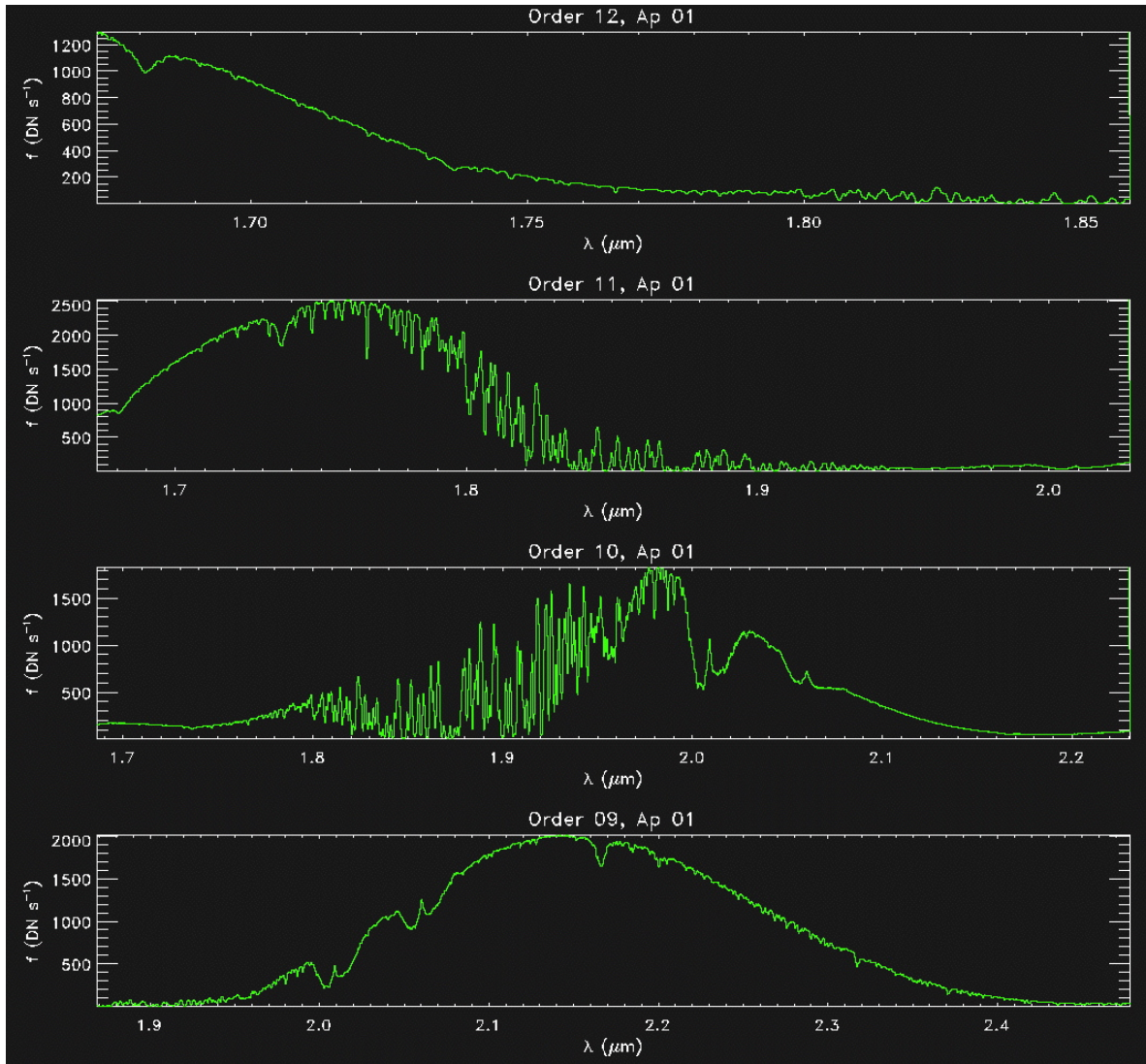
Figure 4-9. LXD_short mode spectral extractions, orders 12-9, for an A0V star. The intrinsic A0V spectrum is multiplied by the grating blaze function, instrument throughput, and telluric spectrum. The extractions for each order go all the way to the edge of the array (i.e. where any part of the 15″ slit contacts the edge of the array).
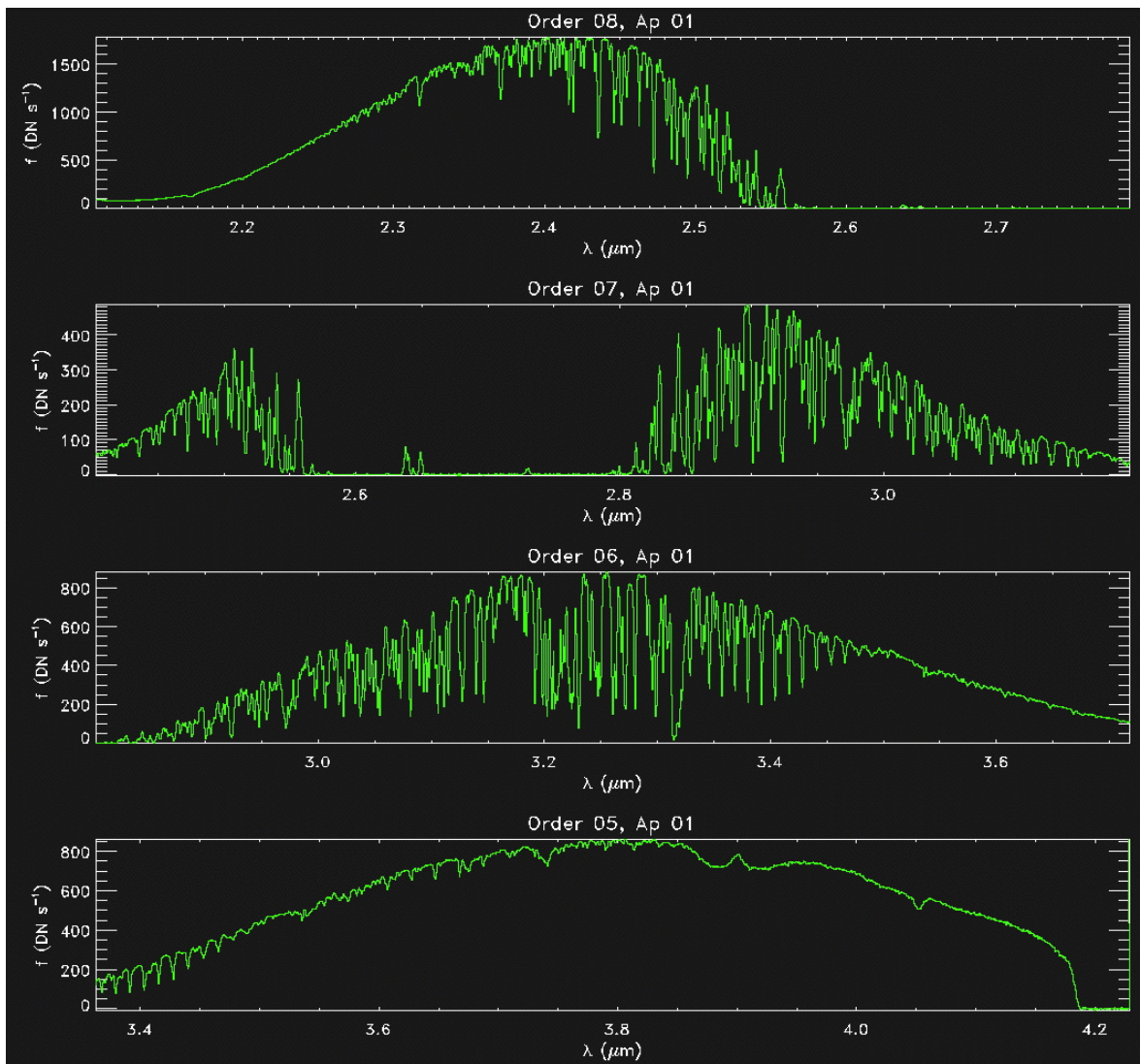
Figure 4-10. LXD_short mode spectral extractions, orders 8-5, for an A0V star.
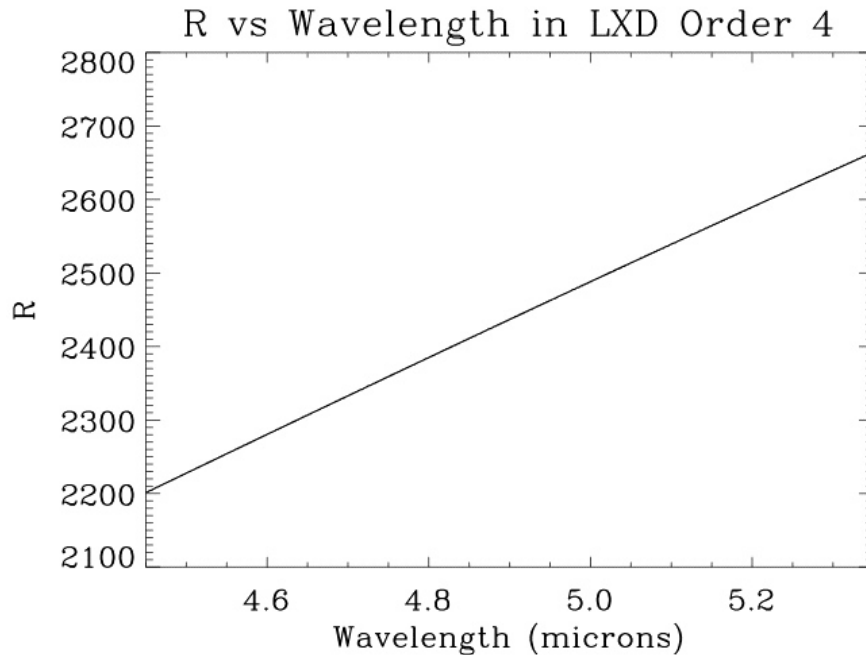
Figure 4-11. Variation of resolving power *R* with wavelength in LXD order four.

4.4 LXD_long mode

The long wavelength long cut-off cross-dispersed mode (LXD_long) covers wavelengths 1.98-5.3 μm in spectral orders 4-10. Given the high sky background and relatively poor telluric transmission in order four at 4.6-5.3 μm the LXD_long mode is only useful for bright sources (point source M'< 7 magnitudes). The long wavelength cut off at 5.3 μm is due to the H2RG detector material.

Figure 4-12 shows LXD_long spectra of an A0V telluric standard star in BDV: the A beam in panel zero (top-left), the B beam nodded 7.5″ within the 15″ long slit in panel one (bottom-left), and A-B in panel two (top-right). The slit width was 0.3″. Note the increasing sky background at longer wavelengths. This causes some scattered light in the raw spectra but this is successfully removed in the A-B subtraction.

Figures 4-13 shows an A0V star spectral extraction for the additional 5 μm order (and long wavelength part of the 4 μm order) accessible with the LXD_long mode out to the edge of the array. The intrinsic A0V stellar spectrum is multiplied by the grating blaze function, instrument throughput (optics and array QE), and telluric spectrum.

Except for very bright sources (point sources M'< 4) on-chip integration times in LXD_long mode are limited by sky brightness at 5 μm. In good sky conditions on-chip integration times are limited to about 3 s in the 0.3″ slit width (and proportionately shorter in wider slits). Nods to the sky should be done no longer than every minute (including any overhead).

Wavelength calibration in SpeXtool for LXD_long mode uses both the arc lamps and sky lines. Arc and flat lamp data are taken using the calibration macros, as described on page 34 in Section 4. Additionally, the observer should take a spectral image of blank sky, with the target off of the slit, for each target. This exposure only needs to be long enough to clearly show the sky lines.
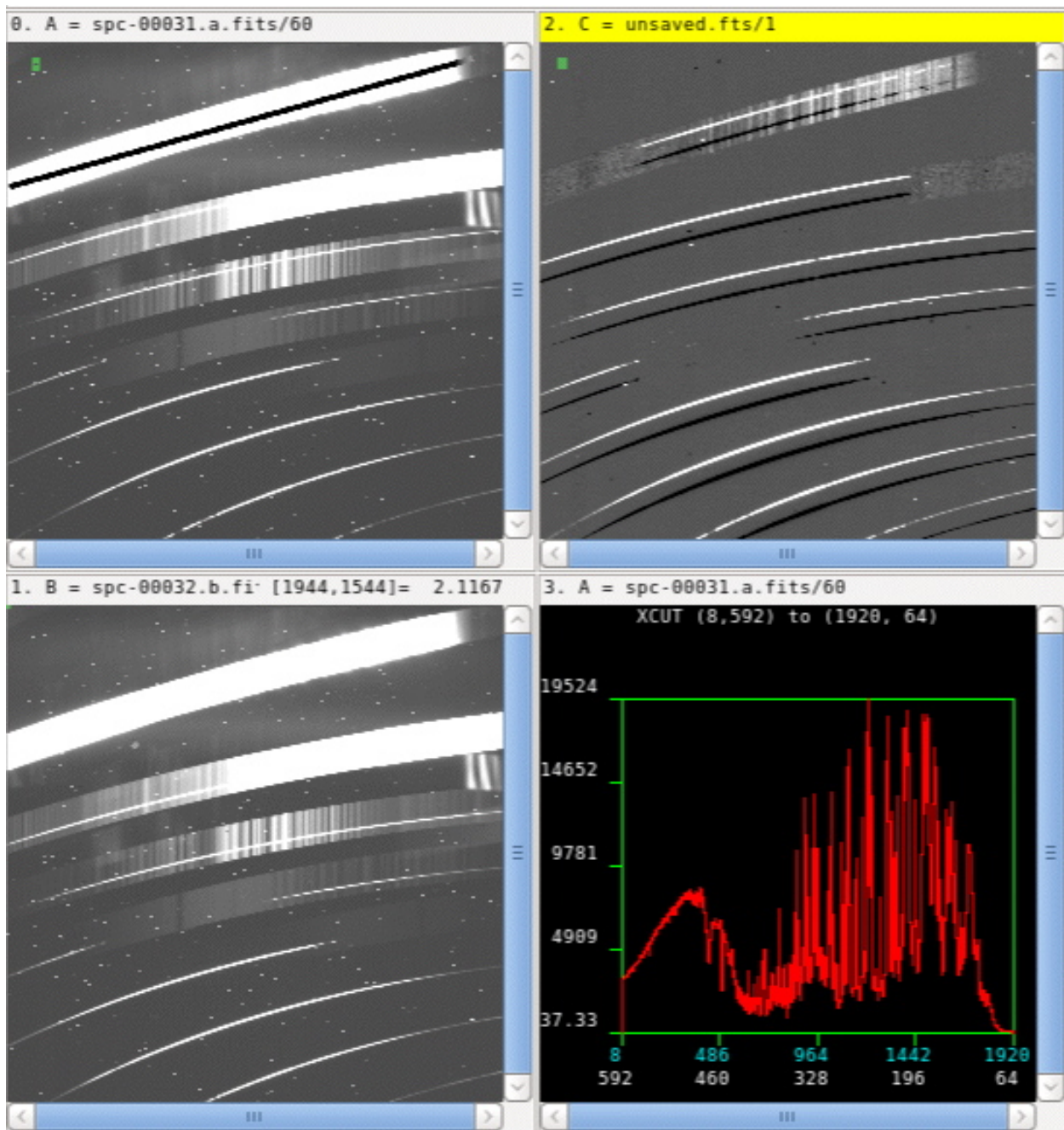
Figure 4-12. An A0V telluric standard star spectrum in LXD_long mode as it appears in BDV: A beam in panel zero (top-left), B beam in panel one (bottom left), and A-B beam in panel two (top-right). Panel three shows an intensity plot versus pixel number for the *xlinecut* drawn in panel zer0 (in DV select *xlinecut* in *DisplayType*). Note the high background and poor telluric transmission at $\lambda > 5.0$ μm. The feature at the right hand edge of orders five and six is a ghost, a narcissus reflection of the grating in the prisms. Since it is from the bright sky and telescope background it subtracts out very well.
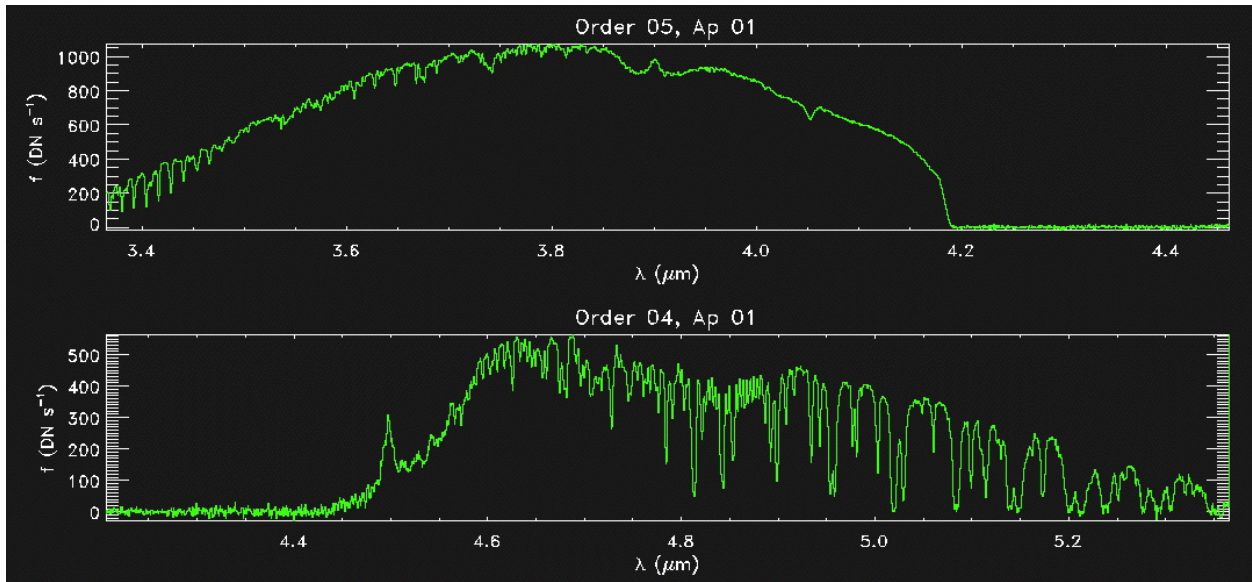
Figure 4-13. Spectral order four at 4.5-5.3 μm is the additional order accessible in LXD_long mode.

4.5 Single-order mode

In single-order mode cross-dispersing prisms are not used. This means that only one spectral order can be observed at a time. However, the throughput is about 20% higher. The order is selected by choosing the appropriate order-sorting filter (see Table 13). Since the order sorter is in the foreoptics, which are in front of the slit and Guidedog, guiding must be done through the order-sorting filter. A slit length of 15″ or 60″ can be used.

Table 13. Order sorter filter wheel.

Position	Filter	Comment
0	Open	
1	*PK_50* pass < 2.5 μm	Blocker for guider filters
2	*SP_2.5* pass < 2.5 μm	Not used
3	*0.1 x STOP*	Reduce flux by x 10
4	*Long4* 4.40-6.00 μm	Single-order long
5	*Long5* 3.59-4.14 μm	Single-order long
6	*Long6* 3.13-3.53 μm	Single-order long
7	*Short3* 1.92-2.52 μm	Single-order short
8	*Short4* 1.47-1.80 μm	Single-order short
9	*Short5* 1.17-1.37 μm	Single-order short
10	*Short6* 1.03-1.17 μm	Single-order short
11	Short7 0.91-1.00 μm	Single-order short
12	CH_4_s 1.58 μm 6%	Imaging
13	CH_4_l 1.69 μm 6%	Imaging
14	Blank	Closed

4.5.1 Single-order short mode

This mode is similar to SXD mode except only one order can be done at a time. The same on-chip integration time limitations apply (see Section 4.1). Guiding through the order-sorting filter (*Short3, Short4, Short5, Short6 or Short7*) does not usually present any problems. For calibration use the equivalent SXD macro e.g. for the 0.3″ slit use the *ucal_sxd_0.3* macro.

4.5.2 Single-order long mode

This mode is similar to LXD mode except only one order can be done at a time. The same on-chip integration time limitations apply (see Section 4.3). Guiding through the order-sorting filter (*Long4, Long5 or Long6*) is problematic because of the high background at these wavelengths. Consequently, it is usually best to use the off-axis guider or MORIS. For calibration use the single order long macros e.g. for the 0.3″ slit use the *ucal_single_order_long_0.3* macro.

5 IMAGING

5.1 Operation

Imaging is done with the 512 x 512 Aladdin 3 InSb array in Guidedog. The FOV is 60″ x 60″ and the pixel scale is 0.12″ per pixel. See Section 2.1 and Table 3 for a description of the array characteristics. The primary purpose of Guidedog is for acquisition and guiding in the infrared (see Section 3) but it can also be used for photometry and science. Filters in both the guider filter wheel (see Table 7) and order sorter filter wheel (see Table 13) can be used. To avoid 'crossing' the filters make sure to use the appropriate *open* positions in either wheel. A few filters in the guider filter wheel require blocking with the *PK50* filter in the order sorter filter wheel to block long wavelength leaks.

To obtain the full 60″ x 60″ FOV set the position angle of the rotator to zero degrees to avoid vignetting in the corners of the array. Imaging can be done in any of the slit in positions (see Table 6). Moving the slit will disturb the spectrograph calibration. Otherwise use the *mirror* position in the slit wheel to image without a slit.

As described in Section 3 Guidedog is controlled from GXUI and GDV (see Figure 3-1). For basic imaging the *Basic* window in the *Obs* window is used. Telescope dither macros are run from the *Macro* window (see Figure 5-1). Observers can also write their own macros.
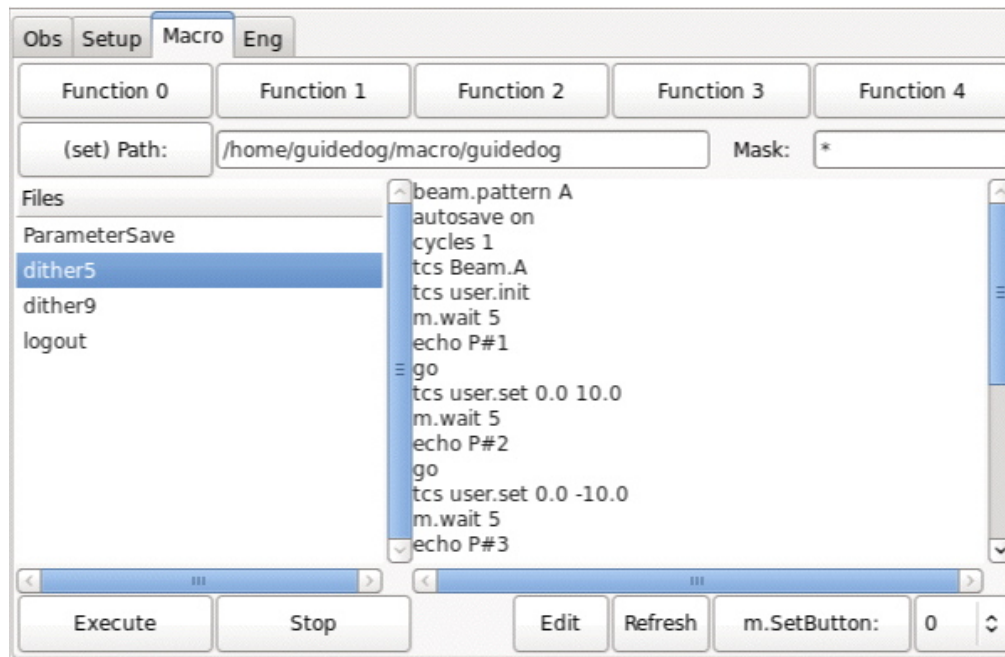

Figure 5-1. Dither macros are run from the *Macro* window. Click on *Execute* to run.

5.2 Flat fielding

The flat field lamps are designed for use with the spectrograph and are too bright and spatially non-uniform to be used for imaging flats. Nighttime sky flat fields work well at *JHK*. Typical integrations times are about one minute. (A total summed signal of 10,000 photo-electrons is required for a S/N of 100). Several

dithered sky images should median combined and normalized to produce a good flat. Short wavelength narrow band filters (λ < 2.4 μm) and the *Z* filter will require twilight flats.

Flat fielding at thermal wavelengths (λ > 3 μm) does not work since thermal sky flux coming *through* the telescope is added to by thermal flux *from* the telescope i.e. the flux does not all come through the optical path as it should for accurate flat fielding. Flat fields constructed from sky dips (high air mass minus low air mass to remove the telescope component) have been tried but we have found that the best method is simply to dither objects around the array by about 10″ per dither position. Without dithering thermal photometry is accurate to a S/N of about 20 (5%) and with dithering it is accurate to a S/N of about 50 (2%). For single stars if the target star and standard star are placed at the same position on the array (avoiding bad pixels) flat fielding is not required and photometry is more accurate.

5.3 Sensitivity

The predicted nighttime sky background for Guidedog in broadband filters (*R*=6) using an instrument, telescope and sky model is plotted in Figure 5-2. The measured array performance from Table 4 is used. The predictions are in good agreement with the photon rates measured at the detector.
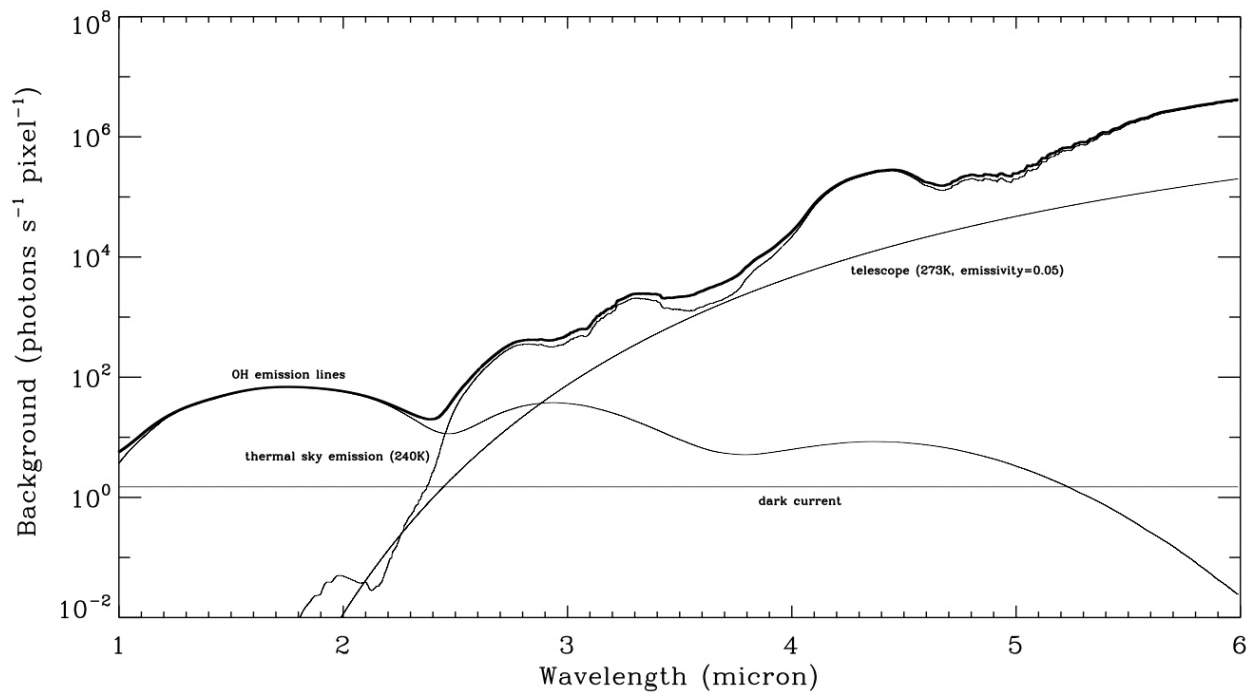
Figure 5-2. Predicted background at the array in Guidedog for broadband filters (R~6). The model assumes a pixel size of 0.12″, a throughput of about 0.2 and a 3 m telescope on Maunakea (2mm of water at 1.15 air mass).

Measured imaging point-source sensitivities for Guidedog are given in Table 14.

Table 14. Measured Guidedog point-source sensitivity in 0.7″ seeing. The observations were background limited.

	10σ1minute	*10σ10minutes*
J_{MK}	18.3	19.5
H_{MK}	17.5	18.7
K_{MK}	17.0	18.2
L'_{MK}	11.9	13.2