SpeX Observing Manual

John Rayner
NASA Infrared Telescope Facility
Institute for Astronomy
University of Hawaii

Revision History

<table>
<thead>
<tr>
<th>Revision No.</th>
<th>Author</th>
<th>Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revision 1</td>
<td>John Rayner</td>
<td>29 Sept. 2014</td>
<td>First release</td>
</tr>
<tr>
<td>Revision 2</td>
<td>John Rayner</td>
<td>06 March 2015</td>
<td>Second release</td>
</tr>
<tr>
<td>Revision 3</td>
<td>Mike Connelley</td>
<td>30 Aug. 2017</td>
<td>Third release</td>
</tr>
</tbody>
</table>
# Contents

1 INTRODUCTION .................................................................................................................. 3  
1.1 Abbreviations .................................................................................................................. 4   
2 UPGRADE CHANGES ........................................................................................................... 5  
2.1 Spectrograph ..................................................................................................................... 5   
2.2 Slit Viewer ........................................................................................................................ 9   
2.3 Spectrograph sensitivity .................................................................................................... 10   
2.4 Spectrograph S/N widget in DV ........................................................................................ 10  
2.5 Spectrograph observing efficiency .................................................................................... 12  
2.6 Data size, transfer and storage ........................................................................................ 13   
3 ACQUISITION AND GUIDING ........................................................................................... 14   
3.1 Imaging and acquisition ..................................................................................................... 16   
3.2 Guiding .............................................................................................................................. 18    
   3.2.1 IR guiding with SpeX ................................................................................................... 18  
   3.2.2 Visible guiding with MORIS ...................................................................................... 23  
   3.2.3 Using the MORIS Widget .......................................................................................... 26  
   3.2.4 Visible guiding with the off-axis guider ....................................................................... 29  
4 SPECTROSCOPY ................................................................................................................ 30   
4.1 SXD mode .......................................................................................................................... 32  
4.2 Prism mode ....................................................................................................................... 35  
4.3 LXD_short mode ............................................................................................................... 38  
4.4 LXD_long mode ............................................................................................................... 42  
4.5 Single-order mode ............................................................................................................ 45    
   4.5.1 Single-order short mode .............................................................................................. 45  
   4.5.2 Single-order long mode ................................................................................................ 45  
5 IMAGING .............................................................................................................................. 46  
5.1 Operation ............................................................................................................................ 46  
5.2 Flat fielding ....................................................................................................................... 46  
5.3 Sensitivity ........................................................................................................................... 47
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.

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

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>Anti-reflection (coat)</td>
</tr>
<tr>
<td>ARC</td>
<td>Astronomical Research Cameras (array controller vendor)</td>
</tr>
<tr>
<td>BDV</td>
<td>Bigdog data viewer screen</td>
</tr>
<tr>
<td>BXUI</td>
<td>Bigdog X-windows user interface</td>
</tr>
<tr>
<td>DN</td>
<td>Data number (intensity display unit in DV)</td>
</tr>
<tr>
<td>DV</td>
<td>Data viewer display</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of view</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width half maximum</td>
</tr>
<tr>
<td>GDV</td>
<td>Guidedog data viewer screen</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical user interface</td>
</tr>
<tr>
<td>GXUI</td>
<td>Guidedog X-windows user interface</td>
</tr>
<tr>
<td>H2RG</td>
<td>Hawaii-2RG detector array</td>
</tr>
<tr>
<td>IfA</td>
<td>Institute for Astronomy, University of Hawaii</td>
</tr>
<tr>
<td>IRTF</td>
<td>Infrared Telescope Facility</td>
</tr>
<tr>
<td>itsme</td>
<td>On-chip integration time</td>
</tr>
<tr>
<td>LXD</td>
<td>Long wavelength cross-dispersed mode</td>
</tr>
<tr>
<td>MDV</td>
<td>MORIS data viewer</td>
</tr>
<tr>
<td>MORIS</td>
<td>MIT Optical Rapid Imaging System</td>
</tr>
<tr>
<td>MXUI</td>
<td>MORIS X-windows user interface</td>
</tr>
<tr>
<td>NDR</td>
<td>Non-destructive read</td>
</tr>
<tr>
<td>QE</td>
<td>Quantum efficiency</td>
</tr>
<tr>
<td>R</td>
<td>Resolving power (λ/Δλ)</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean squared</td>
</tr>
<tr>
<td>S/N</td>
<td>Signal (S) to noise (N) ratio</td>
</tr>
<tr>
<td>SV</td>
<td>Slit viewer</td>
</tr>
<tr>
<td>SXD</td>
<td>Short wavelength cross-dispersed mode</td>
</tr>
<tr>
<td>TBC</td>
<td>To be confirmed</td>
</tr>
<tr>
<td>TCS</td>
<td>Telescope control system at IRTF</td>
</tr>
<tr>
<td>TO</td>
<td>Telescope operator</td>
</tr>
<tr>
<td>XD</td>
<td>Cross-dispersed/disperser</td>
</tr>
</tbody>
</table>
2 UPGRADE CHANGES

2.1 Spectrograph

The Aladdin 3 1012x1024 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.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Aladdin 3</th>
<th>Hawaii-2RG</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format</td>
<td>1024 x 1024</td>
<td>2048 x 2048 light sensitive</td>
<td></td>
</tr>
<tr>
<td>Number of readouts</td>
<td>32</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Sub-array?</td>
<td>Yes, any box</td>
<td>Yes, between rows only</td>
<td></td>
</tr>
<tr>
<td>Pixel size</td>
<td>27 µm</td>
<td>18 µm</td>
<td></td>
</tr>
<tr>
<td>Pixel operability</td>
<td>99%</td>
<td>99%</td>
<td></td>
</tr>
<tr>
<td>Useful wavelength range</td>
<td>0.8-5.5 µm</td>
<td>0.7-5.35 µm</td>
<td></td>
</tr>
<tr>
<td>Average QE</td>
<td>≈80%</td>
<td>≈80%</td>
<td>See plot below</td>
</tr>
<tr>
<td>Operating rev. bias</td>
<td>0.400 V</td>
<td>0.312 V</td>
<td></td>
</tr>
<tr>
<td>Pixel rate</td>
<td>15 µs/pixel (20 slowcents)</td>
<td>3 µs/pixel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5 µs/pixel (3 slowcents)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. full array read out</td>
<td>0.51 s (15 µs/pixel)</td>
<td>0.463 s (3 µs/pixel)</td>
<td></td>
</tr>
<tr>
<td>time</td>
<td>0.12 s (3.5 µs/pixel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read noise: single CDS</td>
<td>40 e RMS (15 µs/pixel)</td>
<td>12 e RMS (3 µs/pixel)</td>
<td></td>
</tr>
<tr>
<td>Read noise: 32 NDRs</td>
<td>12 e RMS (15 µs/pixel)</td>
<td>5 e RMS (3 µs/pixel)</td>
<td></td>
</tr>
<tr>
<td>Dark current</td>
<td>0.2 e/s</td>
<td>0.05 e/s</td>
<td>Median</td>
</tr>
<tr>
<td>Dark current + persistence</td>
<td>&gt;1.0 e/s</td>
<td>0.10 e/s</td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>12 e/DN</td>
<td>1.5 e/DN</td>
<td></td>
</tr>
<tr>
<td>Full well depth</td>
<td>7,000 DN</td>
<td>43,000 DN</td>
<td>To saturation</td>
</tr>
<tr>
<td></td>
<td>84,000 e</td>
<td>65,000 e</td>
<td></td>
</tr>
<tr>
<td>Linear well depth</td>
<td>4,000 DN</td>
<td>30,000 DN</td>
<td>Correctable to &lt; 1%</td>
</tr>
<tr>
<td></td>
<td>48,000 e</td>
<td>45,000 e</td>
<td></td>
</tr>
</tbody>
</table>

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 QE’s 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):**

\[
itime = \frac{30,000}{2 \times \text{rate}} - 0.5
\]

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 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 \(0.461 \times \text{the number of NDRs}\). 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.](image-url)
We also strongly recommend that observers acquire at least 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 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’. Although a median combine works very well (to the level of the read noise) we are planning to replace the final (ZnS) lens in the optical train by a similar lens with an AR coating free from radioactive elements.

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

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 noise 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**

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

<table>
<thead>
<tr>
<th>λ (µm)</th>
<th>SXD (0.3&quot; slit) R=2000</th>
<th>LXD (0.3&quot; slit) R=2500</th>
<th>PRISM (0.3&quot; slit) R~200</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aladdin 3 H2RG</td>
<td>Aladdin3 H2RG</td>
<td>Aladdin 3 H2RG</td>
</tr>
<tr>
<td>1.02</td>
<td>14.47</td>
<td>15.12</td>
<td>17.55 17.98</td>
</tr>
<tr>
<td>1.25</td>
<td>14.45</td>
<td>14.98</td>
<td>17.61 18.00</td>
</tr>
<tr>
<td>1.30</td>
<td>14.60</td>
<td>15.17</td>
<td>17.29 17.52</td>
</tr>
<tr>
<td>1.65</td>
<td>13.71</td>
<td>14.01</td>
<td>16.16 16.37</td>
</tr>
<tr>
<td>1.67</td>
<td>13.78</td>
<td>14.09</td>
<td>12.25 12.82</td>
</tr>
<tr>
<td>2.20</td>
<td>13.62</td>
<td>14.29</td>
<td>11.76 12.46</td>
</tr>
<tr>
<td>2.25</td>
<td>13.50</td>
<td>14.02</td>
<td>11.77 12.47</td>
</tr>
<tr>
<td>3.65</td>
<td></td>
<td>9.61</td>
<td>9.96</td>
</tr>
<tr>
<td>4.77</td>
<td></td>
<td>7.23</td>
<td>7.46</td>
</tr>
</tbody>
</table>

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:

\[
\frac{S}{N} = \frac{G(\text{objectbox} - \text{sidebox})}{\sqrt{G \times (\text{objectbox} - \text{sidebox}) + (G \times \text{skybox})}}
\]

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 Spectrograph observing efficiency

The **limiting flux calculator** on the SpeX 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.

<table>
<thead>
<tr>
<th>itime (s)</th>
<th>coadds</th>
<th>NDRs</th>
<th>Total itime (s)</th>
<th>Clock time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default number of NDRs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>2</td>
<td>30</td>
<td>71</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>3</td>
<td>30</td>
<td>63</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>21</td>
<td>30</td>
<td>62</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>32</td>
<td>30</td>
<td>47</td>
</tr>
<tr>
<td>60</td>
<td>1</td>
<td>32</td>
<td>60</td>
<td>77</td>
</tr>
<tr>
<td>120</td>
<td>1</td>
<td>32</td>
<td>120</td>
<td>137</td>
</tr>
<tr>
<td>NDRs manually set to 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>1</td>
<td>30</td>
<td>58</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>1</td>
<td>30</td>
<td>39</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>1</td>
<td>30</td>
<td>34</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>1</td>
<td>30</td>
<td>33</td>
</tr>
<tr>
<td>60</td>
<td>1</td>
<td>1</td>
<td>60</td>
<td>63</td>
</tr>
<tr>
<td>120</td>
<td>1</td>
<td>1</td>
<td>120</td>
<td>123</td>
</tr>
</tbody>
</table>

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.
2.6 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 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.

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 is 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 5). The slit mirrors reflect a 60"x60" FOV through the guider filter wheel (see Table 6) 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.

![Guidedog user interface showing the GXUI on the left and the GDV on the right.](image)

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 known 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.

<table>
<thead>
<tr>
<th>Position</th>
<th>Slit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Mirror/blank</td>
<td>Mirror to guider, blank-off to spectrograph</td>
</tr>
<tr>
<td>1</td>
<td>0.3” x 15”</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.5” x 15”</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.8” x 15”</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.6” x 15”</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3.0” x 15”</td>
<td>For spectro-photometry</td>
</tr>
<tr>
<td>6</td>
<td>0.3” x 60”</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.5” x 60”</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.8” x 60”</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1.6” x 60”</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3.0” x 60”</td>
<td>For spectro-photometry</td>
</tr>
</tbody>
</table>
Table 7. Guider filter wheel

<table>
<thead>
<tr>
<th>Position</th>
<th>Filter</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Z</td>
<td>0.95-1.11 µm</td>
</tr>
<tr>
<td>2</td>
<td>J$_{MK}$</td>
<td>1.164-1.326 µm</td>
</tr>
<tr>
<td>3</td>
<td>H$_{MK}$</td>
<td>1.487-1.783 µm</td>
</tr>
<tr>
<td>4</td>
<td>K$_{MK}$</td>
<td>2.027-2.363 µm</td>
</tr>
<tr>
<td>5</td>
<td>L$'_{MK}$</td>
<td>3.424-4.124 µm</td>
</tr>
<tr>
<td>6</td>
<td>M$'_{MK}$</td>
<td>4.562-4.803 µm + ND 1.0 (10%)</td>
</tr>
<tr>
<td>7</td>
<td>FeII</td>
<td>1.644 µm 1.5% Cross with PK50 blocker in OSF</td>
</tr>
<tr>
<td>8</td>
<td>H$_2$</td>
<td>2.122 µm v=1-0 s(1)</td>
</tr>
<tr>
<td>9</td>
<td>Br$\gamma$</td>
<td>2.166 µm 1.5%</td>
</tr>
<tr>
<td>10</td>
<td>cont-K</td>
<td>2.26 µm 1.5%</td>
</tr>
<tr>
<td>11</td>
<td>CO</td>
<td>2.294 µm 1.5% (2-0bh) + ND 2.0 (1%)</td>
</tr>
<tr>
<td>12</td>
<td>H+K notch</td>
<td>Optimized for faint object guiding</td>
</tr>
<tr>
<td>13</td>
<td>L$_{nb}$</td>
<td>3.454 µm 0.5%</td>
</tr>
<tr>
<td>14</td>
<td>ZJHK pass &lt; 2.5 µm</td>
<td></td>
</tr>
</tbody>
</table>

3.1 Imaging and acquisition

Images are taken with Guidedog in Basic mode. 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 a selectable 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 anytime by clicking the STOP button.

![Figure 3-3. Basic imaging mode window.](image-url)
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 (obsuring 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. Remove the telescope on-axis mirror and 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 7. Magnitude limits for manual guiding on spillover using the guide buttons in t3remote are about one magnitude fainter.

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

<table>
<thead>
<tr>
<th>Filter</th>
<th>Star in 0.5 &quot;slit (spill-over)</th>
<th>Star in field</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>K</td>
<td>15</td>
<td>17</td>
</tr>
</tbody>
</table>

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.

Detailed procedure:
1. Select desired slit and guider filter.
2. Slew to object and acquire (Section 3.1 above)
3. Set desired position angle on the sky. Click on rotator icon and either Sync Rotator to Parallactic Angle, or enter position angle and Set Rotator (deg).
4. Take an image of the field:
   a. In GUI select Basic (see Figure 3-3).
   b. Set desired itime, coadds and cycles.
   c. Go.

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 3-5).
   b. Move the star into the A box by offsetting the telescope. In GDV select the Offset panel and click Offset Telescope (see Figure 3.6).
   c. Check that the star is in the box by taking another image (Go) and redisplaying the guide boxes (Auto GuideBox Setup).

7. Without a three-button mouse there are alternative ways to move the star:
   a. 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.
   b. 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.
   c. Click Offset Telescope
8. Start guiding on star in slit:
   a. In the GXUI Obs panel select the Guiding panel (see Figure 3-7).
   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 3-4).
   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.

![Guiding panel](image)

Figure 3-8. Guiding panel. All items preceded by an asterisk (*) can be changed while guiding is in progress.
9. 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:
   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 3-8). 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 3-7 and 3-9).
   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.

10. 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.
   c. Click TakeSky. This needs to taken at the same itime as intended for guiding.
   d. Move guide star back into guide box (see items 8 and 9 above).
   e. Click Sub AB.
   f. Start guiding (see items 8 and 9 above). 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.

11. 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 H as necessary (see Figure 3-9).
   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 8 and 9 above.
   g. Click *Go* in GXUI to start guiding.

12. 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. Users operate MORIS from the MORIS X-windows User Interface (GXUI) and display data in the MORIS Data Viewer (GDV) (see Figure 3-10). 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 0.73 µm and 0.98 µm using MORIS limits the spectral range of SpeX. Without the dichroics SpeX can reach about 0.7 µm. Users operate MORIS from the MORIS X-windows User Interface (MXUI – see Figure 3-9), which is similar to GXUI. The dichroics reflect a 60”x60” FOV onto the E2V 512x512 CCD in MORIS. This is the same size and pixel scale (0.12”/pixel) as Guidedog. MORIS has its own filter wheel (see Table 8). Since the dichroics are in front of the internal SpeX rotator the orientation of the left in MORIS is fixed (north up and east to the left in DV). Guiding with MORIS is usually more precise than guiding on an object in the slit since the image centroid is more stable.

![MORIS user interface](image)

Figure 3-11. 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.
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:
1. Select desired slit, guider filter and dichroic.
2. Slew to object and acquire (Section 3.1 above)
3. Set desired position angle on the sky. Click on rotator icon and either Sync Rotator to Parallactic Angle, or enter desired position angle and Set Rotator (deg).
4. Take an image of the field:
   a. In GUI select Basic (see Figure 3-3).
   b. Set desired itime, coadds and cycles.
   c. Go.
      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. 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 reading the current 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. When using MORIS to guide the purpose of this step is to send the nod position to the TCS.
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 3-5).
   b. Move the star into the A box by offsetting the telescope. In GDV select the Offset panel and click Offset Telescope (see Figure 3.6).
   c. Check that the star is in the box by taking another image (Go) and redisplaying the guide boxes (Auto GuideBox Setup).

### Table 9. MORIS filter wheel

<table>
<thead>
<tr>
<th>Position</th>
<th>Filter</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>SDSS g</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>SDSS g</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>SDSS g</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>SDSS g</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Johnson V</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>VK</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>LPR 600</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>LPR 700</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>890_19nm CH₄</td>
<td></td>
</tr>
</tbody>
</table>
7. Without a three-button mouse there are alternative ways to move the star:
   a. 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.
   b. 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.
   c. Click Offset Telescope

8. Start continuous imaging of the star in the slit:
   a. In the GXUI Obs panel select the Guiding panel (see Figure 3-7).
   b. Set itime and coadds. If necessary subtract a sky (see section 3.2.1 item 10).
   c. Since guiding will be done with MORIS set CorrectTo to Off from the pull-down menu.
   d. If desired Autosave can be turned on in GXUI but this is not necessary to guide.
   e. Click Go in GXUI to start continuous imaging. By default the zoomed guide image will appear in ActiveDpy 3 buffer D in GDV.

In MORIS:

9. Select guider filter (see Table 8).

10. Take an image of the field:
    a. In MUI select Basic (see Figure 3-10).
    b. Set desired itime, and cycles.
    c. Go.
    The field in MORIS is always oriented with north at the top and east to the left.

11. 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 GXUI but this is not necessary to guide.
    f. Click Go in GXUI to start guiding. By default the zoomed guide image will appear in ActiveDpy 3 buffer D in GDV.
    g. Once guiding has been started it is usually necessary to fine tune the position of the target star in the slit (GDV). This is done by changing the coordinates of the off-slit guide boxes by using the arrows in the Guiding panel (see Figure 3-11). 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).

13. Set up the spectrograph and start science integrations.
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 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:

Follow “In Guidedog:” steps 1 – 5 listed on page 23 of the SpeX manual. 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 compete, follow these steps:

In MORIS: Start guiding on a star with MORIS

6. Select the **MORIS FilterWheel** filter (see Table 8). Make sure the MORIS **IXON Shutter** is **Open**.

7. Take an image of the field:
   a. In MXUI, select **Basic** (see Figure 3-10), 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
   (ie: 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.
   b. With **DisplayType** set to **Image** click **Ga** in **Display Options** panel. 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 **WH** 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
brightness of the guide star. This can be changed once the guider is started to improve the guiding.

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

f. If desired, AutoSave can be turned on in MXUI, but this is not necessary to guide.

g. 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.
   b. Under Offset in GDV, **click the MORIS GuideBox Adj button** to bring up the MORIS offset window.
   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 3-12). The offset is drawn in the C-buffer image in GDV (See Figure 3-13).
   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 Go 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 3-14).

In BigDog:

14. Set up the spectrograph and start science integrations.
Figure 3-12. *MORIS Guidebox Adjustment and TCS Offset* window. After clicking button 2, the calculated offsets are shown.

Figure 3-13. 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).

Figure 3-14. 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.
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.

Table 10. Visible off-axis guider sensitivity.

<table>
<thead>
<tr>
<th>Magnitude limit (no moon)</th>
<th>Guider time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V=10.0$</td>
<td>0.7</td>
</tr>
<tr>
<td>$V=12.7$</td>
<td>3.5</td>
</tr>
<tr>
<td>$V=14.0$</td>
<td>6.5</td>
</tr>
<tr>
<td>$V=15.0$</td>
<td>8.0</td>
</tr>
</tbody>
</table>
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). There are six spectroscopy modes in SpeX:

1. **SXD** 0.7-2.55 \(\mu\)m, \(R \approx 2000\) matched to 0.3x15” slit
2. **Prism** 0.7-2.52 \(\mu\)m, \(R \approx 200\) matched to 0.3x15” slit or 0.3x60” slit
3. **LXD_short** wavelength 1.67-4.2 \(\mu\)m, \(R \approx 2500\) matched to 0.3x15” slit
4. **LXD_long** wavelength 1.98-5.3 \(\mu\)m, \(R \approx 2500\) matched to 0.3x15” slit
5. **Single-order short** wavelength 0.9-2.4 \(\mu\)m, \(R \approx 2000\) matched to a 0.3x60” slit
6. **Single-order long** wavelength 3.1-5.3 \(\mu\)m, \(R \approx 2500\) 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 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 (\(i\)\(t\)ime in BXUI).
   a. Set \(i\)\(t\)ime 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 \(i\)\(t\)ime allowed to operate in the linear range of the array: \(i\)\(t\)ime=30,0002 \(\times\) rate\(\approx\)0.5
      The \(i\)\(t\)ime can be less than this to satisfy the required S/N. We recommend \(i\)\(t\)imes no longer than 200 s even if allowed (see section 2.1).
   d. Set desired \(i\)\(t\)ime, coadds, cycles and beam.pattern.
   e. Click Go for bright objects or Flush Go for fainter objects (\(i\)\(t\)ime \(>\) 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 \(i\)\(t\)ime, 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

![Image](image_url)

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 displayed 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 ($t_{\text{itime}}$) 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.

![Image of graph showing variation of resolving power R with wavelength in order three.](image)

**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 $\lambda > 2.5$ $\mu$m (towards the right in BDV). This together with telluric absorption at $\lambda > 2.5$ $\mu$m limits the long wavelength limit to about 2.52 $\mu$m. The effective cut-off at about 0.7 $\mu$m 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 grating blaze function, 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.
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_long 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.
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.
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).
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 zero (in DV select xlinecut in DisplayType). Note the high background and poor telluric transmission at $\lambda > 5.0 \mu m$. 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 $\mu$m is the additional order accessible in LXD$_{\text{long}}$ 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 10). 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 11. Order sorter filter wheel.

<table>
<thead>
<tr>
<th>Position</th>
<th>Filter</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>PK 50 pass &lt; 2.5 µm</td>
<td>Blocker for guider filters</td>
</tr>
<tr>
<td>2</td>
<td>SP 2.5 pass &lt; 2.5 µm</td>
<td>Not used</td>
</tr>
<tr>
<td>3</td>
<td>0.1 x STOP</td>
<td>Reduce flux by x 10</td>
</tr>
<tr>
<td>4</td>
<td>Long4 4.40-6.00 µm</td>
<td>Single-order long</td>
</tr>
<tr>
<td>5</td>
<td>Long5 3.59-4.14 µm</td>
<td>Single-order long</td>
</tr>
<tr>
<td>6</td>
<td>Long6 3.13-3.53 µm</td>
<td>Single-order long</td>
</tr>
<tr>
<td>7</td>
<td>Short3 1.92-2.52 µm</td>
<td>Single-order short</td>
</tr>
<tr>
<td>8</td>
<td>Short4 1.47-1.80 µm</td>
<td>Single-order short</td>
</tr>
<tr>
<td>9</td>
<td>Short5 1.17-1.37 µm</td>
<td>Single-order short</td>
</tr>
<tr>
<td>10</td>
<td>Short6 1.03-1.17 µm</td>
<td>Single-order short</td>
</tr>
<tr>
<td>11</td>
<td>Short7 0.91-1.00 µm</td>
<td>Single-order short</td>
</tr>
<tr>
<td>12</td>
<td>CH4_s 1.58 µm 6%</td>
<td>Imaging</td>
</tr>
<tr>
<td>13</td>
<td>CH4 1 1.69 µm 6%</td>
<td>Imaging</td>
</tr>
<tr>
<td>14</td>
<td>Blank</td>
<td>Closed</td>
</tr>
</tbody>
</table>

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 6) and order sorter filter wheel (see Table 10) 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 5). 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 (see Figure 3-2). 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.](image)

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
Several dithered sky images should median combined and normalized to produce a good flat. Short wavelength narrow band filters ($\lambda < 2.4 \mu m$) and the Z filter will require twilight flats.

Flat fielding at thermal wavelengths ($\lambda > 3 \mu m$) 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).](image)
Measured imaging point-source sensitivities for Guidedog are given in Table 12.

Table 12. Measured Guidedog point-source sensitivity in 0.7" seeing (TBC). The observations were background limited.

<table>
<thead>
<tr>
<th></th>
<th>$10\sigma$1minute</th>
<th>$10\sigma$10minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{MK}$</td>
<td>18.3</td>
<td>19.5</td>
</tr>
<tr>
<td>$H_{MK}$</td>
<td>17.5</td>
<td>18.7</td>
</tr>
<tr>
<td>$K_{MK}$</td>
<td>17.0</td>
<td>18.2</td>
</tr>
<tr>
<td>$L'_{MK}$</td>
<td>11.9</td>
<td>13.2</td>
</tr>
</tbody>
</table>