The LIRIS@WHT cookbook

for visiting and support astronomers

Isaac Newton Group of Telescopes

Mischa Schirmer, Version 0 - 1.0.5

Miguel Santander, until Version 1.0.15

Raine Karjalainen, until Version 1.0.24

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The cover image shows the cluster ID66 of massive stars, taken with LIRIS by the MASGOMAS project (image credit: Annique Lenorzer, Mischa Schirmer)

Contents

0.1 Document history

Version 1.0.24 (2013-11-18)

- Table 4.2 expanded.
- All tables centered.

Version 1.0.23 (2013-06-26)

- Dome flat and spectoscopic flat instructions updated

Version 1.0.22 (2013-05-18)

- Documentation for nod5_pol script updated
- New fflamp and petals commands

Version 1.0.21 (2013-03-01)

- Slitname change from l0p75ext6 to lext6

Version 1.0.20 (2012-12-14)

- Updates to THELI availability and usage
- Troubleshooting has been moved under the LIRIS webpages

Version 1.0.19 (2012-10-05)

- Corrections to neutral density filters usage
- Troubleshooter item added

Version 1.0.18 (2012-06-17)

- LIRIS MOS specialist: Cecilia Fariña (cf at ing.iac.es)
- Small updated to Spectropolarimetry section
- LIRIS MOS using 2-point nodding
- Added information of read modes
- Troubleshooter item added

Version 1.0.17 (2012-06-04)

- Clarified the mndr in ag_spec_nod script
- Four top ring lamps

Version 1.0.16 (2012-06-01)

- Specialist change: Miguel Santander replaced by Raine Karjalainen (rk at ing.iac.es)
- Removed the references to DEs.
- Updated the Spectroscopic flats subsection
- Added the 5 and 10 arcsec slits
- Updated the service observations information

Version 1.0.15 (2010-07-16)

- Corrected the clearreads LIRIS command
- Added [coave] syntax option to [ag]_spec_nod, [ag]_mdither, [ag]_mdither_ext and rdither
- Added [-start_center] syntax option to [ag]_spec_nod
- Added orientative recommended arc exposure times for 1″ slit (Table 4.3)

Version 1.0.13 (2009-11-25)

- Added general advices on standard stars subsection
- Added preliminary spectroploarimetry section
- Added information on polarimetric domeflats

Version 1.0.13 (2009-11-25)

- Added spectroscopy task for quicklooking spectra

Version 1.0.12 (2009-09-11)

- Added rdither command: random dithering for imaging
- Updated lspec grism descriptors
- Corrected syntax in spectroscopy commands in MOS section and imaging sections

Version 1.0.11 (2009-03-16)

- Added notes on the lspec command
- Added information about the reflected ghost image feature

Version 1.0.10 (2009-03-04)

- Slight update in the Troubleshooting section and section 4.
- Documented the reflected ghost image feature

Version 1.0.9 (2008-09-13)

- Improved the MOS mask acquisition and calibration sections

Version 1.0.8 (2008-08-18)

- Added [mndr] and [clean] syntax options to ag_mdither and ag_mdither_ext
- Added [clean] syntax option to mdither, mdither_ext, ag_spec_nod and ag_spec_ext
- Added instructions on aborting observing scripts
- Added troubleshooting on restarting LIRIS mechanisms GUI

Version 1.0.7 (2008-06-12)

- Removed user-non-concerned-about Support Astronomer notes; those are now relocated to the internal webpage

Version 1.0.6 (2008-03-12)

- Specialist change: Mischa Schirmer (original author of this manuscript) replaced by Miguel Santander
- Updated filters and grisms tables

Version 1.0.5 (2007-09-26)

- Updated the SA notes concerning MOS handling
- Updated the description of how to obtain calibrations in MOS mode
- Smaller clarifications throughout the text

Version 1.0.4 (2007-07-08)

- Changed the tex style from article to book

Version 1.0.3 (2007-06-05)

- Explained the warning message one gets with the `lobject_inslit` command at zenith distances larger than 75 degrees, and what to do in that case.
- The section in the Appendix about the slit mask alignment measurement was expanded, in particular for the MOS masks.

Version 1.0.2 (2007-05-26)

- Added a section with various checks to be done in the afternoon and at twilight when LIRIS comes back to the telescope for a new run.
- Expanded the trouble-shooting section in the Appendix

- Fixed some minor items throughout the text

Version 1.0.1 (2007-03-05)

- Section 3 has now a display of the TCS info.
- Fixed Table 4.3 in Sect. 4 and Table 5.1 in Chapter 5.
- The description and name of the `[ag_]spec_ext` script in Sect. 6.2.2 was wrong.
- Added the spectral atlas for the medium resolution K-band grism in Appendix B.
- Included the nonlinearity plot shown in Fig. 1.1

Version 1.0.0 (2007-01-17)

The LIRIS@WHT cookbook has its first light.

0.2 Scope of this document

The present manual is thought as a guide line for visiting (and supporting) astronomers, and based on the authors' own experiences with LIRIS at the WHT. It is not an instrument handbook describing all the technical details, but focusses on those issues relevant for a successful observation. This includes the preparation of the observations and the observing strategy, the observations themselves, and the data reduction.

In Chapter 1 an overview of the most important characteristics of the instrument is given. Chapter 2 helps you planning your observations with LIRIS, and Chapter 3 gives you an overview of the WHT observing system. In Chapter 4 we outline some important detector features you should be aware of, and show you how you can obtain calibration frames. The next two chapters focus on LIRIS in imaging and spectroscopy mode. Lastly, in the Appendix you find the filter transmission curves and a wavelength atlas, as well as an example of how to reduce imaging data with a programme called *THELI*.

Chapter 1

LIRIS - an overview

1.1 Instrument properties

LIRIS is a near-IR multi-mode instrument mounted at the Cassegrain focus of the 4.2m WHT telescope. Its main observing modes are imaging in broad and narrow-band filters, and spectroscopy with low- and medium resolution grisms. Both long-slit and multi-object spectroscopy are available. Furthermore offered are imaging polarimetry and spectro-polarimetry, as well as a coronographic mode. All of which are described below.

1.1.1 Detector

LIRIS uses a HAWAII detector with 1024×1024 pixels. Its basic characteristics are given in Table 1.1. Note that the BIAS and DARK level are not very stable and change throughout the night. Therefore, the BIAS (pre-read) is determined automatically before every exposure and subtracted right away. If you require darks, take them immediately before or after your exposures.

1.1.2 Instrument layout

Most optical and mechanical parts of LIRIS are contained in a cryostat, and are therefore unaccessible during observations. LIRIS is warmed up and opened usually only once per semester. During these sessions, usually new multi-object slit masks are introduced. Smaller reconfigurations take place as well.

The LIRIS cryostat contains 5 wheels,

- a slit mask wheel, containing slit masks and the coronographic mask
- the first filter wheel with narrow-band filters and a Wollaston prism for spectro-polarimetry
- the second filter wheel with broad and narrow-band filters
- the pupil wheel for optimised sky backgrounds

Table 1.1: Overview of the LIRIS detector

Detector size	1024 x 1024 pixels
Pixel size	18.5 μm
Pixel scale	$0\farcs251$
Field of view	$4\farcm27\times 4\farcm27$
Full-well capacity	100000-150000 e-
Spectral range	0.85-2.5 μm
Quantum efficiency	90% (K), 80% (J)
Readout noise (CDS)	< 10 e$^-$
Readout noise (MNDR)	< 3 e$^-$
Gain	3.5$-$3.7 e$^-$ / ADU
Bad pixels	$\sim$1.5%, most of them near the edges
Nonlinearity	< 2% within 25000 ADU (see Fig. 1.1). Before Dec. 2006: < 1% within 0-10000 ADU, <2.5% within 10000-20000 ADU.
Charge persistency	< 1%, disappears after three clearing reads (automatic)
Saturation limit	45000 ADU (before Dec. 2006: 35000 ADU)
Dark current	$\sim$ 0.065 e$^-$/s at 83 K
Readout time	0.9s
Minimum exposure time	0.8s

- the grism wheel, with low and medium resolution grisms and a Wollaston prism for imaging polarimetry.

Depending on the individual observations, the observer selects from a series of pre-defined instrument setups, which then automatically configure LIRIS. For example, by typing `limage ks` one selects "*Ks*-band imaging" as an observing mode, which will automatically clear the slit and the grism wheel, and choose the optimal pupil for the *Ks* filter. The observer does not have to deal with individual wheel movements, even though such are possible if desired.

1.1.3 Overheads

Any change of the LIRIS wheel configuration takes about 1 minute on average. That includes filter changes, or switching from imaging to spectroscopy or polarimetry mode. The LIRIS wheel movements are made in parallel in order to minimise the overall overhead. Please be aware of the fact that the overhead for centering very faint objects (mag 17$-$18 or fainter) on a slit for spectroscopy can easily amount to 15 minutes, depending on the integration time needed to make the object visible. More overheads are given in Table 1.2.

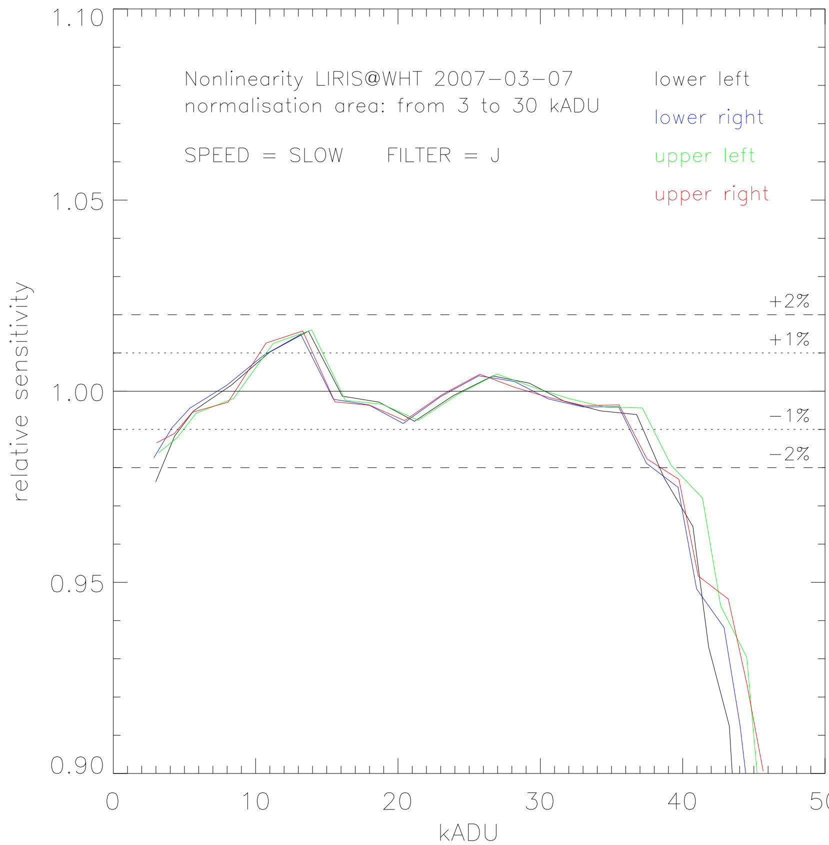

Figure 1.1: The linearity of the LIRIS detector.

Table 1.2: General LIRIS overheads

Detector read-out time	1s
Time until image is displayed and saved after read-out	4s
Time until you get the prompt back after read-out	2s
Average time for filter change	1 min
Average time for grism change	1 min
Average time for switching between imaging / spectroscopy / polarimetry / coronographic modes	1 min
Acquisition of a guide star	2 min
Acquisition of object onto slit for spectroscopy	5 – 15 min
Acquisition of a multi-object spectroscopy mask	10 – 15 min
Restarting the DAS if communication with LIRIS is lost	0.5 min
Restarting the entire observing system	3 – 5 min

Table 1.3: LIRIS maximum frame rate (0.8s exposure time)

Window size	frame rate [s^{-1}]
1024×1024	0.37
512×512	0.45
256×256	0.64
128×128	0.77
64×64	0.85

1.1.4 Detector windowing and maximum frame rate

Up to four non-overlapping windows can be specified for the LIRIS detector. The resulting image is as big as the unwindowed data, showing the windowed sections in their proper locations. Thus, unwindowed flatfields can still be applied correctly. To define, enable or disable a window, you type in the system console (Sect. 3.2.1)

```
window liris n ‘‘[xmin:xmax,ymin:ymax]’’ enable
window liris n enable
window liris n disable
```

where `n` is the number of the corresponding window.

Windowing makes only sense if a source has to be covered with higher time resolution. However, the gain is much less than expected, as Table 1.3 shows. By using a window as small as 64×64 pixels and the shortest possible exposure time of 0.8s, a factor of 2.3 can be gained as compared to a full-frame read-out. The maximum frame rate is then about 0.85 images/s.

1.1.5 Data store modes and read modes

The bias and dark level of near-IR detectors is usually not stable over time. Hence, one bias image (the so-called *pre-read*) is taken immediately before the actual exposure (*post-read*). The default setting is to store only the difference between the pre-read and the post-read (store mode = `DIFF`). Alternatively, the difference and the pre-read (`DIFF_PRE`) or the pre-read and the post-read (`PRE_POST`) can be stored. For the latter two, a multi-extension FITS file is generated. For data reduction, there is nothing else one can do with the pre-read apart from subtracting it from the post-read. Therefore, the recommended setting for the store mode is `DIFF`. To set the storemode from the system console, do

```
storemode liris [diff | diff_pre | pre_post]
```

To set the readmodes from the system console, do

```
rmode liris mndr Nr Nav
```

Table 1.4: LIRIS filters

Filter name	type	cut-on[μm]	cut-off[μm]	wheel
y	broad	0.969	1.067	2
z	broad	0.996	1.069	2
j	broad	1.170	1.330	2
h	broad	1.490	1.780	2
ks	broad	1.990	2.310	2
ucm	narrow	1.177	1.186	1
jc	narrow	1.216	1.244	1
pabeta	narrow	1.277	1.310	1
hc	narrow	1.558	1.582	1
fe2	narrow	1.632	1.656	1
ch4	narrow	1.640	1.740	1
he1	narrow	2.043	2.073	2
h2v10	narrow	2.106	2.138	1
brg	narrow	2.150	2.182	2
h2v21	narrow	2.231	2.265	1
kc	narrow	2.253	2.287	2

This sets the number of multiple non-destructive reads (MNDR) to *Nr* and the number of coaverages to *Nav*. *Nr* is the number of times that the array is read non-destructively prior and after an integration period. The array data from the *Nr* pre- and post-integration reads, respectively, are averaged independently. *Nr* is an integer between 1 and 16 (default is 1; i.e. double correlated sampling). *Nav* is the number of accumulated exposures that are averaged and written as a single output file. We recommend to set $Nr = 1$ for imaging and $Nr = 4$ for spectroscopy, since in the latter case the readout noise becomes dominant over the sky background noise.

1.2 Observing modes

In the following an overview of the various observing modes are given. Details are contained in Chapters 5 and 6, where we explain their usage in detail.

1.2.1 Imaging

The imaging mode is offered with a large selection of broad and narrow-band filters, which are listed in Table 1.4. Apart from the standard configurations, filters in wheel 1 can be arbitrarily combined with filters in wheel 2.

Table 1.5: LIRIS slits and grisms

Mask name	slit width		
l0p65	0.″65		
l0p75	0.″75		
lext6	0.″75	6 offset slits for larger wavelength coverage (see Sect. 6.4)	
l1	1.″0		
l2p5	2.″5		
l5	5.″0		
l10	10.″		
Grism name	**resolution**	**spectral range**	**scale**
lr_zj	960	$z-J$ ($0.887-1.531\mu$m)	6.1 Å/pix
lr_hk	945	$H-K$ ($1.388-2.419\mu$m)	9.7 Å/pix
mr_k	2500	K	*low efficiency
hr_j	2500	J ($1.170-1.356\mu$m)	1.8 Å/pix
hr_h	2500	H ($1.520-1.783\mu$m)	2.6 Å/pix
hr_k	2500	K ($2.053-2.416\mu$m)	3.5 Å/pix

1.2.2 Long-slit and multi-object spectroscopy

LIRIS supports long-slit spectroscopy, using a series of slits with different widths. Multi-object spectroscopy is supported as well. The number of slitlets per mask is ~ 20, the slitlets have a length of 10″ (user-definable) and are 0.″8 wide. Three reference sources must be included in each MOS masks for proper mask alignment. Further information about possible spectroscopic configurations are given in Table 1.5.

1.2.3 Polarimetry

LIRIS offers polarimetry in imaging as well as in spectroscopy. All filters or grisms used for normal imaging and spectroscopy are available in polarimetry mode as well. The only restriction for spectro-polarimetry is that a particular slit of 0.″75 width has to be used. LIRIS displays four polarisation angles of 0, 45, 90, and 135 degrees simultaneously (see also Fig. 5.1). For this purpose, the field of view is truncated to $4' \times 1'$.

1.2.4 Coronography

The diameter of the coronographic mask is 1.″2. It can be used with any imaging filter. The coronographic mask is located in the slit wheel and can be replaced by a MOS mask if demand for multi-object spectroscopy is high.

Chapter 2

Before your time application / observing run

LIRIS is a very easy-to-use instrument. Therefore, only a minimum of preparations is required before your observing run. In order to use your time at the telescope in an optimal way,

- make sure you know when your targets are visible. ING offers a very nice tool for that purpose at `http://www.ing.iac.es/ds/staralt/index.php` .
- prepare finder charts in advance
- decide if and which standard stars you want, and write down not only their names but also their coordinates.

All this sounds self-evident, but unfortunately unprepared observers are still not uncommon in these days. Thus, please don't leave this to the very last moment!

2.1 Exposure time calculator

Use the exposure time calculator at `http://www.iac.es/project/LIRIS/` to estimate the total amount of observing time you need for your targets. However, be aware that the ambient conditions (atmospheric temperature, dust level, solar activity) can change the IR sky background brightness by more than a magnitude. Thus, the ETC estimates can always only be a rule of thumb, and you may want to sacrifice (or gain) the one or other target. However, this decision can only be made at night when you know the conditions.

2.2 Observing strategy

2.2.1 Blank sky fields

In order to get a proper sky background model, you need to dither the exposures. For point-like sources, or sources much smaller than the dither pattern, you can stay on the target field. However, if your target is extended, it is mandatory that you go to a blank sky field very close to the target to obtain a sky estimate. In that case, only 50% of your observing time is available for the actual science target. There is **no way** you can obtain the sky background from images of an extended target if the dither pattern is not at least 2.5 as big as the target itself. If you can't accomodate this within the field of view of LIRIS, you must go to a blank field. Keep this in mind when writing your proposal. At the telescope, the chopping to a blank sky field is handled automatically by means of dedicated observing scripts.

2.2.2 Individual exposure times

The individual exposure times are difficult to estimate. Most observers want to stay below 20−25 kADU for their science target in order be in the linear regime ($< 2\%$ nonlinearity) of the detector (see also Fig. 1.1). This of course depends on the sky background, dust level and extinction, and the current seeing. The individual integration times are therefore best determined by means of test exposures just before the actual observations.

2.3 Service mode

2.3.1 Available observing modes

Up to 8 hours of time can be allocated through ING's service programme[1].
INCLUDED observing modes for service mode are:

- imaging and imaging polarimetry, using all available filters
- spectroscopy, using all available long slits and grisms.

EXCLUDED observing modes for service mode are:

- multi-object spectroscopy
- coronography

2.3.2 Restrictions

The LIRIS detector and read-out mode can be configured in several ways. However, in service mode the following restrictions apply:

- the read-out speed is set to slow for all observations
- the pre-read will be subtracted automatically from the images (store mode set to `DIFF`)
- single read-out (correlated double sampling) is used for imaging
- four non-destructive read-outs are used for spectroscopy.

[1] `http://www.ing.iac.es/ds/service/serviceform.php?instrument=LIRIS`

2.3.3 Calibrations

ING takes only a limited number of calibration images in service mode. Please take into account the following when submitting a service proposal:

- DARKS and BIASes:
  Dark exposures are not taken by default, due to changes of the corresponding instrument characteristics during the night. If you require dark exposures, they must be taken immediately before or after your observations at night time, and thus have to be included in the total time you request. Note that the use of BIASes is rather limited for the same reasons as for the DARKs, they are not provided unless specificly asked.

- STANDARD STARS:
  Since the sky in the near-IR changes rapidly, observations of standard stars will not be taken unless explicitly asked for in the proposal and accounted for in the total time requested (photometry can often be done by means of 2MASS). If you request standard star observations of any type (photometric, spectrophotometric, telluric), then please explicitly state

  1. which (RA, DEC) specific standard star you wish for each object
  2. which instrumental configuration you wish (filters and grisms).

  The reason for this is that applicants are often very unspecific concerning their standard stars, or unaware of the need for particular standards (various spectral types, for example, depending on the main target), or unaware of the fact that certain standard types do not exist in the vicinity of their targets. Thus, any standards required must be defined in the proposal by the applicant.

- FLATs, spectroscopic FLATs and ARCs:
  These will be taken automatically at the beginning or the end of the night and do not have to be requested.

2.4 Multi-object spectroscopy

2.4.1 Number of available mask positions

LIRIS can accomodate about $6-8$ MOS masks at the same time. To change masks, the LIRIS cryostat has to be warmed up, which is preferentially done only once per semester since there is some risk involved for the sensible IR detector array. If the number of applications for MOS mode is very high, also two warming ups can be scheduled per semester, but this depends on different factors and should not be taken as granted. Rather, the one or other long-slit or the coronographic mask will be traded in to accomodate more MOS masks.

2.4.2 MOS mask preparation

The MOS masks are produced by an external company using an electromagnetic discharge process. The slitlets are $0\farcs8$ wide and by default $10''$ long. About 20 such slitlets can be put per mask. The length of the slitlets is user-definable. They can be made shorter, but should optimally still allow for a 3-point dither pattern for optimal sky background subtraction. The slitlets of one mask do not need to have the same length.

The MOS masks are inserted into a portion of the focal plane of the telescope which is free of distortions. Therefore, it is sufficient that the observer provides a target list with accurate ($0\farcs1$ or better) RA and DEC coordinates. The target list must include the coordinates of three reference stars which are used to accurately align the mask on the sky. Ideally, these three reference stars form a triangle that extends over a large part of the detector area. The reference stars must be highlighted in the list since they will not get slitlets assigned in the mask but circular holes.

The coordinate list must be sent at least two months in advance of the scheduled warming-up of the cryostat to IAC[2]. The company that produces the masks needs one month for the production, hence the long lead time. It is your responsibility to provide the coordinate lists in due time. If you fail, you run the risk that by the time of your observing run your masks will not be available in LIRIS. Any questions concerning the scheduling and production of MOS masks should be directed to IAC.

[2]contact: José Acosta, jap@iac.es

Chapter 3

Getting started at the telescope

3.1 Introduction by your support astronomer

Your observing support scientist (OSS) will usually meet you at around 15:00 in the WHT control room. The basic introduction into LIRIS (imaging only) takes about one hour for observers with no previous observing experience at the WHT. For spectroscopy, or complicated imaging programmes that require a detailed discussion of the observing strategy, the introduction can last 2 hours.

The OSS will usually stay with the observer during the first night of the run until around 23:00, unless problems or other issues require a longer stay. The WHT observing support assistant (OSA) will be present all night. The OSS can be contacted on their mobile phones (written on the white board in the control room).

3.2 The WHT/LIRIS observing system

The observing system will be ready and waiting for you to start your observing run. It consists of some basic commands and several windows, which are explained in detail below.

3.2.1 Basic observing commands

Most operations with LIRIS are handled from the command line, in a console showing a `SYS>` prompt. From therein you launch exposures, scripts, change filters or switch e.g. between imaging and spectroscopy. Most tasks are explained further below in the corresponding sections. Here we give an overview of the most basic commands.

To change into imaging mode and put a certain filter (see Table 1.4)

```
limage <filter name>
```

To change into spectroscopy mode and put a certain slit (see Table 1.5)

```
lspec <grism name> <slit name>
```

NOTE: You can use the wheel position number instead of the name of the slit/grism.

However, if you do that, keep in mind that the script will sometimes return an error, even when the mechanism actually arrives to the desired position.

To take an exposure

`run liris <exp time> [‘‘title’’]`

To take an exposure without saving (the file is called `s1.fit` and will be overwritten)

`glance liris <exp time> [‘‘title’’]`

To take N exposures

`multrun liris N <exp time> [‘‘title’’]`

To take an [autoguided] series of 9 dithered exposures

`[ag_]mdither 9 <exptime> [‘‘title’’]`

Move the Acq/Comp mirror in

`agcomp`

Move the Acq/Comp mirror out

`agmirror out`

Make a telescope offset

`tcsslowoff <xoffset> <yoffset> 10`

The offsets are given in arcseconds, the numeric value specifies the speed by which the telescope moves.

3.2.2 The A&G-box and 4MS display

The Acq/Comp mirror Between the telescope and LIRIS is the so-called A&G-box, which amongst others contains the autoguider, a set of neutral density filters, a tungsten lamp and two arc lamps for wavelength calibration. In addition, there are a couple of mirrors which lead the light into the currently mounted Cassegrain instrument, in our case LIRIS.

The current status of the A&G-box is displayed in the A&G-box status window (Fig. 3.1 and 3.2). The configuration of the A&G-box is handled by means of the 4MS console (Fig. 3.3).

If you want to take spectroscopic flats with the tungsten lamp, or arc spectra with the arc lamps, then you have to move in the Acq/Comp mirror. This can be achieved from within the first (or the second) menu tab of the 4MS console (`A&G`, or `A&G observer`). Alternatively, you can use the `agcomp` command in the system console. Moving the mirror into the beam takes about 20 seconds. The light path in the A&G-box display will be updated correspondingly (Fig. 3.2). Note that with the Acq/Comp mirror in place, LIRIS can not see the sky anymore.

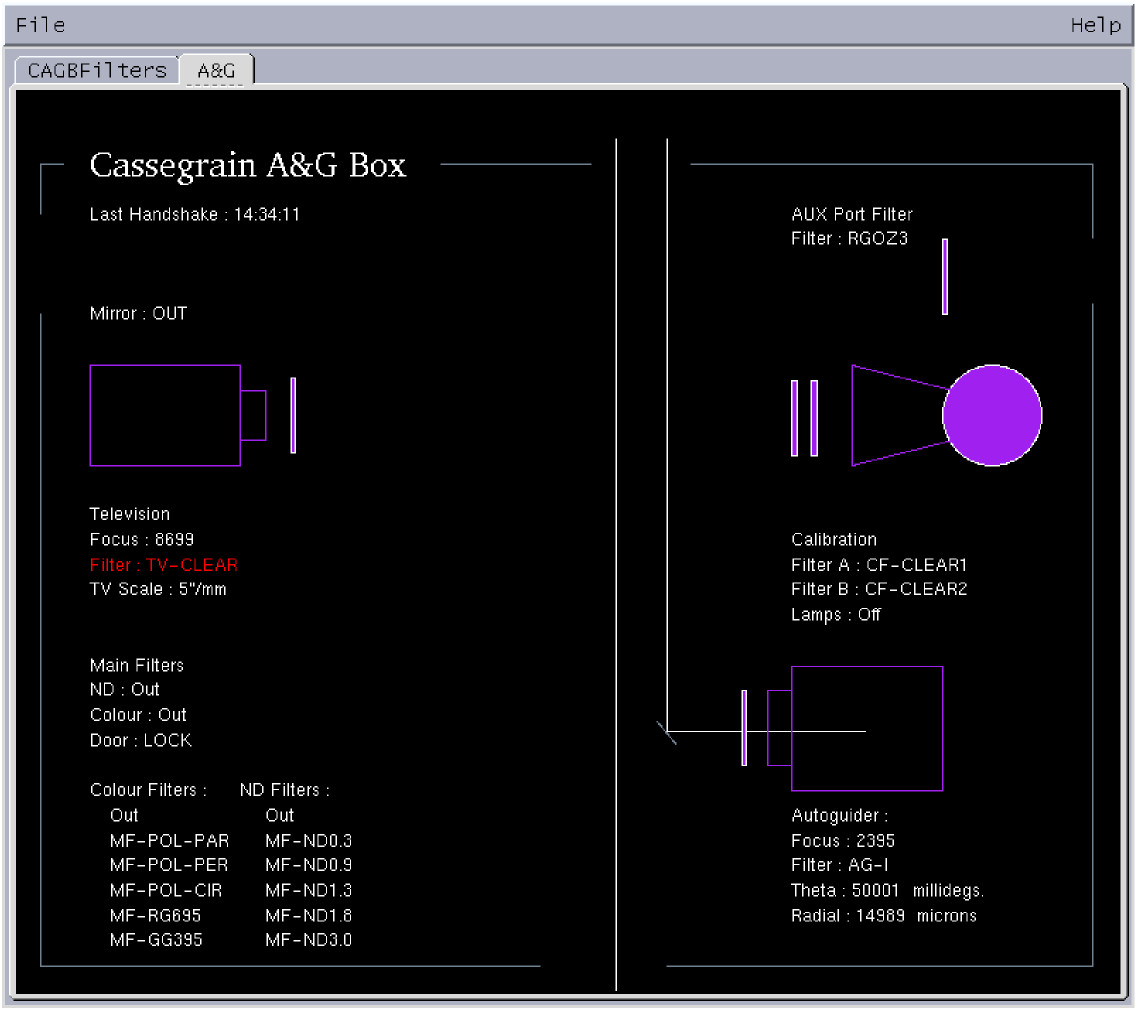

Figure 3.1: The A&G box. In that state LIRIS can see the sky. In this representation the telescope is on top of the figure, and LIRIS below.

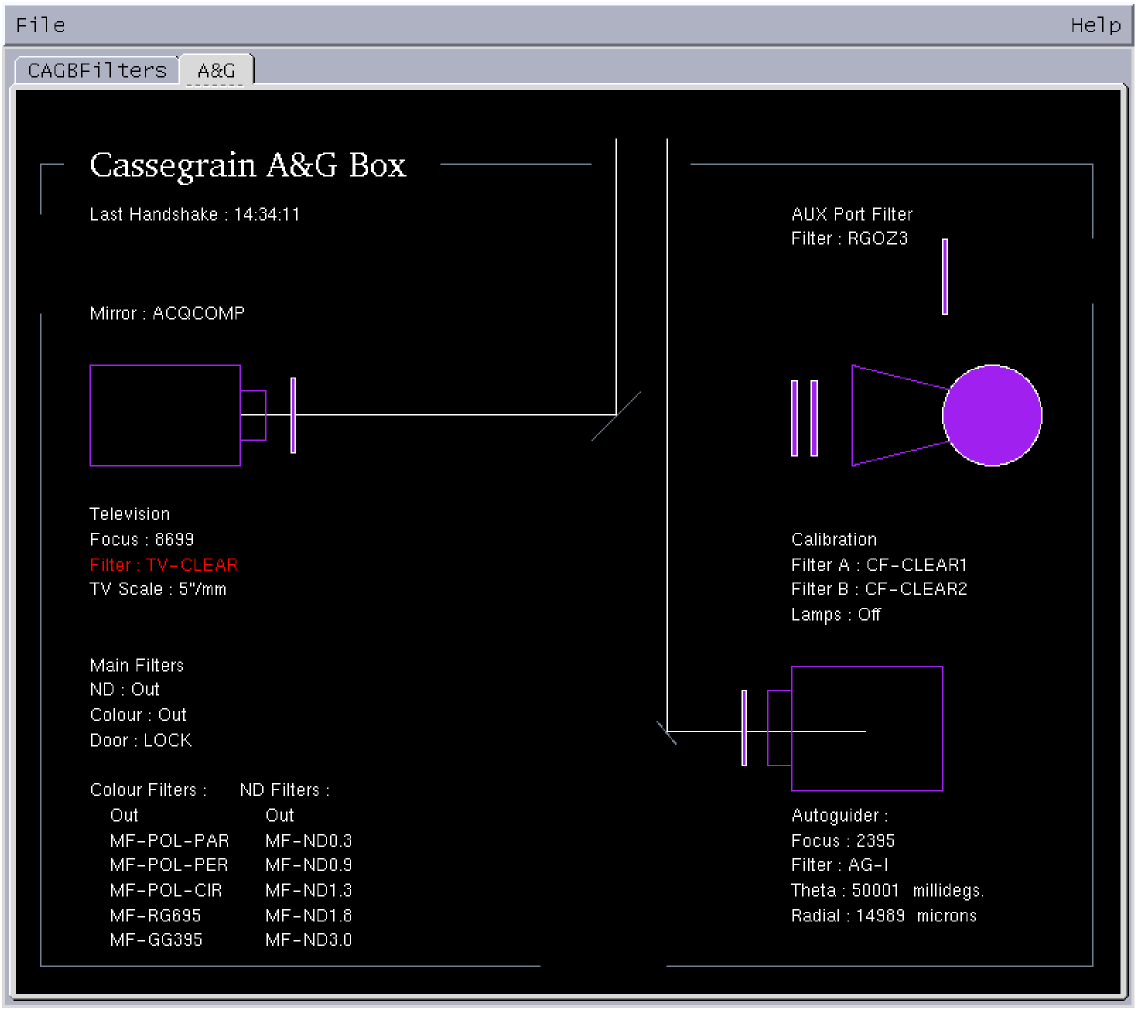

Figure 3.2: The A&G box. In that case LIRIS can not see the sky, but the tungsten and arc lamps for spectroscopic flats and wavelength calibration.

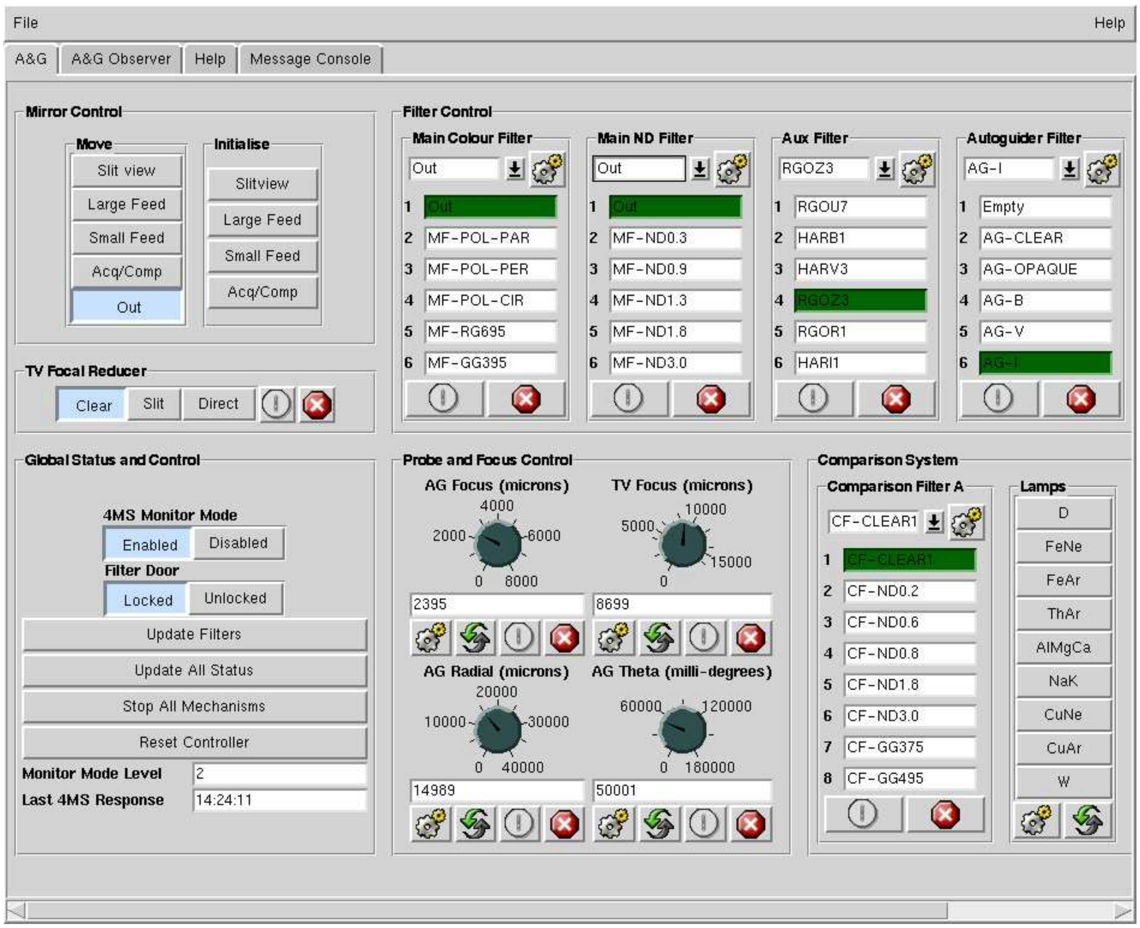

Figure 3.3: This GUI controls the A&G box.

To move the Acq/Comp out again, just click the same push button again and confirm the action (or use the `agmirror out` command).

Autoguider Filter In the 4MS window, you can select the filter used for the autoguider. This is largely irrelevant for imaging, since exposure times are very short. However, for spectroscopy you want to select the *I*-band filter. The latter is closest to the near-IR and therefore differential tracking effects at higher airmasses due to atmospheric dispersion are minimised. As a default, we recommend to use the *I*-band filter always, unless you can't find a bright enough guide star.

Neutral density filter If you observe very bright sources you may want to consider a neutral density filter. You can choose from a broader range of ND filters from the 4MS window. However, be aware that these filters lead to significant vignetting. In addition, the density has been evaluated for the optical only. The transmission in the near-IR can be higher than expected (and not be neutral any more), also because these filters are warm and not cold. Hence, instead of using the A&G-box ND filters, using a LIRIS narrow-band filter is probably a better alternative if high flux levels are a problem. Consider the *jc*-, *hc*- and *kc*-continuum filters.

3.2.3 The camera server window

The black camera server window (Fig. 3.4) shows under the LIRISCASS menu tab the current status of the LIRIS camera. Apart from telling if communication with LIRIS has been established successfully, this is the

- total exposure time of a started exposure
- elapsed exposure time of the current exposure
- current exposure number of a sequence of exposures
- read-out speed
- read-out mode, i.e. CDS (correlated double sampling) or MNDR (multiple non-destructive reads)
- detector windowing.

3.2.4 The real time display (RTD)

Any exposure taken with LIRIS will be displayed in the RTD, which uses the commonly known DS9 programme. The behaviour of the RTD is controlled over the *RTD control panel* (Fig. 3.5).

One of the most frequent applications is to subtract a previously (dithered) exposure from the current image, yielding a sky-subtracted image (see the `OBS-REF` option below).

Figure 3.4: The LIRIS camera server window

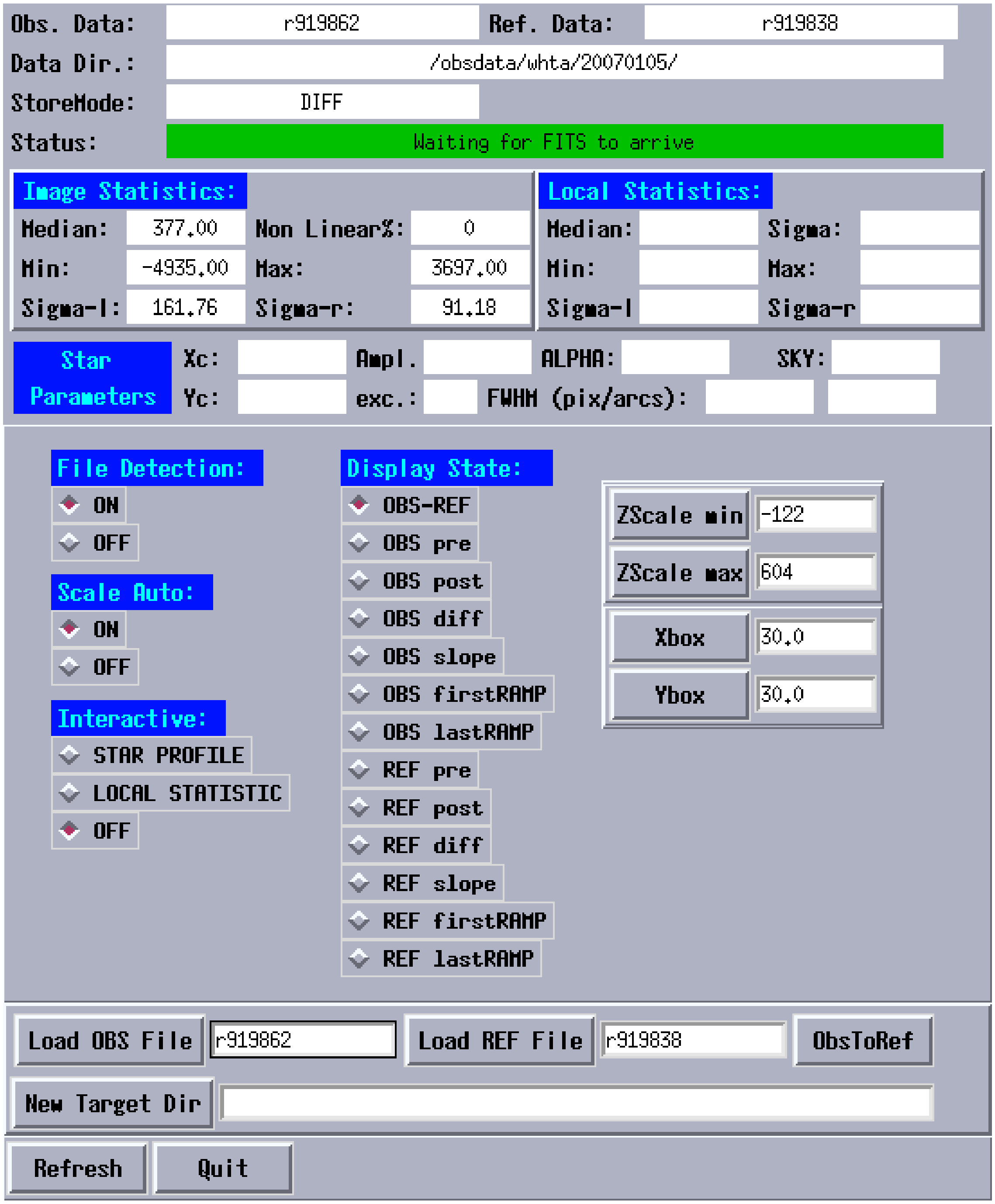

Figure 3.5: The LIRIS RTD control panel

Therein, faint objects are better visible. Further display options are available if the store mode (Sect. 1.1.5) is other than `DIFF`, in which case e.g. the pre-read can be shown as well.

On the RTD control panel, amongst others the following items can be found:

- **Observation data:** Shows the file name of the image actually displayed
- **Reference data:** Shows the file name of the image loaded as reference data (see below)
- **Data directory:** Shows the directory where the data is being stored
- **Store mode:** The store mode of the data
- **Status:** Status of the RTD. Usually, this will say that the RTD is waiting for a new image to arrive.
- **File detection:** If you activate this box, the new images are automatically loaded into the RTD.
- **Scale auto:** Automatic or manual image scaling.
- **Star profile:** When you activate this task, you can measure the image seeing. Switch `File detection` off, then point the cursor on the star you want to measure. Press "b" on the keyboard to move the little green box onto the star, then "q" to perform the measurement and to quit. The results will be displayed in the **Star parameters** section.
- **Display state:** This section offers several options to display the data:
  - OBS-REF: Displays the difference between the current image and the reference image (for sky subtraction)
  - OBS pre: Displays the pre-read of the current image
  - OBS post: Displays the post-read of the current image
  - OBS diff: Displays the post minus pre of the current image
- **Refresh:** Refreshes the image shown in ds9
- **ObsToRef:** Loads the current observation data as reference data
- **Load OBS/REF:** Loads any fits files of the data directory either as Observation data or as Reference data. Just type the file name of the image in the corresponding field.

In the example of Fig. 3.5, the difference of the images `r919862.fit` and `r919838.fit` is selected to be displayed in DS9.

To restart the RTD, i.e. if it crashed, do the following:

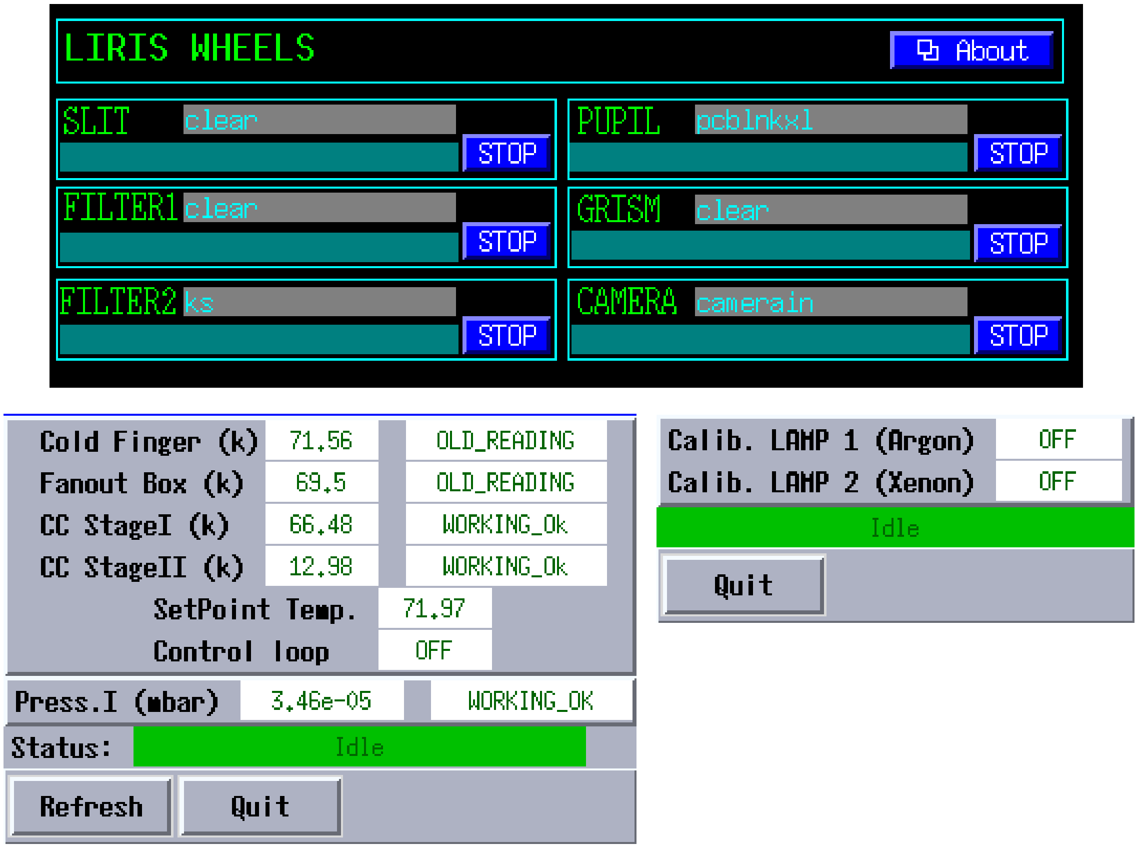

Figure 3.6: The LIRIS status mimics. Top: the current filter/slit/grism configuration; lower left: the temperature display (window looks a bit different nowadays); lower right: the status of the two arc lamps

```
startudasrtd
```

This command kills the current ds9 session and the RTD control panel before relaunching them. Should the old windows not get terminated, close them manually.

3.2.5 The three status mimics

Three windows (Fig. 3.6) tell you about the current status of the LIRIS instrument: the current configuration of LIRIS, the temperatures inside the cryostat, and if the arc lamps are switched on/off.

3.2.6 The night log and TCS info

You do not need to take notes about all the exposures you are taking with LIRIS. At the end of the night a night log is created which contains all relevant information. You can

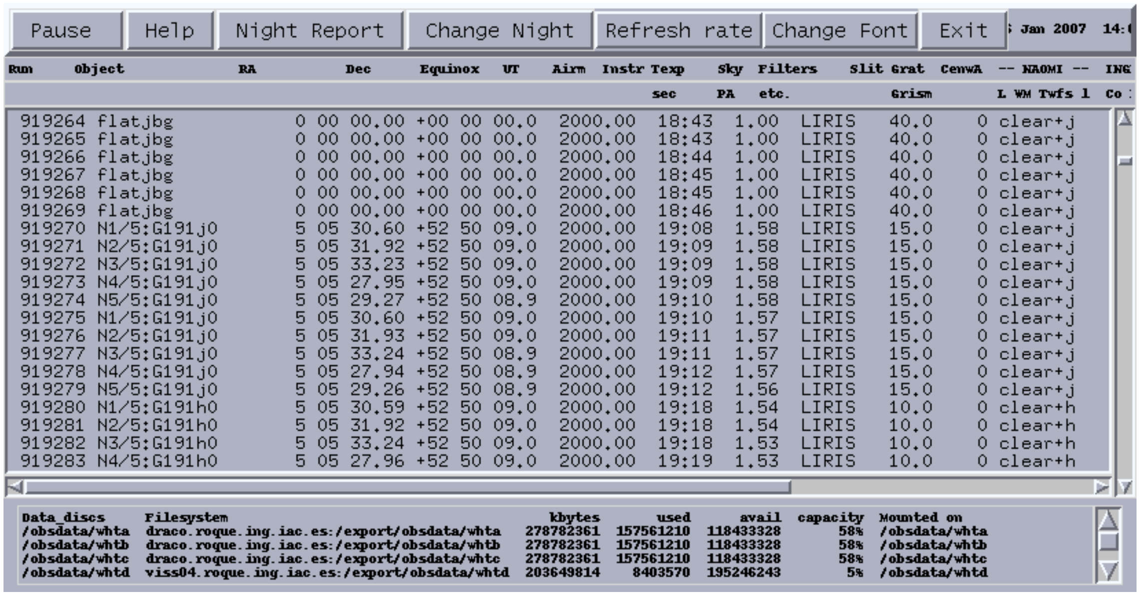

Figure 3.7: The night log.

see the night log at any time during the night and put comments into it (Fig. 3.7). The night log will be put online[1] the next day.

You can ask the OSA to send you a window showing the current status of the telescope, the *TCS display* (Fig. 3.8). Therein, you find the RA and DEC coordinates, azimuthal and elevation angles, airmass etc. You can bring up the TCS display yourself by typing

`tcsinfo &`

[1]http://www.ing.iac.es/Astronomy/observing/inglogs.php

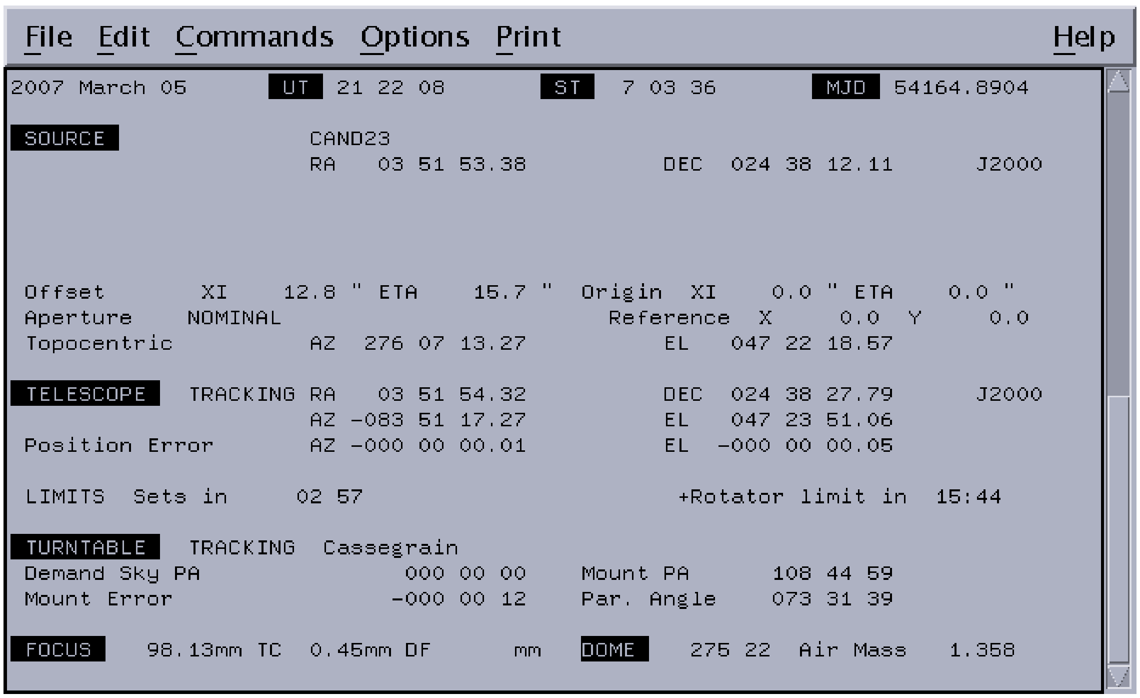

Figure 3.8: The TCS display

Chapter 4

Before you start observing with LIRIS

4.1 Features

4.1.1 Scrambled pixel mapping

Due to some issues which are not further explained here, some of the pixels in the LIRIS image are not in the places where they should be. At some point in the digitisation process, the LIRIS data is in the form of a one-dimensional array, and part of this array is shifted by one index. When the two-dimensional image gets reconstructed, some of the pixels get dislocated. In particular, this affects the lower left quadrant, which is entirely shifted by one pixel to the right (easily recognisable in an arc image and in the sky lines of long-slit spectra). Its rightmost column gets wrapped around and appears on the left edge. A few isolated pixels in the other read-out quadrants are also dislocated. When you use the *THELI* reduction package (Sect. C), all LIRIS images get automatically descrambled.

4.1.2 Very bright sources and detector remanence

Very bright sources will leave a ghost image imprinted on subsequent exposures, which becomes visible when a dither offset has been applied in between. A default of 3 clearing reads is automatically applied before a new exposure is taken, which lowers the amplitude of the ghost to about $0.1 - 0.2\%$ of the brightness of the original source. If this is still too much, you can increase the number of clearing reads by

```
clearreads LIRIS n
```

Using values of 6 or larger for `n` should largely eliminate the ghosting, for the expense of a increased overhead (additional $\sim$ 2s for $n = 6$). This holds for imaging and spectroscopy.

4.1.3 Very bright sources and reflected ghost image

There is a special case, when doing spectroscopy of very bright sources (and sometimes in flat fields), in which a ghost image of the source, reflected around the centre of the chip (i.e. optical axis), will show up in the detector. This has been noticed mainly in MOS spectroscopy mode, but also in long-slit mode.

Hopefully, due to these ghosts being reflected around the center of the detector, their location can be predicted by a script (hosted both in the Instrumental Issues section of the LIRIS webpage and in `/home/whtobs/liris/utils/findghost/`), and accounted for during data reduction.

4.1.4 Detector reset anomaly

Near-IR detectors have very different properties than the CCDs used in optical instruments. While they are not exposed, they are continuously resetted and rapidly reach a *resetting equilibrium*. Contrary, when a series of exposures is made, the detector reaches an *imaging equilibrium*. In the ideal world, there is no difference between these two states. In the real world, it takes about three exposures to go from the resetting equilibrium to the exposure equilibrium. This is recognised in a varying sky background that stabilises for the rest of the exposure series.

However, even after the sky backgrounds have been calculated and subtracted correspondingly, there is an instable component showing up as a discontinuous jump (Fig. 4.1) between the upper and the lower two read-out quadrants. The amplitude of this jump depends amongst others on exposure time, illumination level, and the order of the image in a series of continuous exposures. There is also a large erratic component involved, hence this discontinuity can not be modelled as a function of the parameters mentioned. Each image has to be corrected for this effect individually. Since the effect is also present in flat fields, the photometry of objects in the corresponding regions can be affected by $5 - 20\%$.

If you have dithered observations (see Sect. 5.2), and you take a series of e.g. 10 exposures per dither point, then the detector reaches the *imaging equilibrium* with the third exposure. All subsequent images will have the same image background as this third exposure. When you then move the telescope to the next dither point, the detector is resetted during the slew and goes into the *resetting equilibrium* again and thus is in the same state as just before the first exposure sequence. Therefore, the image backgrounds are the same for the i-th exposures in the n-th sequence. The consequence is that the sky background has to be determined separately for each group of images.

Example: You have 12 images per dither point, and you know that the detector settled into its equilibrium with the third exposure. Then you need to calculate three different sky backgrounds. The first is for the group of images 1, 13, 25 etc in the entire obseving series. Images 2, 14, 26 etc form the second group. All the remaining images have the same sky background and form the third group. After the three sky models have been subtracted from their corresponding images, the exposures can be merged again and treated together for the remaining reduction steps. See also Sect. C.3 and C.4 for how to do that with the *THELI* software package.

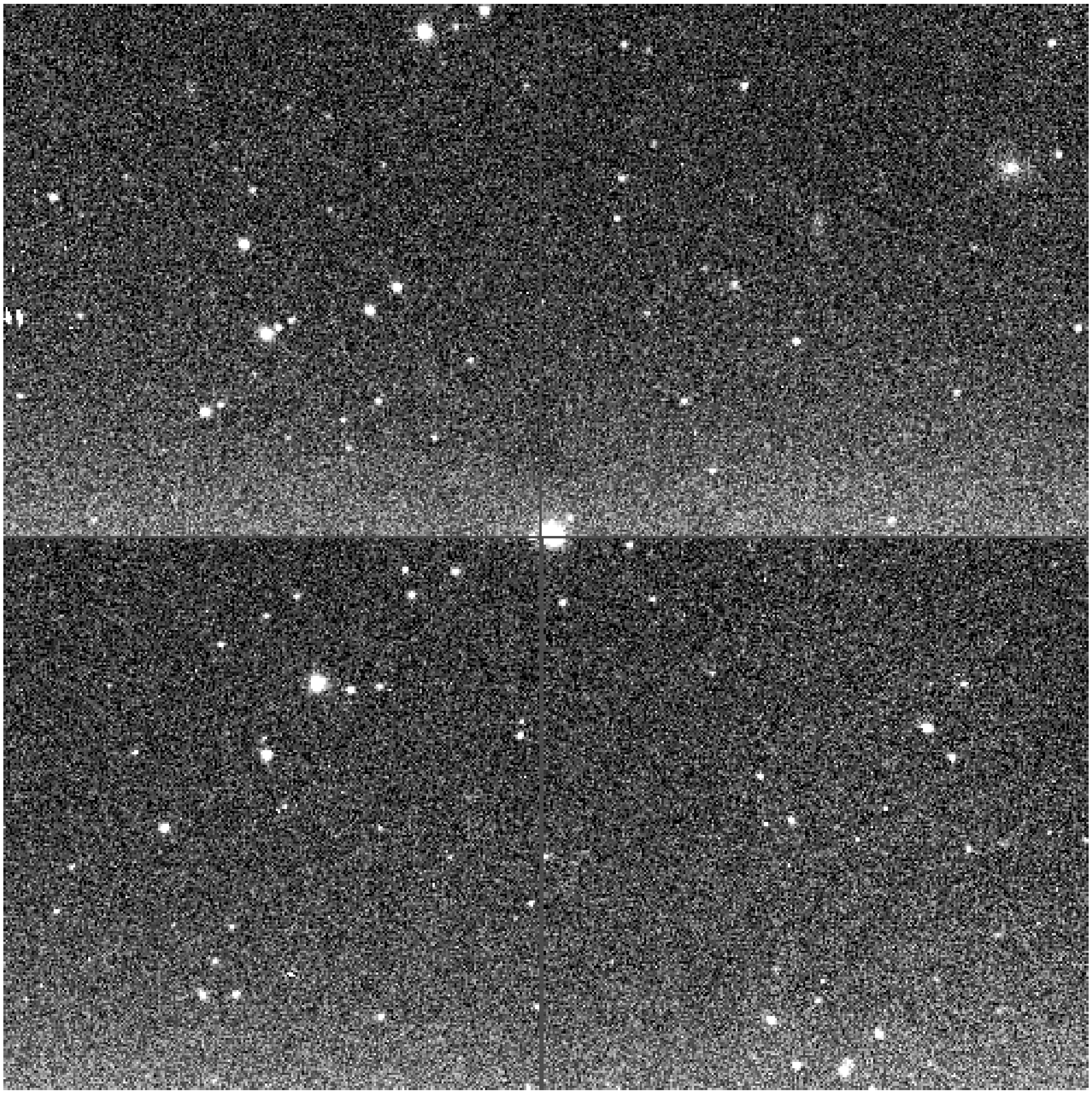

Figure 4.1: The reset anomaly for LIRIS, after subtraction of an average sky background model. The amplitude and sign of the discontinuous jump seen varies from exposure to exposure. It is usually less pronounced than in this example, and often absent after sky subtraction. It can be corrected for by subtracting an average column from the image.

Please note that a certain fraction of images in the first group, which suffers most from the reset anomaly (and the poorer temporal sampling), can still have bad image backgrounds after sky subtraction. These images should be discarded. When you plan your observing strategy, take this into account and increase e.g. the number of exposures (`nruns`) taken per dither point by one.

4.2 Checklist before the observing run

Before you actually start observing with LIRIS, there are a few settings you have to check. Normally, LIRIS will be ready to observe when you arrive at the telescope. However, it can happen that during the afternoon checks the setup has been slightly modified and is not as you want it. Therefore, take 5 minutes and verify the following.

From within the 4MS window (Fig. 3.3) and the A&G box display (Fig. 3.1), check that

- the Acq/Comp mirror is out, so that LIRIS can see the sky. The latter is indicated by a continuous line through the A&G-box display. Unless you want to take spectroscopic flats or arcs, move the Acq/Comp mirror out.
- no neutral density or other filter is in the main path
- the autoguider has the I-band filter
- the tungsten calibration lamp (W) is switched off.

As for LIRIS itself, check that LIRIS is "responding", that the read-out speed is set to slow, and that you have no windows set. All this can be controlled by the LIRIS server window (Fig. 3.4). To change the read-out speed to slow, or to disable any windowing, type in the system console

```
rspeed liris slow
window liris n disable
```

where `n` is the number of the window you want to disable.

If the camera server says that LIRIS is not responding, which will be indicated in big red letters, then this can usually be fixed with a `dasreset` or a `startobssys` in the yellow DASxx console (June 2012 DAS31 in use, this can change). Ask your OSA or OSS for help, or see the trouble-shooting section under LIRIS home page.

4.3 Calibrations

4.3.1 Biases and Darks

The bias and dark level of LIRIS is unstable with time, as is the case for most near-IR detectors. A bias image (pre-read) is taken and subtracted automatically for every image taken. Further calibration with extra biases is thus not needed.

The dark current of LIRIS is very small. Extra dark calibrations are usually not necessary since the dark contribution is automatically subtracted from the data during the sky subtraction. This is considered superior than an extra calibration, since the correction is determined from the data itself. If you want extra dark calibration, then take at least 30 darks immediately before and after your observation, and possibly in between if your exposure sequence is long. Reject the first 5 darks from each series since they are not representative. Before you can take a series of N darks, you must first move in some blanks into LIRIS:

```
lblanks
<multbias|multdark> liris <N> <int time>
```

Since bad pixels usually saturate quickly in detectors, a master dark can serve as a very good bad pixel mask.

4.3.2 Flats

Since the read-out time of LIRIS is short, you can aim for a large number (>30) of flats per filter in order to obtain an optimal S/N ratio. Flat fields are essential for LIRIS since the detector is not homogeneously sensitive and shows some cosmetic features. Most of hese are corrected well by flatfields, others disappear later on with the sky background subtraction. The flatfields can be considered as very stable (within few percents) over long periods of time (months).

Although ideally one should separately reduce (or discard) the first and second flat exposures (because of the detector reset anomaly), getting 15000-20000 ADU will minimise the DRA and allow one to get the pixel to pixel sensitivity.

Skyflats are superior over domeflats since they preserve the natural light path, and do not suffer from possibly enhanced fringing effects coming from the flatfield lamps. Narrow-band flats can be taken already before sunset or after sunrise, broad-band flats just after sunset. Ask the OSA to either switch off the tracking of the telescope, or use one of the dither scripts (see Sect. 5.2) to make sure that stars do not end up on the same detector pixels. The OSA will point the telescope to a suitable position on the sky. A number of N flat fields can be obtained with the command

```
multflat liris <N> <integration time> ["title"]
```

(no dithering), or

```
mdither 9 <integration time> ["title"]
```

Domeflats can be done using a weak flat lamp which is mounted on the top-ring of the telescope. Make sure the mirror petals are open

```
petals open
```

Table 4.1: Exposure times for dome flats.

Filter	z	J	H	Ks	brg	$he1$
Exp. time[s]	2.5	3	1.7	∼2	4	4

switch the weak lamp on with a command

```
fflamp 1 on
```

Let the four additional, much stronger flat lamps turned off (they can be used for spectroscopic flats, see below). Even in narrow-band filters LIRIS is too sensitive for even one of the brighter lamps. Individual exposure times for all four broad-band filters and two narrow-band filters can be found in Table 4.1. However, note that in particular for the K-band filters around 2μm the illumination level mostly depends on the dome temperature rather than the lamp brightness. The corresponding exposure times can therefore be different for your observing run.

For *z*, *brg* and *he1* filters one should switch on also the second top-ring lamp with command 'fflamp 2 on' and use the exposure times given in the Table 4.1.

To switch off the top ring lamps type

```
fflamp all off
```

and to close the mirror petals one can use the

```
petals close
```

command.

Polarimetric flats must be taken as low on the sky as possible since the twilight sky is highly polarised at larger elevations. Ask the OSA to point away from the Sun and explicitly to lower the telescope to about 20 degrees. Even though skyflats should be preferred, in the case of polarimetry domeflats can be a good alternative for the more complicated skyflats. In this case, it is advisable to take a series of domeflats, then turn the LIRIS turntable by 90 degrees (ask the OSA to do this), and then take another series of domeflats.

4.3.3 Spectroscopic flats

For spectroscopic flats at zJ wavelengths you can use the tungsten lamp that is integrated in the A&G box. In order to bring the light from the lamp to the detector, you need to move the Acq/Comp mirror into the light path, include a neutral density filter (ND= 1.8), and switch the tungsten lamp on. All this can be done from within the 4MS window (Fig. 3.3). In the `A&G Observer` menu tab, select the "W" for the tungsten lamp, then click the gears symbol next to it to switch the lamp on (or off). In the Mirror Control section, select Acq/Comp to move the mirror in (or out).

Now bring LIRIS into spectroscopic mode and do not forget to insert the slit mask you want as well. Then take N spectroscopic flats.

```
lspec <grism name> <slit mask name>
multflat liris <N> <int time> ["title"]
```

Once you are done, switch off the lamp and move the acq/Comp mirror out of the beam so that LIRIS can see the sky again. Do not forget to remove the ND filter. Table 4.2 shows how long to expose in order to achieve an exposure level of about 20 kADU (and thus minimise the detector reset anomaly effect). Of course you can also take dome flats with the zJ grism (see next paragraph).

For spectroscopic flats with the HK or the K grism, you should not use the tungsten lamp due to the presence of a broader absorption feature. Instead, observe the illuminated dome. Open the mirror petals

```
petals open
```

look for the Table 4.2 to see what dome flat lamps are needed. If all 5 lamps are needed then switch them all on

```
fflamp all on
```

but leave the dome illumination itself switched off, since the latter features lots of emission lines. You must take out the Acq/Comp mirror (you might want to do the same frames without any lamps on). Even though by observing the dome means looking through just a few meters of air, you will see the very prominent absorption lines due to water vapour, forming the natural separation between the *H*- and the *Ks*-bands.

For example in the case of the widest slit one should use only the two faintest dome flat lamps. Dome flat lamps can be switched on one by one with a command

```
fflamp N on
```

where N is the desired lamp (1 = 9W, 2 = 25W, 3 = 150W, 4 = 500W and 5 = 500W).

Dome flat lamps can be switched off one by one with a command

```
fflamp N off
```

where N denotes the lamp number.

When no longer needed you can switch off all the dome flat lamps

```
fflamp all off
```

and close the mirror petals with

```
petals close
```

command.

4.3.4 Arcs

For wavelength calibration LIRIS offers an Argon lamp (lamp 1) and a Xenon lamp (lamp 2). Bring LIRIS into spectroscopic mode and do not forget to insert your desired slit mask. Switch on one or both calibration lamps. This can take a short while since the lamps have to warm up. Move the Acq/Comp mirror into the light path (see also Sect. 3.2.2), and then take the arc images (2 exposures per setting are sufficient).

```
agcomp
lspec <grism name> <slit mask name>
llampon 1
[llampon 2]
multarc liris <N> <int time> "Arcs"
llampoff ALL
agmirror out
```

Guidelines for arc exposure times are given in Table 4.3, the spectral atlas can be found in Appendix B. For the lr_zj grism two exposure times are recommended since there is a small number of bright lines that saturate quickly. For the medium resolution K grism, the number of arc lines is rather small. You may want to switch both lamps on at the same time.

It is usually sufficient if arcs are taken at the beginning of the night. You are free to take more before or after your target. However, the best wavelength calibration comes from the numerous sky lines themselves, since they are tied directly to each individual exposure.

Table 4.2: Orientative exposure times for spectroscopic flats.

Grism	Slit	Light source	ND filter	exposure time
lr_zj	l0p65	tungsten lamp	ND=0.9	0.9s
lr_hk	l0p65	dome flat lamps: 1-5	–	1.5s
mr_k	l0p65	dome flat lamps: 1-5	–	10s
hr_j	l0p65	tungsten lamp	ND=0.6	1s
hr_h	l0p65	tungsten lamp	ND=0.6	1s
hr_k	l0p65	dome flat lamps: 1-5	–	7s
lr_zj	l0p75	tungsten lamp	ND=1.2	1s
lr_hk	l0p75	dome flat lamps: 1-5	–	1.3s
mr_k	l0p75	dome flat lamps: 1-5	–	7.5s
hr_j	l0p75	tungsten lamp	ND=0.7	1s
hr_h	l0p75	tungsten lamp	ND=0.6	1s
hr_k	l0p75	dome flat lamps: 1-5	–	5.5s
lr_zj	l1	tungsten lamp	ND=1.8	1.5s
lr_hk	l1	dome flat lamps: 1-5	–	1s
mr_k	l1	dome flat lamps: 1-5	–	5s
hr_j	l1	tungsten lamp	ND=0.8	1s
hr_h	l1	tungsten lamp	ND=0.9	1.5s
hr_k	l1	dome flat lamps: 1-5	–	4s
lr_zj	l2p5	tungsten lamp	ND=2.3	1s
lr_hk	l2p5	dome flat lamps: 1-3	–	1.5s
mr_k	l2p5	dome flat lamps: 1-5	–	1.5s
hr_j	l2p5	tungsten lamp	ND=1.8	1s
hr_h	l2p5	tungsten lamp	ND=2.0	1s
hr_k	l2p5	dome flat lamps: 1-5	–	1s
lr_zj	l5	tungsten lamp	ND=2.6	0.9s
lr_hk	l5	dome flat lamps: 3	–	1s
mr_k	l5	dome flat lamps: 4-5	–	1s
hr_j	l5	tungsten lamp	ND=2.2	0.9s
hr_h	l5	tungsten lamp	ND=2.3	1.3s
hr_k	l5	dome flat lamps: 1-4	–	1s
lr_zj	l10	tungsten lamp	ND=3.0	1s
lr_hk	l10	dome flat lamps: 1-2	–	2.2s
mr_k	l10	dome flat lamps: 4	–	1.1s
hr_j	l10	tungsten lamp	ND=2.6	1s
hr_h	l10	tungsten lamp	ND=3.0	1.5s
hr_k	l10	dome flat lamps: 1-3	–	1.5s

Table 4.3: Orientative exposure times for arcs with the 1″ wide slit.

Grism	Slit	exp time [sec] Argon lamp (1)	exp time [sec] Xenon lamp (2)
lr_zj	l1	2.5 (low)	4 (low)
lr_zj	l1	10 (high)	15 (high)
lr_hk	l1	7 (low)	5 (low)
lr_hk	l1	30 (high)	35 (high)
hr_j	l1	10 (low)	10 (low)
hr_j	l1	30 (high)	30 (high)
hr_h	l1	20 (low)	23 (low)
hr_h	l1	40 (high)	45 (high)
hr_k	l1	30 (low)	35 (low)
hr_k	l1	55 (high)	60 (high)

Chapter 5

Imaging

5.1 Focusing

Focusing LIRIS is best done manually. The focus is usually found at 98.10 ± 0.05, refocussing during the night is not necessary unless the seeing conditions were bad during the focus run and improve significantly later at night. To change the telescope focus, type

```
focus <value>
```

in the system console. To find the optimal focus, take into account that the seeing improves significantly with increasing wavelength and decreasing airmass. Select the *Ks*-band filter (`limage ks`) and ask the OSA to point the telescope somewhere close to zenith. Integrate between $5 - 10$ seconds to average out seeing effects, and then select a non-saturated star from the display (a peak count of 25 kADU is fine, but much fainter stars do as well).

In the RTD control (see Fig. 3.5), switch the automatic file detection off and select *Star profile*. Point the cursor onto the desired star, press "b" and then "q" on the keyboard. Under *Star parameters*, you will then find the current FWHM image seeing. Increase the focus in steps of 0.05 and repeat the process, until you have identified the optimal focus. In the latter, the stars are perfectly round, whereas defocused images show degraded PSFs, which makes the recognition of the best focus easy. You do not need to interpolate between the focus steps of 0.05 unless the image seeing is extremely good (below $0\farcs5$) and you want absolute best performance (performance is still very good if you are 0.025 steps away from the best focus, even in very good seeing).

If the seeing is good (better than $0\farcs8$), you will find the focus very easily. If the seeing is bad, e.g. you see noticeable changes in FWHM in two subsequent exposures without changing focus, or no difference in two images with different focus, then don't spend too much time in focusing. If you can't tell the difference between two or three different focus images, just take the value in the middle. Even if this is not the true focus, the seeing will blur the image so much that the difference is absolutely negligible. In bad seeing, you can also increase the step size to 0.1 to make focusing a bit easier. If the seeing is so bad that you can't find a focus, just ask the OSA for the focus value of the previous night. You can safely adopt it in such conditions.

There is also an IRAF-based focus routine available (see the LIRIS user's guide on the LIRIS webpage[1] for details). However, manual focusing is faster, more intuitive and less complicated.

5.2 Imaging scripts

First, switch LIRIS into imaging mode (see Table 1.4 for the filters available):

```
limage <filter name>
```

5.2.1 Imaging without blank sky fields

To obtain dithered images, with or without autoguider, do

```
[ag_]mdither <ndit> <int time> ["title"] [-ncyc=int] [-nruns=int]
             [-xoffset=float] [-yoffset=float] [-jitter=float]
             [-mndr=int]† [-clean=int] [-coave=int]
```

This moves the telescope to `ndit=(2,3,4,5,8,9)` dither positions. The dither points are arranged in a regular grid. If the autoguider is used, take the `ag_mdither` script. At each dither position `nruns` images are taken with the specified integration time. Every subsequent `coave` (default 1) images are coaveraged (please note that this overrides any previously defined coaverage value). The dither pattern is repeated `ncyc` times. The step size of the pattern is given by `xoffset` and `yoffset` (in arcsec, defaulted to 12″). When the script has finished, the telescope returns to the starting point, which is the centre of the dither pattern. You can set the `jitter` parameter to a maximum value of 30% of the `x/yoffset` parameter. If the `x/yoffset` are different, then the smaller one serves as the reference. Each dither point will then be offset from its nominal position by a random vector of the specified length.

We strongly recommend to use the `jitter` option, as this increases the sampling of the sky and therefore leads to better results.

On the other hand, the `clean` option sets the number (default 3) of clearing reads (see chapter 4) before the first exposure in each position. Finally, the option marked with †, `mndr` is only available with autoguiding on. The number of *multiple non-destructive reads* is automatically set to `mndr`= 1, if the `mndr` is not set. Like that, the exposures taken get read out just once, and faster read-out, but minimal read-noise suppression, are achieved (this is usually enough in imaging mode, due to its inherently high sky background).

Alternatively, you can use the `rdither` script, which takes dithered images following a random pattern of a specified number of points `npts` (at present this script can only be used without autoguiding):

[1] www.ing.iac.es/Astronomy/instruments/liris/liris_cookbook_ch4.html

```
rdither <npts> <int time> ["title"] [-nruns=int] [-offset=float]
          [-jitter=float] [-mndr=int]† [-clean=int] [-coave=int]
```

5.2.2 Imaging with blank sky fields

If your target is extended, then you need to chop to a blank sky field frequently (every few minutes) so that you can calculate a sky background model from it. For this purpose you can use

```
[ag_]mdither_ext <ndit> <int time> <sky_offset> <pa_offset> ["title"]
                 [-ncyc=int] [-nruns=int] [-xoffset=float]
                 [-yoffset=float] [-jitter=float] [-mndr=int]†
                  [-clean=int] [-coave=int]
```

This does essentially the same as the normal `mdither` script, but it goes to a blank sky position after one cycle. The offset of the blank position with respect to the target is specified by `sky_offset` in arcsec and the position angle `pa_offset`. No autoguiding is performed at the sky position field since the guide star is driven off the guider chip. It will be re-acquired automatically when moving back to the target field.

5.3 Choosing the correct values for `ncyc` and `nruns`

The following factors influence your choice for the `ncyc` and `nruns` parameters:

- The more `nruns` you do per dither position, the smaller the total execution time will be. This is because the telescope makes less dither offsets, and if autoguiding is selected, it has to re-acquire the guide star less frequently. In particular in *Ks*-band these overheads can become comparable to the typical integration time of 10s, and therefore increase the execution time very significantly.

- The less `nruns` and the more `ncyc` you do (with jittering), the better your spatial and temporal sampling of the sky background will be. If the sky conditions vary rapidly, you must not use too many `nruns` since otherwise you will not be able to correct properly for the sky any more.

- If you set `nruns=1` (one exposure per dither point), then all your exposures have the same sky background (but still suffer from the reset anomaly, see also Sect. 4.1.4). This makes the data reduction more easy. If you set `nruns` to a value larger than 1, be aware of the fact that some (5−20%) of the first exposures at each dither point can have uncorrectably bad sky backgrounds and must be discarded. Thus, your number of `nruns` should preferably be equal or larger than 3 in order to minimise the loss.

- The sky varies faster with increasing wavelength. The speed of this variation is also different from night to night, and can not be determined in advance. Make sure that you fit enough dither points into the characteristic time scale, i.e. do not make `nruns` too large. For *Ks*-band, this is as short as 5 minutes, in *J*-band it can be $20 - 30$ minutes.

5.3.1 Example 1

You want a total integration time of 3600s in *Ks*-band. Choosing an integration time of 15 seconds leaves you with 240 exposures. Take the 8-point dither pattern, hence you must take 30 exposures per dither point. Choosing `nruns=5` and `ncyc=6` gives you exactly this. In that case you would spend 75 seconds ($\sim$ 85 seconds with overheads) per dither point, and you would get 8 different sky positions in about 11 minutes. This would be a good sampling of the sky variation in *Ks*. Since the sky in *Ks* is very bright and objects are usually sparse, you can calculate a good sky model from just 5 dither pointings. If you feel this is not good enough, decrease the exposure time from 15 to 10 seconds, and increase `ncyc`.

5.3.2 Example 2

You want a total integration time of 5000s in *J*-band. The sky varies much slower than in *Ks*, and is also less bright. Thus you can expose for 60s, which would require the use of the autoguider for optimal results. 60s does not divide 5000s, so increase it to e.g. 62.5s or accept a slightly smaller total integration time. Hence, with 62.5s you must take 80 exposures. This calls for the 8-point dither script, which you could repeat 10 times (`ncyc=10` and `nruns=1`, or `ncyc=5` and `nruns=2`). Expect a loss of 5% (max 10%) of exposures due to uncorrected effects of the reset anomaly or other factors. If you want to compensate for the loss, increase the exposure time by a small amount, or choose e.g. the 9-point dither pattern over the 8-point dither pattern, leaving all other settings unchanged.

5.4 Integration times and co-averaging

The integration times of individual exposures depend on the sky background, the maximum peak brightness desired, and the sampling rate of the sky. If you want to stay below 2% non-linearity for the object of interest, then choose the integration time such that the peak brightness of your object does not exceed 20-25 kADU.

Typical (maximum) integration times in the $zJHKs$ filters are given in Table 5.1. In the optimal case you should achieve a sky background level of a few 1000 ADU for optimal results (minimised systematics). Exposures in narrow-band filters can happen to have less than 1000 ADU.

Table 5.1: Typical (maximum) integration times used for imaging

Filter	z	J	H	Ks
Exp time[s]	120	60	30	20

In particular in Ks-band with its high background you may want to require a certain minimum number density of objects per exposure, e.g. when observing high galactic latitude fields. You can achieve this by co-averaging N subsequent exposures taken at the same dither position,

```
coave liris N
```

This is the same as setting `nruns=N` in the `mdither` scripts, but only the combined exposure will be stored instead of the N individual exposures. If the total time required for N exposures reaches about 1 minute, you should consider using the autoguider to ensure a proper alignment of the stacked exposures. Do not make the co-averaging too large, in order to still be able to sample the sky background frequently enough with dithered exposures (see also Sect. 5.3).

5.5 Polarimetry

Polarimetry works essentially as normal imaging, i.e. one uses the same scripts. Switch LIRIS into polarimetry mode using

```
lipol <filter name>
```

You then get in one exposure simultaneously four image slices (Fig. 5.1) of $4' \times 1'$ in size. These correspond to polarisation angles of 0, 90, 135, and 45 degrees, respectively, counted from the top to the bottom of the image. Any other polarisation angles can be achieved by means of instrument rotation (a half-wave plate will be installed soon, though). Just ask the OSA for a new sky position angle. Since the flux is divided by four, you may want to adjust the exposure times, but see Sect. 5.3 and 5.4.

When using the `mdither` scripts for imaging, you want to decrease the default value of $12''$ for `yoffset` since the field of view is only $1'$ wide in the y-direction. Alternatively,

```
nod5_pol <int time> ["title"] [-ncyc=int] [-nruns=int] [-xoffset=float]
         [-jitter=float]
```

does a five-point dither pattern, where the images are offset along the x-axis. This is identical to the `mdither` script with the `yoffset` set to zero. However, in that case the jitter value can not be set to a value larger than zero, hence the existence of the `nod5_pol` script.

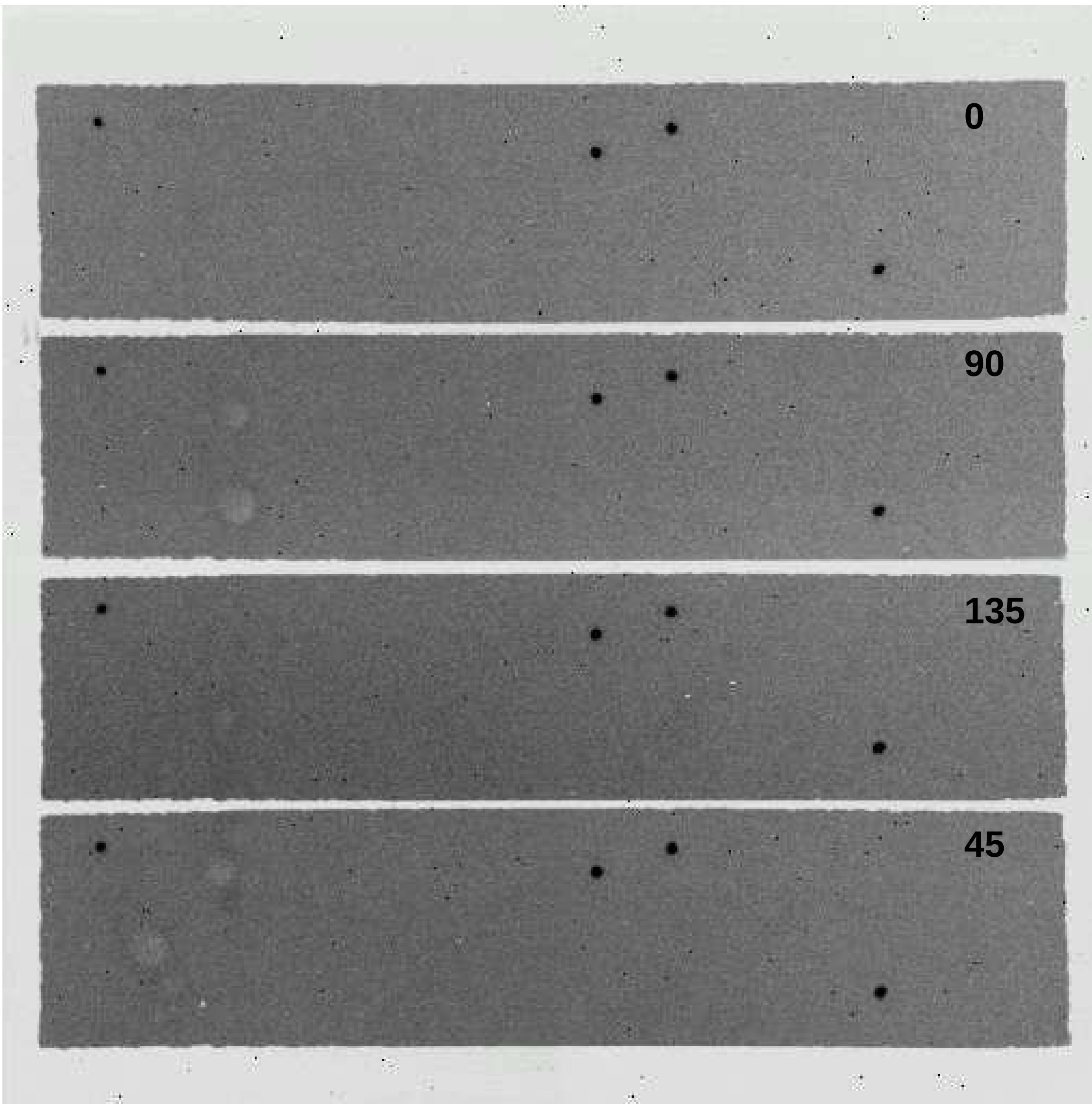

Figure 5.1: An image taken in polarimetry mode. Four polarisation vectors are mapped simultaneously, their orientations are given in this figure.

5.6 Coronography

To get into coronography mode, do

```
lcor <filter>
```

Two occulting spots, 1.″2 diameter, are available, one in the upper left, the other in the lower right quadrant. The source can be centred behind one of the two masks using

```
lobject_inslit <corup|cordown>
```

If you are not happy with the alignment, ask the OSA to make small offsets in the desired direcion. Note that you have to be guiding in order to ensure that the source stays behind the mask over longer times. You should already be autoguiding before you make fine correcions.

WARNING: The lobject_inslit command will NOT WORK for zenith distances larger than 75 degrees (airmass 4). The flexures of LIRIS have not been measured for such angles. If you really want to observe at this airmass, then ask the OSA to bring the object onto the mask.

5.7 Autoguiding

The WHT tracks rather well. As a rule of thumb one can expose for 60s without noticeable image degradation in the optical. In the near-IR the seeing is significantly better, and therefore tracking errors show up quicker. We recommend to guide for exposures longer than 40s. For exposures with less than 40 seconds guiding is superfluous, for exposures of less than 20 seconds the guiding overheads become comparable to the exposure itself and are therefore unacceptable. Also note that the initial acquisition of the guide star is a bit cumbersome with the WHT and can take 2-3 minutes. If you can't decide if you should guide or not, shorten the exposure times a bit and go for non-guiding. You will save a significant amount of overhead. For exposure times over 60s the guiding overhead is negligible.

When you need guiding, tell the OSA to centre the guide star in the guide probe, so that the offsets of the `ag_dither` script do not drive the guide star off the probe. The field of view of the latter is $\sim 1'$ and therefore could accomodate a 9-point dither pattern with a step size of $20''$ and a jitter of up to $5''$. Do not forget to tell the OSA that you are using a large dither pattern, so that he can configure the guider's tracking window accordingly.

5.8 Filter change overheads

Changing LIRIS filters (and other wheels) takes on average 1 minute, ranging from 18 to almost 90 seconds. The filter change overheads are not symmetrical, i.e. changing from e.g. z to H takes significantly more time than changing from H to z. Thus, if you observe many targets in several filters and with short integration times, the filter change overhead

Table 5.2: Some filter change overheads (in seconds)

to / from	*z*	*J*	*H*	*Ks*	*brg*	*heI*
z	0	18	63	47	74	69
J	80	0	58	43	69	64
H	34	39	0	68	23	21
Ks	54	54	55	0	39	34
brg	55	55	86	58	0	80
heI	55	56	79	64	18	0

becomes an important factor which can be optimised. If you observe many targets in different filters, you can easily save half an hour per night by selecting the proper filter order. For example, observing in the order *H-J-Ks* is optimal as it takes only 82s for the filter change, whereas *J-H-Ks* is worst with 126s. Doing *H-J-Ks-brg-heI* takes 132s, as compared to 296s for *J-brg-heI-H-Ks*. Table 5.2 lists the overheads for some filter changes. If you use other filters not mentioned in this table and plan frequent filter changes, then it is worth making a few timing measurements in the afternoon before your run and work out the optimal strategy. Note that filters can be changed while the telescope moves to the next target.

5.9 Aborting imaging scripts

If for whatever reason you must abort an ongoing observing script ([ag_]mdither, [ag_]mdither_ext or nod5_pol), please **never** abort it by pressing ctrl+C. Instead, carry the exposure command to the background (if you haven't done that yet by adding "&" to the command) by pressing:

```
control+Z
```

and then typing:

```
bg
```

Now that the command is in the background, type:

```
labort
```

and answer yes to the question it asks.

Chapter 6

Spectroscopy

6.1 Long-slit object acquisition

In order to acquire an object on one of the long slits, the following steps must be done.

1. Obtain an image of your object, preferably in the filter where it appears brightest. If necessary, subtract a dithered exposure from it to remove the uneven sky background (Sect. 3.2.4). Overplot the desired slit from the *LIRIS slits* button in the DS9 display.

2. The object should be brought to within $10'' - 15''$ of the slit. Usually, the default pointing will be good enough for this. If not, ask the OSA to move the object closer to the slit. Ideally, you want the object at a detector y-coordinate of $400 - 430$.

3. Ask the OSA for a guide star.

4. Once the guider has started and stabilised (see the guiding errors displayed in the *TCS info display*), do a *Star profile* (Sect. 3.2.4) on your object. In the *Star parameters* field, the x- and y-centroids of the object will be displayed.

5. Launch the following command:

   ```
   lobject_inslit <slit> <x-centroid> <y-centroid> [-noyoff]
   ```

   This will move the object onto the specified slit. If the `noyoff` option is given, the object will be driven only along the x-axis onto the slit, and no y-offset will be made. Otherwise, the object will be centered about $25''$ below the middle of the detector, at a pixel y-coordinate of 400. **WARNING: The lobject_inslit command will NOT WORK for zenith distances larger than 75 degrees (airmass 4). The flexures of LIRIS have not been measured for such angles. If you really want to observe at this airmass, then ask the OSA to bring the object onto the slit.**

6. When you got the prompt back, wait another $20 - 30$ seconds to allow the guider to stabilise. Then take another image to verify that the object is centred in the slit overplotted. If it is not centred, take another exposure to make sure that the seeing is not fooling you. If it is still not centred, repeat the `lobject_inslit` command with the new object position as an argument.

7. OPTIONAL: If you want to make sure that the object is actually in the slit, take a through-slit exposure, using the command

   ```
   lslit <slit>
   ```

   to move in the desired slit. Then take the exposure. Note that very faint objects will hardly be visible in this image due to the lack of exposed pixels in its surroundings (lowered contrast). If the object appears centred on the overplotted slit, it can in general be considered as being acquired. Through-slit exposures are usually not necessary.

8. Switch to spectroscopy mode, using

   ```
   lspec <grism> <slit>
   ```

   then start your observing script (see Sect. 6.2) below.
   NOTE: You can use the wheel position number instead of the name of the slit/grism. However, if you do that, keep in mind that the script will sometimes return an error, even when the mechanism actually arrives to the desired position.

Please note that the use of the autoguider is strongly recommended in the acquisition process, even for objects that require only very short exposure times (such as standard stars). The reason is that the acquisition process usually takes $3 - 5$ minutes, including switching from imaging to spectroscopy mode. During this time the source can have slightly wandered off the slit, and then you have to re-acquire it. One such iteration takes already much longer than just using the autoguider right away from the beginning.

Blind offsets from a known source to a (very faint) invisible source are in principle possible. However, you will have no guarantee that your object actually ended up on the slit. If you can not make your object visible with LIRIS in a 2- or 3-minute exposure, then you should ask yourself why you have not applied for spectroscopic time at a larger telescope. An exception is multi-object spectroscopy, where you have three reference stars in an individually taylored slit mask, and thus can be sure that the target, even though very faint, is in the slitlet.

Since the sky background saturates quickly, you can achieve long integration times using a co-averaging of subsequent exposures. For example,

```
coave liris 10
run liris 15
```

gives you an average of ten 15 second exposures, i.e. an integration time of 2.5 minutes. This helps in the acquisition of very faint targets. Do not forget to switch the co-averaging off once you start taking spectra. Otherwise, you will stay for a very long time on the same dither point, and a proper sky background subtraction will become impossible.

6.2 Spectroscopy scripts

The scripts for spectroscopic observations are very similar to the imaging scripts (Sect. 5.2).

6.2.1 Spectroscopy without blank sky fields

To obtain dithered (*nodded*) spectra using the autoguider, do

```
[ag_]spec_nod <int time> ["title"] [-ncyc=int] [-nruns=int]
            [-offset=float] [-mndr=int] [-clean=int]
            [-jitter=float] [-start_center] [-coave=int]
```

This nods the telescope in an *AB-BA-AB-BA* fashion, with *A* and *B* being the two nodding positions. If the `-start_center` option is specified, the telescope will consider the starting position as the middle point between *A* and *B* and will therefore offset half the `offset` value down before starting the script. If the autoguider is not desired, use the `spec_nod` script (not recommended, see Sect. 6.1).

At each nodding position `nruns` images are taken with the specified integration time. Every subsequent `coave` (default 1) exposures are coaveraged (please note that this overrides the value you might have previously set).The *AB* pattern is repeated `ncyc` times. The nodding step size is given by `offset` in arcsec, defaulted to $12''$. When the script has finished, the telescope returns to the starting point. You can set the `jitter` parameter to a maximum value of 30% of the `offset` parameter. Each nodding point will then be offset from its nominal position by a random vector of the specified length. For guided version of the script, with `ag_` in the beginning, the number of *multiple non-destructive reads* is automatically set to `mndr`= 4, if the `mndr` parameter is not set. Like that the exposures taken get read out 4 times and averaged, in order to suppress the read-noise. On the other hand, the `clean` option sets the number (default 3) of clearing reads (see chapter 4) before the first exposure in each position.

If you require three nodding positions, then use

```
ag_spec_nod3
```

It has the same parameters as the normal `ag_spec_nod` script. One cycle consists of a *ABC* pattern. The first exposure will be taken at position $A = (0, 0)$, the second one at $B = (0,$`offset`$)$, and the third one at $C = (0,$`-offset`$)$.

6.2.2 Spectroscopy with blank sky fields

If your target is extended, then you need to chop to a blank sky field frequently (every few minutes) so that you can calculate a sky background model from it. For this purpose you can use

```
[ag_]spec_ext <int time> <sky_offset> ["title"] [-ncyc=int]
              [-nruns=int] [-offset=float] [-mndr=int]
              [-clean=int] [-jitter=float] [-invert]
```

This moves the telescope in an *Obj-Sky Obj-Sky...* fashion, where the sequence *Obj-Sky* forms one cycle. *Sky* refers to a blank sky position. The sky positions are randomly generated to lie on a 15″ long segment perpendicular to the slit, centred at (`sky_offset`, 0). No autoguiding is performed at the sky position field. Use the `invert` option to reverse the sky offset.

6.3 Quick-looking your spectra

An IRAF package is available to help you getting a quick look at your LIRIS data while you are observing at the telescope. To use it, follow these steps:

1. Open an iraf session from the ICS screen from where you are observing (whticsdisplay1), and do:
   `> iraf`

2. This will open a DS9 and iraf session. Now change to the directory where the data is, for example:
   `ecl> cd /obsdata/whta/20091125`

3. Load the following packages::
   `ecl> twodspec`

   `ecl> longslit`
   `ecl> liris_ql`
   The prompt will now be `liris_ql>`

4. At present, there is only `lspec_ql`, a task to quicklook (combine, sky subtract and extract) a pair of nodding spectra (a dithered image quicklook task is currently under way). To get information about the use of `lspec_ql`:
   `liris_ql> help lspec_ql`

5. And to use it:
   `liris_ql> lspec_ql imageA imageB positionA`

6. Where `imageA` is the rootname of the spectrum in position A of the nodding pattern, `imageB` is the rootname of the spectrum in position B, and `positionA` is the approximate row coordinate in which the spectrum of the object is, in position A. For example:
   ```
   liris_ql> lspec_ql r1235560 r1235561 745
   ```

This quicklook task is suitable both for longslit spectroscopy and multiobject spectroscopy.

6.4 Wavelength coverage

With LIRIS, spectra in the range $0.9 - 2.5\mu$m can be taken. The low resolution grisms cover the zJ- and the HK-bands, whereas the medium resolution grism is so far only available for K. The low resolution grisms have a sufficient overlap, i.e. the zJ-grism covers the onset of H, whereas the HK-grism still shows the red end of J. Thus, the spectra can be tied together. The blue end of the spectrum is left, the red end on the right side in the exposures.

If extended (actually, shifted) wavelength coverage is desired, the *lext6* slit mask can be used. This long slit is vertically divided into 6 slits, with the upper half containing 3 slits shifted to the right, and the lower half containing another 3 to the left. Thus, if an object is positioned in one of these slits, the wavelength coverage is shifted to the right (red), and vice versa. As compared to the normal long slits, the wavelength range covered is shifted by about 10, 20 and 30% (~150, 300 and 450 pixel offsets) of its normal extent in the corresponding direction, depending on which slit you use. To position an object in a given slit of this slit mask with shifted coverage to the red, do

```
lobject_inslit lext6r1 <x> <y> [-noyoff]
lobject_inslit lext6r2 <x> <y> [-noyoff]
```

or, the most extreme case,

```
lobject_inslit lext6r3 <x> <y> [-noyoff]
```

To do the same with shifted coverage to the blue, do

```
lobject_inslit lext6b1 <x> <y> [-noyoff]
lobject_inslit lext6b2 <x> <y> [-noyoff]
```

or

```
lobject_inslit lext6b3 <x> <y> [-noyoff]
```

6.5 General Advices

6.5.1 Integration times

Spectroscopy is much more sensitive to sky background variations than imaging, since the various night sky emission lines can change rapidly and independently from each other. Only for the very faintest targets should you expose for 600s. We recommend to keep exposure times down to 300s or less.

6.5.2 Autoguider stability

Once an object is acquired and the guider running, the object will stay well-centred on the slit for times longer than an hour. It is usually not necessary to re-check the acquisition unless you notice a drop in flux (beware, that could also just be due to clouds). If you observe very faint targets which do not show a recognisable signal in one exposure, check the acquisition after two hours (or as frequent as you feel comfortable).

For very faint targets that do not leave a clearly traceble signal after one exposure, it is a good idea to orient the position angle of LIRIS such that a bright source falls elsewhere on the slit. This source can then be used as a reference when the spectra are combined, taking into account the offsets.

Aligning the slit along the parallactic angle is usually not necessary (but of course feasible if desired).

6.5.3 Standard stars

Spectrophotometric standard stars are frequently used in near infrared spectroscopy for flux and sensitivity calibration, as well as for correcting telluric (atmospheric) features in the spectra.

Most observational programs require a spectrophotometric standard to be observed every ∼2 hours, at similar airmass (i.e. similar telluric absorption bands optical depth), and close to the targets if possible, but how much/many exactly depends upon each individual case. The more accurate the flux/sensitivity correction are, the more often (and closer in time) you should observe a standard, and the closer in airmass it should be to your target (up to a difference as small as 0.05 in airmass).

In general, the less emission/absorption features your standard star has, the easier its spectrum is to be modeled, and the better suited it is for calibrations. Frequently used stars include late `B` and Early `A` stars of luminossity class `V`, but solar-like stars (i.e. `G2V`) are also useful.

ING does not have a comprehensive list of suitable spectrophotometric standards. Instead, we recommend to use an online search utility to find stars suitable for your observing programme, like the following one (external link):

```
http://www.gemini.edu/sciops/instruments/nearir-resources?q=node/10175
```

6.6 Spectropolarimetry

This mode has not been commissioned yet. The following are little more than a few indications on the scripts to be used.

Spectropolarimetry works essentially as normal spectroscopy, i.e. one uses the same scripts. Switch LIRIS into polarimetry mode using

```
lspecpol <grism name> <slitname>
```

You then get four spectra slices simultaneously in one exposure, corresponding to polarisation angles of 45, 135, 0, and 90 degrees, respectively, counted from the top to the bottom of the image [this has yet to be confirmed!]. Any other polarisation angles can be achieved by means of instrument rotation.

The script used for observing, once the target has been normally acquired in the special spectropolarimetric slit, is the usual `ag_spec_nod`. However, since the spectropolarimetric slit is only 50 arcsec long, you may want to decrease the value of the `offset` in the `ag_spec_nod` observing script.

6.7 Multi-object spectroscopy

6.7.1 Acquisition

The acquisition of a MOS mask is similar to that for a long slit. The only major difference is that you have to specify three reference sources instead of one.

1. Ask the OSA to rotate the instrument to the required sky position angle. Switch the autoguider OFF.

2. Take two dithered images with an offset of about 5″ for sky subtraction. Subtract them from each other in the RTD display.

3. Overplot the mask from the DS9 display (using the *LIRIS MOS* button in the menu bar), or load it directly in DS9 via *Region*→*Load*→`/wht/var/liris_<maskname>.reg`

4. Measure the three x- and y-coordinates using the *Star profile* task in the RTD control (see Sect. 3.2.4).

5. Acquire the mask in a first approximation, calling

   ```
   lobject_inslit <mask name> <x1> <y1> <x2> <y2> <x3> <y3>
   ```

   This routine will calculate shifts and rotations. The rotations are expected to be small (but can still lead to large movements of the guide star, hence the guider has to be switched off for this step). It is preferable to correct first for rotation angle and later adjust the offset. It is possible to correct separately both effects when using `lobject_inslit`.

   The reference stars must be given in the right order, which you can check by means of the overlaid mask in DS9. If you do not remember the order of your reference sources, have a look at

   `/wht/var/liris_slitdb_pos.dat`

   Therein, you will find an entry for your MOS mask in the form

   ```
   maskname 3 x1 y1 x2 y2 x3 y3
   ```

   with `xi` and `yi` being the pixel coordinates of the reference sources.

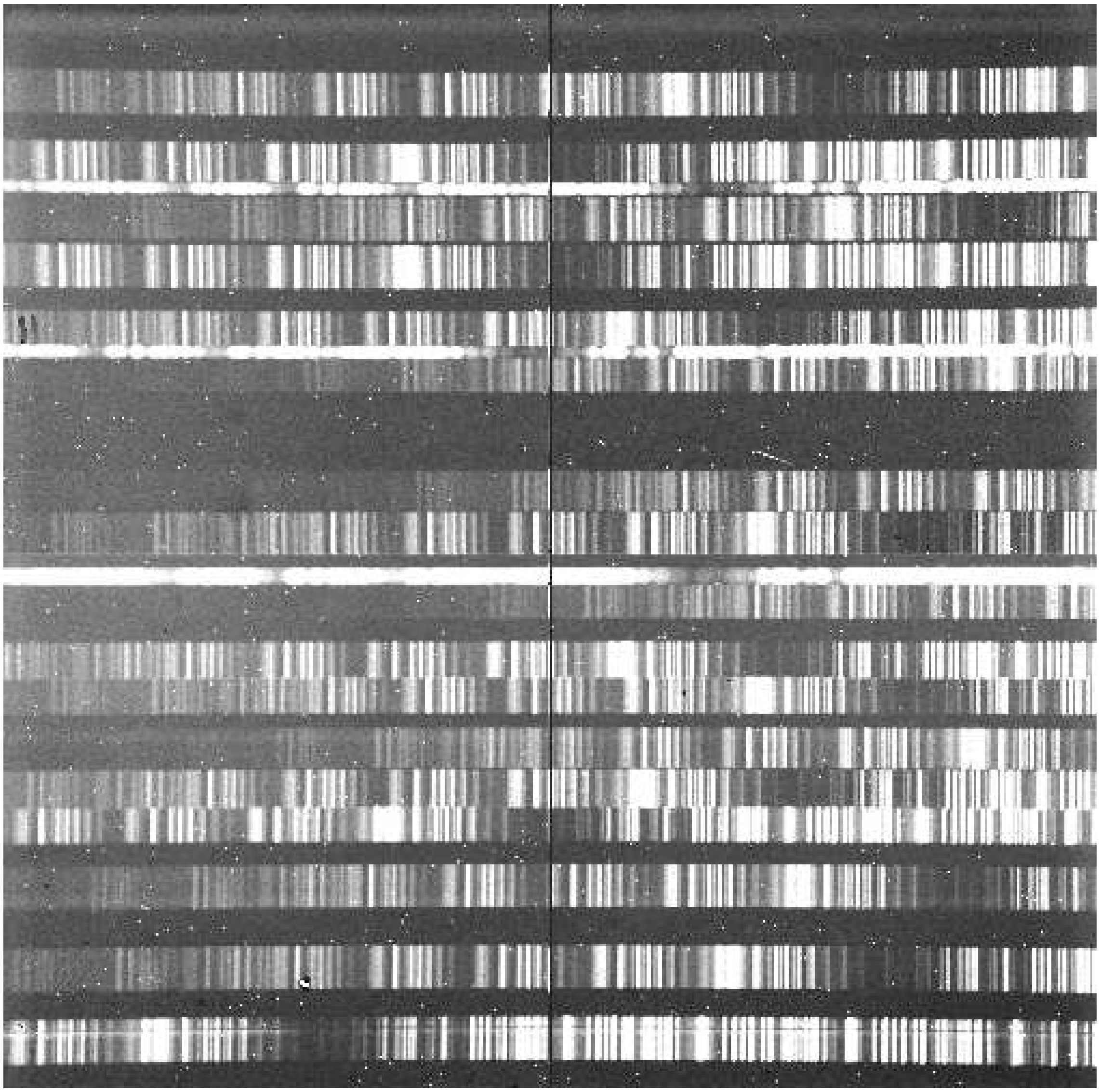

Figure 6.1: A 600s exposure through a MOS mask. The spectra are dominated by sky lines, hence it is important that the slitlets are chosen long enough (default: 10″) to accomodate three dither positions. The spectra of three reference stars used for mask alignment can be seen as well.

6. The mask is now roughly acquired. Switch the autoguider ON. If possible, select filter *I* in the Autoguider in order to minimize differential atmospheric refraction effects.

7. Repeat steps 4 and 5 for the fine-tuning of the mask position. It can be less time consuming to centre the mask manually at this point. The routine `lobject_inslit`

can still be used here, however it is better to ask the OSA for small offsets. The offsets can be computed using `lobject_inslit`, but answer "no" when the move confirmation is queried. Sometimes the autoguider needs some time to stabilize, specially when seeing is not very stable. It is better to check positions on several subsequent images.

8. When the reference stars are well centred, insert the mask without changing to spectroscopy mode by using the command

   `lslit <mask_name>`

9. Take an image through the mask. Check that the reference stars are still in the centre of the holes. It may be necessary to play with the contrast in the RTD display (switch off the *autoscale* option and select *Z-min* and *Z-max* values to have enough dynamical range in the display).

   If the reference stars are still on position, then you can proceed to the next step. Otherwise, a further adjustment is needed, which can be done manually or following the procedure described in step 12.

   Note that at this point the *Star profile* task in the RTD control may not work, because the background around the star is abrupt.

10. Switch to spectroscopy mode:

    `lspec <grism_name>`

    and start the observations.

    Keep in mind to use the proper script, `ag_spec_nod` or `ag_spec_nod3`, depending on the way the mask was designed (if the slitlets are large enough, you can fit 3 nodding points). Pay attention to the offset value when nodding in order to have the targets always within the slitlets.

11. The centering of the mask should be checked at least once every hour. The relative position between the Autoguider lock star and the science target may change due to differential atmospheric refraction, specially if the telescope elevation is low. In order to check centering, switch to imaging mode without moving the mask, using the command

    `limage <filter> <mask_name>`

    In this way the mask will stay in the light path.

12. Take an image through the mask. If the reference stars are not in the right position, recentering is needed. The required offset can be estimated either manually or either using the routine `recenter_mos`. This task only runs in the *whtdrpc1* computer. Select a working directory (`/scratch/whta/...`) and copy there the file `liris_<mask_name>.mask` which can be found in the directory `/wht/var/`. Then do

```
source  whtobs/liris/setup_liris_utils
```

to load the LIRIS utilities package, and then you can run

```
recenter_mos <image_throughmask.fit> <liris_<mask_name>.mask>
```

This routine will give the offset needed, pass the values to OSA and ask him to execute the move in *APOFF* mode.

13. Go back to step 10 and continue your observations.

6.7.2 Calibration – standard star in a few slitlets

Apart from arcs and spectroscopic flats (see Sect. 4.3) you might want to observe a standard star in a few or all the slitlets. The latter method can easily consume 30 minutes of time. We recommend to use it only if really necessary. In many cases it will be sufficient to put the standard in the left- and rightmost slitlet, and in one close to the middle of the mask. This gives you full wavelength coverage.

The method is as follows and essentially identical to long-slit spectroscopy. First, go to the standard source and roughly position it in the desired slitlet by

```
lacq_mask <mask_name>_slitN
```

where `slitN` refers to the slitlet number N (see the slitlet overlays in the <mask_name> button in *DS9*). Also, note that after lacq_mask command the aperture 0 may need to be reset to 0 0. Ask the OSA to do so if required.

Now do the fine-centering by measuring the position of the centroid of the star (`x, y` in pixels) and doing

```
lobject_inslit <mask_name>_slitN x y
```

Once you are fine with the centering (overlay your mask from within the RTD), switch to spectroscopy mode and get your exposures:

```
lspec <grism> <maskname>

[ag_]spec_nod3 <int time> ["title"] [-ncyc=int] [-nruns=int]
               [-offset=float] [-mndr=int] [-jitter=float]
               [-clean=int] [-coave=int]
```

Note that `offset` should not be larger than about 1/3 of the length of your slitlets, otherwise the star will be driven outside the slitlet.

Alternatively, you can use

```
[ag_]spec_nod <int time> ["title"] [-ncyc=int] [-nruns=int]
              [-offset=float] [-mndr=int] [-jitter=float]
```

```
            [-clean=int] [-start_center] [-coave=int]
```

with the `-start_center` option to start at the center of the slitlet and nod the telescope up and down by the `offset amount`.

The advantage of this method is that is a very controlled way of obtaining your standard spectra, as it works like for longslit spectroscopy. In addition, you can use autoguiding, which is not possible with the method described below due to the large offsets made. The disadvantage is that it requires several switches between imaging and spectroscopy mode, which increases the overhead. If you want only three or less slitlets covered, this is the method of choice. But see the last paragraph of the following section.

6.7.3 Calibration – standard star in all (or a few) slitlets

If your science requires your standard star to be taken in all slitlets (which can take 30 mins or longer), the procedure is different from the one outlined in Sect. 6.7.2.

In a first step, point the telescope to your standard star and then bring it close to the first reference hole in the MOS mask:

```
lacq_mask <mask name>
```

Then, measure the reference star centroid (see e.g. Sect. 6.1)

```
lobject_inslit <mask name> <xcentre> <ycentre>
```

The telescope will calculate and show you the corresponding offsets, and asks for confirmation to execute the move. At this point, DO NOT allow the telescope to move (answer: n). Instead, pass the offset shown to the OSA and ask him to execute the move in APOFF mode. The reason for this is that the `tweak` command sent by the `lobject_inslit` script would change the aperture 0 definition of the TCS, which was set previously to a different value by `lacq_mask` (which you executed in first place). Once the telescope has moved, re-check the pointing (overplot your slitmask in the RTD). If you are not satisfied, repeat this step.

Now you can bring LIRIS into spectroscopy mode and run a dedicated script that will cycle through all slitlets, using a 2-point nodding pattern for each slitlet:

```
lspec <grism> <mask name>
lpos_mult <mask name> <int time> [-offset=float] [-nruns=int]
```

Note that `offset` should not be larger than about 1/2 of the length of your slitlets, otherwise the star will be driven outside the slitlet. At each nodding position, `nruns` exposures are taken. Due to the large offsets from slitlet to slitlet, no autoguiding is possible.

Due to the large number of large offsets made, it is possible that due to error propagation the centering on the last slitlets is not perfect anymore. To evaluate this, or in case of trouble-shooting, run `lpos_mult` in imaging mode and see how the standard star is positioned. Once happy, do it for real in spectroscopy mode.

The `lpos_mult` script looks up the slitlet positions in the file

```
/wht/var/liris_maskname.mask
```

It is possible to remove any entries of unwanted slitlets from this file after creating a backup copy, and the standard star will then be put only onto the remaining slitlets (e.g. the leftmost, middle, and rightmost slit). Discuss this possibility with your support astronomer. The advantage of this method is that, as compared to the more manual approach in Sect. 6.7.2, it reqires only one switch from imaging to spectroscopy mode, and hence saves a lot of overhead. The disadvantage is that all the offsets will be made in an unsupervised way, and it can happen that after a series of offsets the standard star is not properly centred anymore in the slitlets.

6.8 Aborting spectroscopy scripts

If for whatever reason you must abort an ongoing observing script ([ag_]spec_nod, [ag_]spec_ext or [ag_]spec_nod3), please **never** abort it by pressing ctrl+C. Instead, carry the exposure command to the background (if you haven't done that yet by adding "&" to the command) by pressing:

```
control+Z
```

and then typing:

```
bg
```

Now that the command is in the background, type:

```
labort
```

and answer yes to the question it asks.

Appendix A

Filter transmission

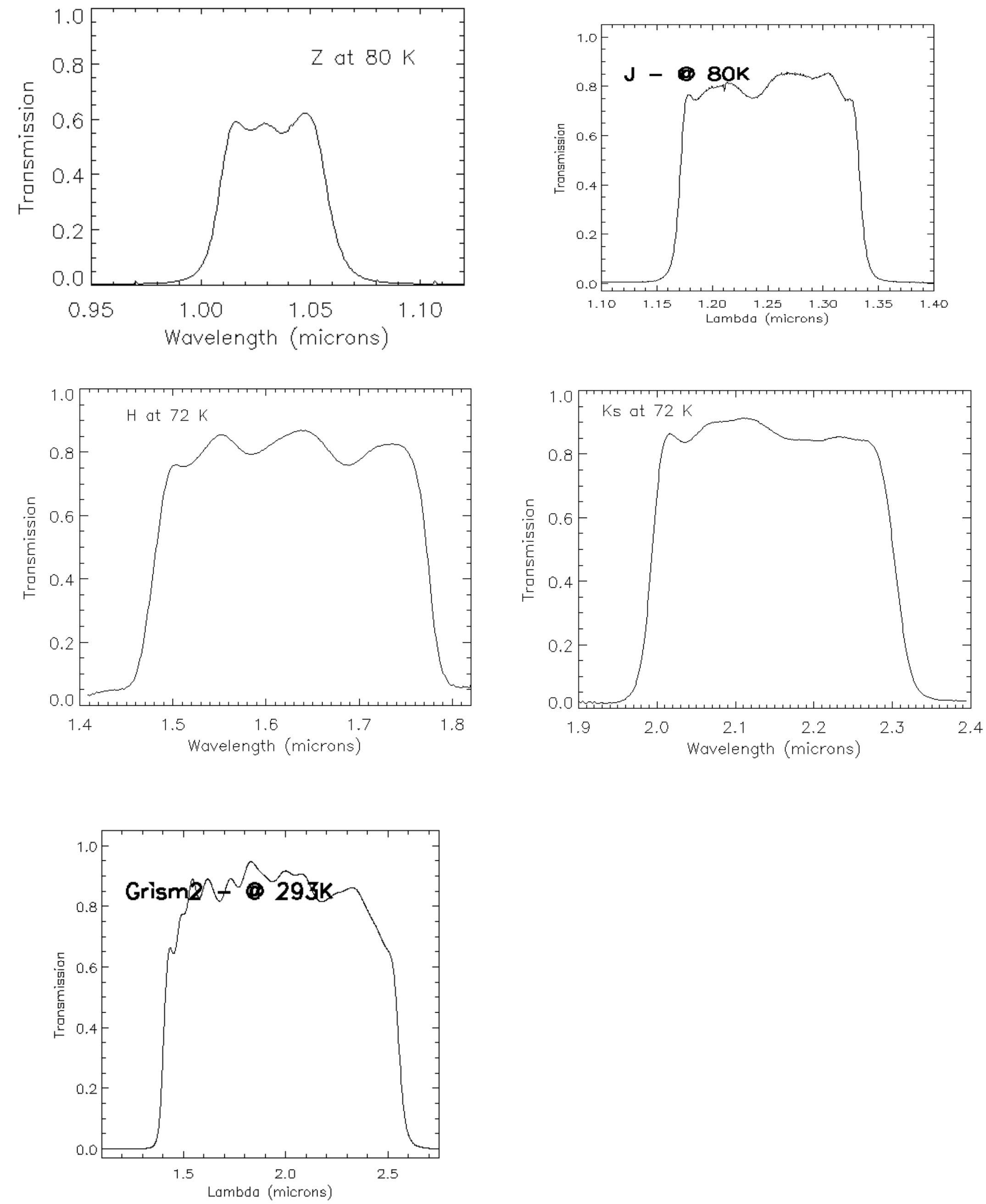

Figure A.1: Cold transmission of the z, J, H, Ks broad band filters, and the spectroscopic HK bandpass for the low-resolution HK grism.

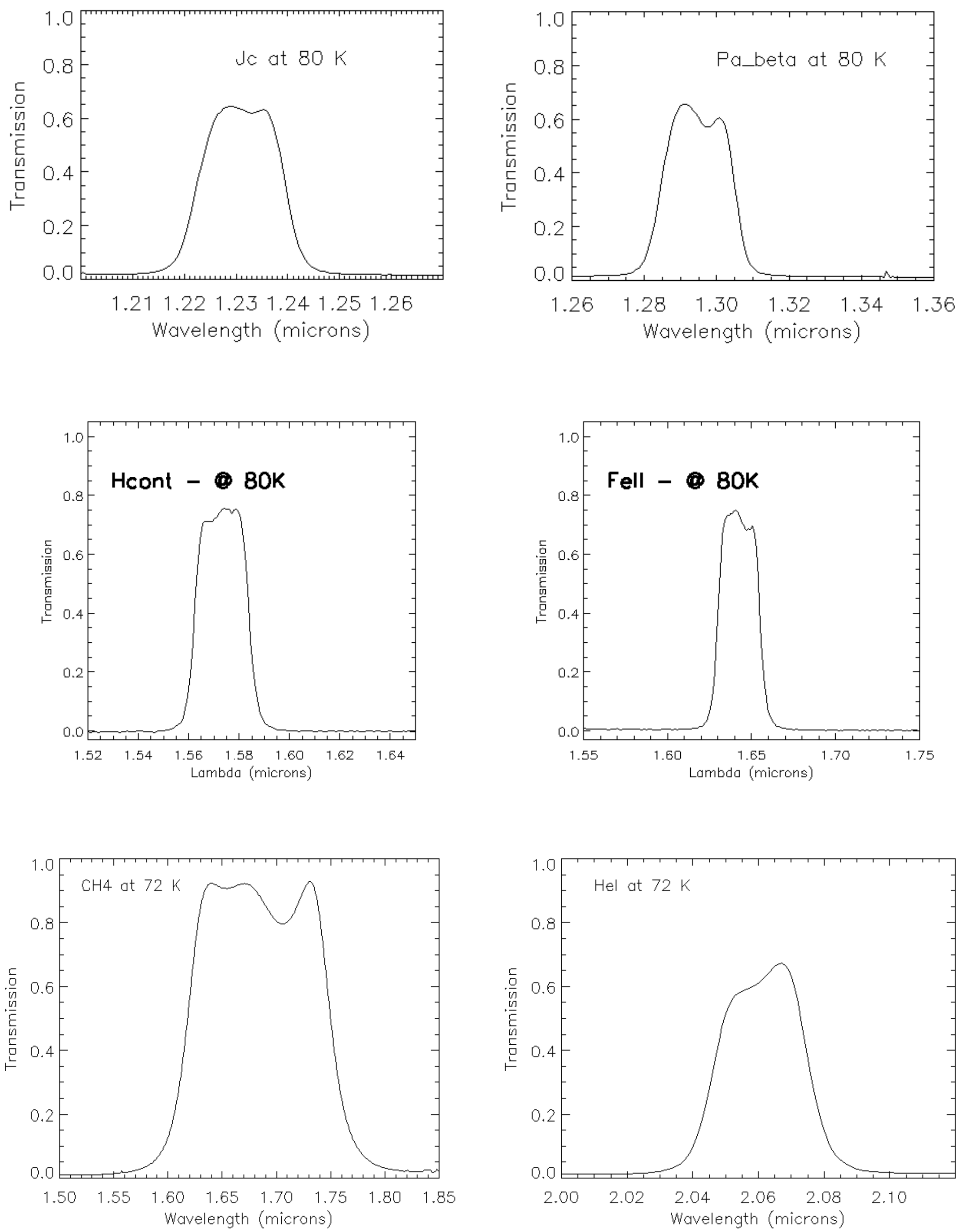

Figure A.2: Cold transmission of the *jc*, *pabeta*, *hc*, *feII*, *ch4* and *heI* narrow band filters.

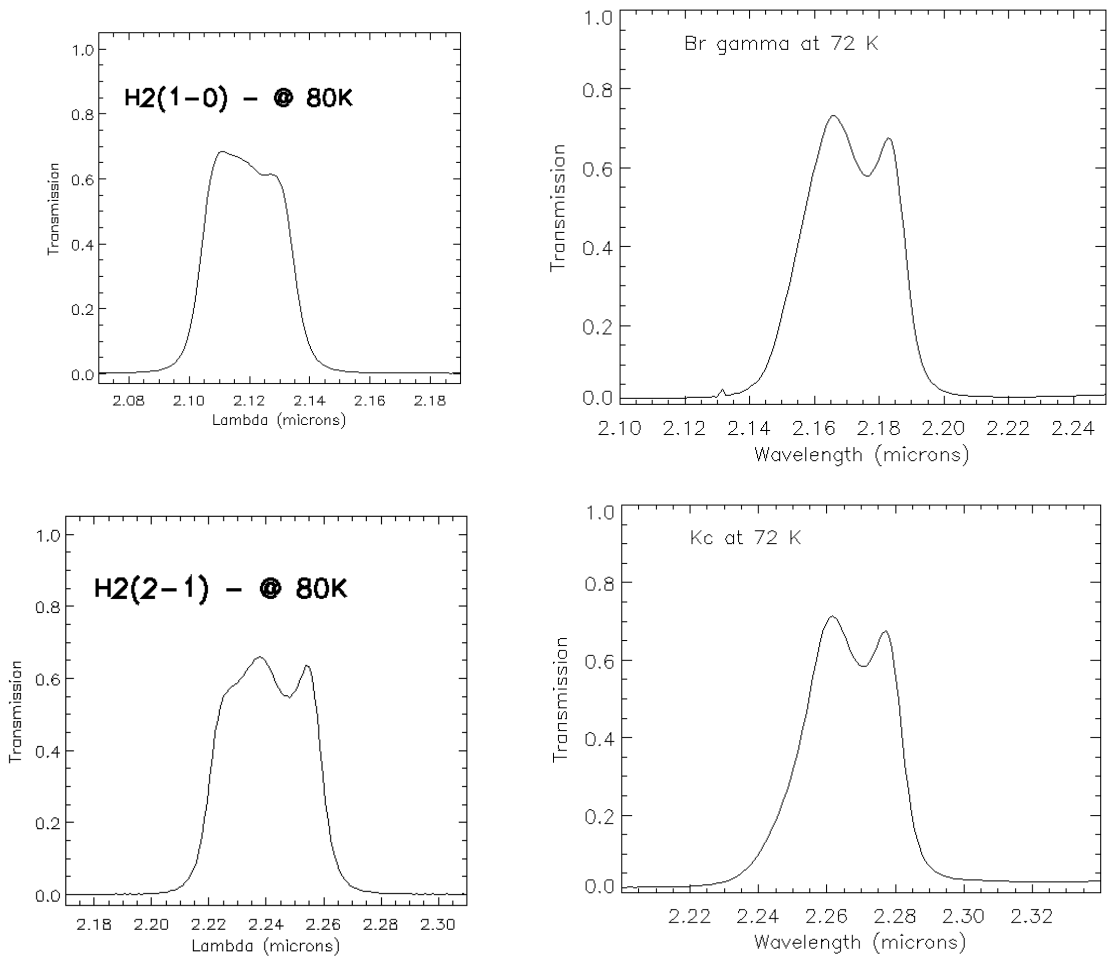

Figure A.3: Cold transmission of the *h2v10*, *brg*, *h2v21* and *kc* narrow band filters.

Appendix B

Spectral atlas

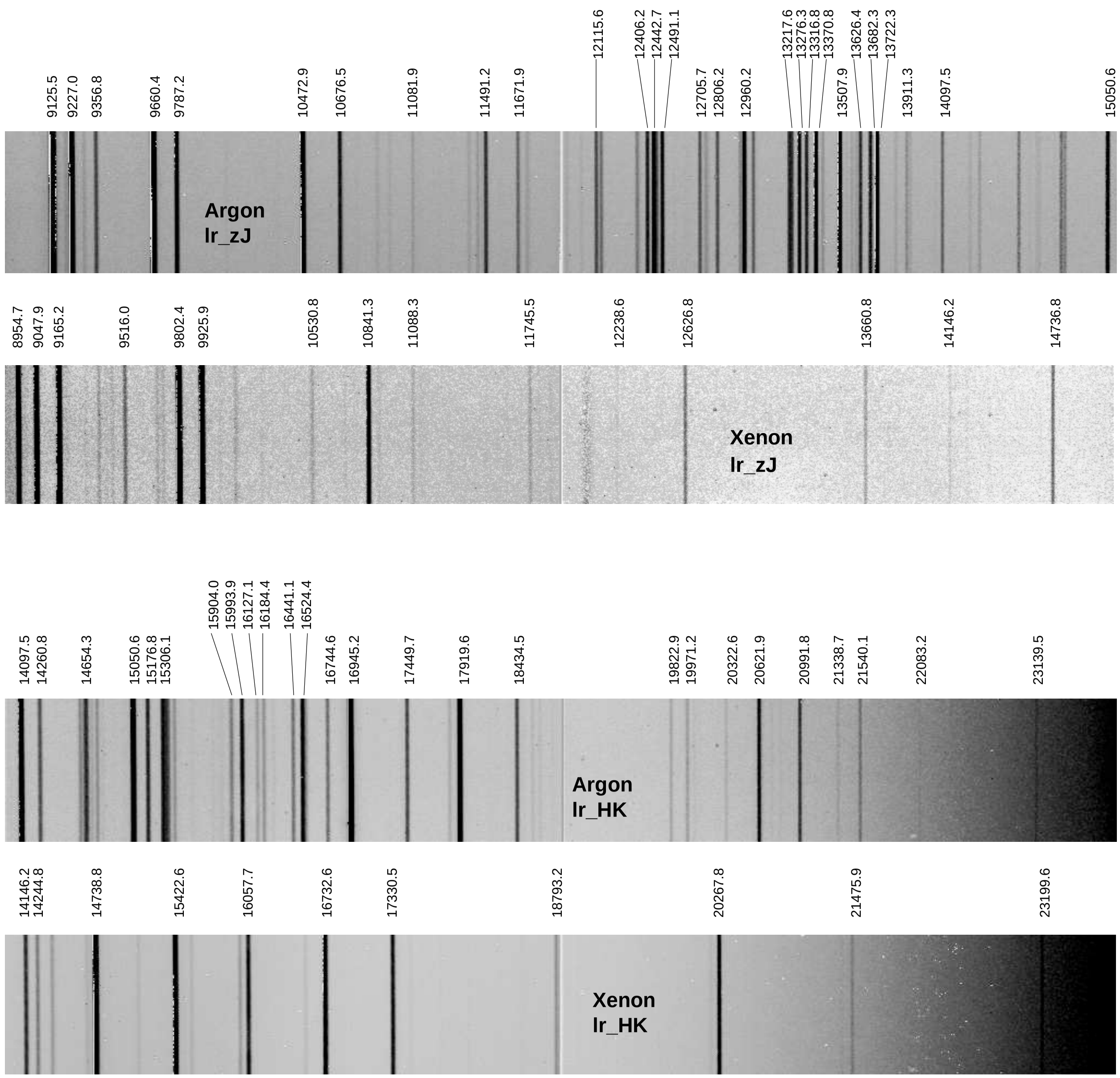

Figure B.1: Argon and Xenon arc lines for the lr_zJ and the lr_hk grism.

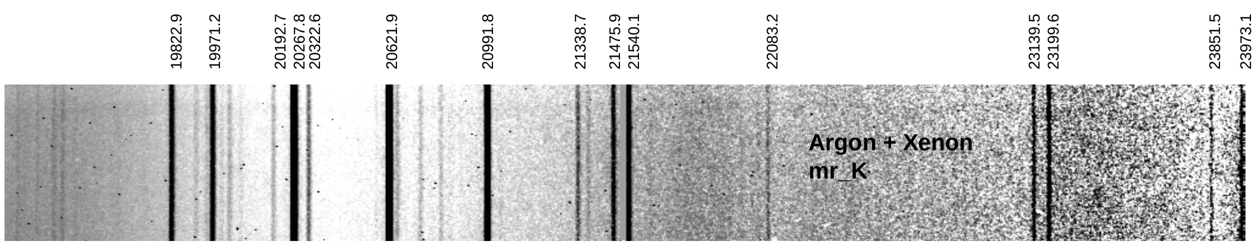

Figure B.2: Combined Argon and Xenon arc lines for the `mr_K` grism.

Appendix C

Imaging data reduction with *THELI*

On all ING public linux machines, including both WHTDRPC1 and WHTDRPC2 machines in the control room, there is *THELI* [1] installed, which can be used for a full reduction of your imaging data obtained with LIRIS. It is available to whtguest users (whtguest01, whtguest02 and whtguest03). To start *THELI* , type 'theli' at the prompt, for example

```
whtdrpc1:/home/whtguest> theli
```

In the following, we assume you took a set of dithered exposures in *Ks*-band of NGC 1234 with `nruns=6` and `ncyc=2`, and 10 seconds exposure time. The target is compact, so that no blank sky fields were required. You have taken a set of bright skyflats as well. We give here a rough step-by-step guide for a typical simple imaging session, without going deeper into details or exploiting the full functionality of *THELI* . The result obtained can be considered being of science grade quality. Intermediate results serve as a quick-look step.

C.1 Organising the data and initialising *THELI*

Create a new directory in `/reduction/local/whtguest` or `/scratch/`, let's say `myrun`, and therein subdirectories called `FLAT` and `SCIENCE`. The data taken in your night can be found under `/obsdata/whta/20070125`, if January 25th, 2007, was the date of your observing run. Copy all the flats into `FLAT`, and all exposures of your target into `SCIENCE`.

In *THELI* , you find seven *processing groups* (hereafter PG),

- Initialise
- Preparation

[1] Available via anonymous ftp from `http://www.astro.uni-bonn.de/~theli/`

- Calibration
- Superflatting
- Weighting
- Astrom/Photom
- Coaddition

In the *Initialise* PG, enter a new LOG file name, e.g. `NGC1234_Ks` and then clear the processing status. This is needed since *THELI* automatically loads the last LOG file from the previous reduction run when launched. *THELI* is fully parallised, but LIRIS has only one detector. Hence, select 1 CPU for the number of CPUs used. Then, from the instrument list on the right, select `LIRIS@WHT` as the instrument.

In the *data directories* part, enter the full path of your data as the main path, and `FLAT` and `SCIENCE` in the corresponding sections. If the path names are identified by *THELI* to be correct (i.e. existing), the background colour of the fields will change from red to green.

C.2 Preparation

Activate the *Split FITS / correct header* task and set the file suffix to `.fit`. Two commands will appear in the command window at the bottom of *THELI* . Click the green *Start* button to execute this step. The task gets a green background colour, indicating that it has been done already. When finished, you will get a *Done* message printed in the yellow message window.

What happens at this step is that a standardised FITS header is written that *THELI* can understand. The LIRIS image is also descrambled (see Sect. 4.1.1).

In the `FLAT` and `SCIENCE` directories you will now find files ending in `_1.fits`, and a `ORIGINALS` directory, which contains the unprocessed raw data.

C.3 Calibration

The bias (pre-read) (Sect. 1.1.1) is automatically subtracted from the image before it is stored by the observing system software. Hence, mark the *Do not apply BIAS /DARK* box at the top.

Several tasks can be done in one go, which we will do here.

- Mark the the *Process flats* task. Upon execution, this will create a master flat called `FLAT_1.fits` in the `FLAT` directory.
- Activate the *Spread sequence (IR)* task. As described in the example of Sect. 4.1.4, one has to split the series of exposures taken at one dither point into different groups of similar sky background. Our example consists of 6 exposures at each dither point, and the detector equilibrium will be reached with the third exposure. Hence, we enter 3 and 6 in the `group` and `length` fields, respectively. This task will create

three subdirectories SCIENCE_S1-3, at the same level in the directory tree as the SCIENCE directory, and group the corresponding images therein.

- Activate the *Calibrate data* task. We also need to calculate a superflat (or sky background model), hence choose the *Calculate SUPERFLAT* option. Enter 6, 5 and 256 for the fields *DT*, *DMIN* and *SIZE*. These are *Sextractor* parameters that are used in the detection and masking of objects, before the images are combined for the sky background. For the *Window size* you enter 0.

Then click *Start* and all tasks will be executed.

After finishing, you will find a file SCIENCE_Si_1.fits in the SCIENCE_Si directory. This is the corresponding sky background model for these exposures. It has not yet been applied. The exposures themselves have a string OFC in their file name, meaning that they have been flat fielded.

This procedure assumes that the sky background has not changed significantly within the time of the entire exposure series, i.e. within $5 - 20$ minutes. If your exposure series is longer, either split it into different SCIENCE directories, or choose a dynamic superflat (e.g. *Window size*=4). See the *THELI* documentation for more details.

C.4 Superflatting

In the *Superflatting* PG, select *Subtract SUPERFLAT* and *Merge sequence (IR)*. These tasks will scale and subtract the sky background model from the data in directories SCIENCE_Si, and then recollect the corrected images in the SCIENCE directory. They have now the extension OFCU in their file name, indicating that the sky background has been subtracted. The old OFC images are found in the OFC_IMAGES subdirectory.

A certain fraction of images will still suffer from the reset anomaly, i.e. they look like in Fig. 4.1. To correct for this effect, you can calculate and subtract an average column from the data. This process is called *Collapse correction*. Enter 2.0 and 5 for *DT* and *DMIN*, and specify x to indicate that the feature you want to correct for runs horizontally.

Once run, the file names change into OFCUC. It is now the time to look at quite some of them to make sure that they are satisfying. They should largely be flat and in the ideal case not show any features anymore in the sky background, apart from possible slow large-scale variations. If one or two images still look very uneven (most likely the very first image of the entire sequence), then feel free to just delete them. Check the *THELI* documentation for more details, and when to modify the numeric parameters.

C.5 Weighting

Here *THELI* calculates indiviual weight maps for each exposure. You want to do the *Create global weights* and the *Create WEIGHTs* tasks. Upon execution, you will find a WEIGHTS directory on the same directory level as SCIENCE.

C.6 Astrom/Photom

In this PG *THELI* downloads an astrometric reference catalogue from the web, and extracts an object catalogue for each image taken. The object catalogues are then compared to the reference catalogue to correct for inaccurate CRPIX1/2 header keywords (i.e. a zero-order astrometric solution). Thereafter, a full distortion correction is performed and relative photometric zeropoints obtained. Remaining sky background residuals can be modelled and subtracted at the end.

For the reference catalogue, choose *Web (CDS)* and *USNO-B1* as a source, enter a search radius of $3'$ and a magnitude limit. Leave the *RA* and *DEC* fields empty. If you observed an empty field and don't see many stars (say, less than 20), then enter 21 for the magnitude limit. If you see numerous stars, try 17 or 18. If your field is extremely crowded, lower the magnitude limit to 12. Then click *Get catalogue* and wait until you get a response in the yellow message window, telling how many stars there are found. This can take a while, and *THELI* will appear unresponsive during that wait. You should adjust the magnitude limit such that you obtain between $10 - 200$ reference sources.

Then select *Create source cat.* For a very empty field, enter 3 and 5 for *DT* and *DMIN*, respectively. If you see a few dozen stars, you may go with (5|5) or (5|10). If the field starts to show hundred sources, go with (10|10), and if it is very crowded try (50|10). The reason for this is to keep a reasonable number of objects that will be matched with the reference catalogue. In general, the tolerance for these parameters is very large, so don't think too much about it and just try. We recommend you create the catalogues now before proceeding to the next step.

Then, activate *Astro+photometry*, and choose *Astrometrix* (1st choice, but slower) or *Scamp* (2nd choice, but faster). Both calculate full astrometric solutions including distortion correction. Both will usually run on most data sets. If one fails, try the other. If both fail, try changing the detection parameters and possibly the magnitude limit. If they still fail, just go with the *Shift only* option. The latter does not care about distortions or sky coordinates and matching with the reference catalogue, it just determines the offsets of all exposures with respect to the first image. This can be useful in very sparse fields where hardly any sources are visible. For a more detailed discussion, see the *THELI* manual. The astrometric solution will be stored in `SCIENCE/headers`, the object catalogues in `SCIENCE/cat`. For the latter a *skycat* version exists for each image, which can be used for overplotting.

To subtract the remaining sky residuals, enter 1, 5 and 256 for *DT*, *DMIN* and *SIZE*. Choose *Model sky* for the method, or any of the other options. The manual will describe which ones are useful for which case. After sky subtraction, images `OFCUC.sub.fits` exist in the `SCIENCE` directory.

C.7 Coaddition

Lastly, the coadded image is created. You do not need to provide any parameters. Just execute the task. This will create a `SCIENCE/coadd_DEFA` folder, the coadded image therein will be called `coadd.fits`. If the astrometric solution has failed (i.e. you see double sources or big warps), switch to a different solution method than the one used, and/or obtain a denser/less dense object/reference catalogue. Run the astrometric solver again, and then the coaddition. You do not need to re-run the sky subtraction. If you do not want to overwrite the old coaddition, enter an arbitrary 4 character long string in the *ID* field. If you enter e.g. `BBBB`, the new coaddition directory will be called `coadd_BBBB`.

Unless you have chosen *Shift only* for the astrometry, the coadded image has a full astrometric calibration. No absolute photometric calibration is done.