LOW DISPERSION SURVEY SPECTROGRAPH LDSS-2

Observer Manual

The Durham-RGO LDSS-2 team

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This document is intended to tell observers how to prepare and carry out observations with LDSS-2. It also contains information about operations which would not normally be carried out by observers but which are included for information and as a guide for support astronomers.

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1.1 Overview

LDSS-2 is a common-user wide-field multiaperture spectrograph mounted at the Cassegrain focus of the 4.2m William Herschel Telescope.

LDSS stands for 'Low Dispersion Survey Spectrograph'. LDSS-2 is the second such instrument. The first, known as LDSS or LDSS-1, is a non-common-user instrument at the AAT. LDSS-2 excels at obtaining spectra of large numbers of faint objects. Its high throughput and excellent sky subtraction lead to spectacular performance at very faint limits while its relatively large field of view and multiobject capability provide a large multiplex advantage for statistical projects.

LDSS-2 is similar to LDSS-1 but is easier to operate, having a greater level of automation. It also has a different optical design to cope with the WHT's f/11 Cassegrain focal ratio and to provide better images to exploit the superior seeing on La Palma. The optics of LDSS-2 form a focal reducer based on the design of Charles Wynne and Sue Worswick, and can be used for direct imaging over an $11'$ field of view.

LDSS-2 operates as follows. The telescope is focussed onto a multiaperture mask held in an 8-position wheel. The light then passes through various apertures cut in the mask and enters the collimator which converts the input f/11 beam into parallel light, before passing it through either a filter and/or a grism. The light is then focussed by the camera onto an external detector with a final focal ratio of f/2. The camera can be moved along the optical axis slightly to allow the images to be optimized for different wavelengths of interest. Removable Hartmann masks are provided in the filter and grism wheels to aid focussing.

Four grisms are provided of which 3 can be mounted in the grism wheel at the any one time. These cover a range of spectral resolution $200 < R < 1000$, where $R \equiv \lambda/\Delta\lambda$. Up to 7 filters can be mounted in the filter wheel at once. Three broad-band filters (the BVR Harris set as used by NOAO) are provided together with 3 other filters designed for use in spectroscopic mode to suppress unwanted orders.

By using clear positions in the aperture and grism wheels, LDSS-2 can be used to give direct images in the chosen filter passband over a very wide field of view. It thus doubles as a high throughput, wide-field imager. This capability is essential for target acquisition and allows astrometry for mask manufature to be obtained in near real-time.

Fig. 1 shows a schematic of LDSS-2 and how it relates to the telescope system and Fig. 2 shows the main elements of the optical system (excluding the reconfigurable components). The main properties of LDSS-2 are summarized in Table 1.

Figure 1: Schematic of LDSS-2

Table 1: Summary of LDSS-2

Instrumental properties	
Image scale at f/11 telescope focus	4.51 arcsec/mm
Image scale at f/2 camera focus	24.6 arcsec/mm
Collimator field of view	11.5 arcmin diam
Image size (90% encircled energy)	< 25–30μm imaging
	$< 40\mu$m spectroscopic
Design wavelength range	370–750 nm
Dispersions	4 grisms: 10–47nm/mm
Peak efficiency of main optics	84% at 600nm
Aperture wheel	8 positions (7 masks + 1 clear)
Filter wheel	8 positions (BVR + 1 clear)
Grism wheel	3 grism positions + 1 clear + 2 Harts
Access doors	2 doors, remotely locked
Tektronix CCD detector	
Format	1024×1024
Pixel size	24×24 μm
Image scale	0.59 arcsec/pixel
Detector field of view	10.1×10.1 arcmin
Gain	1.3 e/ADU
Read noise	4 ADU rms
Bias	2300 ADU

Figure 2: Main optics of LDSS-2, showing (from left to right) the Cassegrain focal surface, collimator, pupil plane, camera and detector window. Some rays corresponding to angles on the sky up the full field of view are shown.

1.2 Aperture Masks

The multiaperture masks consist of a number of slits (typically 300μm wide = 1.5 arcsec) cut in a brass disk. The masks may be made at the telescope using a specialized manufacturing facility which provides masks of very high quality which can be made close to the time of observation. If arranged with technical staff, masks can be made in 'real-time' from coordinates supplied from an analysis of a direct image taken with LDSS-2. To allow accurate sky subtraction for each object, it is best to use slits at least 5-10" long so that there is plenty of sky either side of the object spectrum. In principle this means that there is space to fit 60-100 spectra on the detector, but the distribution of objects on the sky means that this maximum is not achieved in practice. A typical field will have space for about than 30-40 spectra.

The masks must be positioned flat in the focal plane of the telescope so that images are in focus at all positions over the mask. This means that the masks can not be tilted to allow any form of slit viewing. The acquisition of each field uses fiducial holes in the mask as described in Section 5.3.

In some cases, you may wish to use LDSS-2 with a longslit. Normally a traditional longslit spectrograph (e.g. ISIS/FOS-2) would be preferred for single object observations since these offer adjustable slit-jaws that are inclined to permit slit-viewing. However there may be occasions where you need to mix multiaperture and longslit work, especially for flux calibration where you might observe a spectrophotometric standard through a longslit. Here you have two choices:

- Treat your longslit observation as a multiaperture observation where there happens to be only one slit. In this case, you would design and manufacture individual masks for each field with fiducial holes to allow the telescope to be precisely aligned with the target field.
- Use a longslit mask that has already been manufactured (see below). Since this will not have fiducial holes, you will need to use a variant of the usual target acquisition technique.

Target acquisition procedures are discussed in Sections 5.3 and 5.4.

In addition to the multiaperture masks that are custom-made for each target field, there are masks already manufactured that have special functions.

Matrix mask: A regularly spaced square grid of holes used for positional calibration and distortion mapping. The pitch is 10 arcsec. See Section 4.8 for further information.

Focus mask: This consists of three well-spaced parallel slits, each of dimensions 0.32×90mm (1.4×405 arcsec). This is required for the Hartmann tests to check focus, rotation and tilt. See Section 4.6 for further information.

Standard longslit mask: A single, centrally placed longslit for traditional longslit spectroscopy. Dimensions are 0.32×50mm (1.4×225 arcsec). *Note that this (and all the other masks) is not inclined so cannot be used with the slit-viewing TV system.*

Wide longslit mask: For spectrophotometry so that all the light from the object will go down the slit. Dimensions are 1.2×45mm (5×200 arcsec).

Very wide longslit mask: Even wider than the wide longslit for really bad seeing or for easy acquisition. Dimensions are approximately 15×200 arcsec. Note that the edge quality is poor.

1.3 Grisms and Filters

LDSS-2 has four grisms, of which 3 can be mounted in the grism wheel at the any one time. These grisms give a choice of three spectral resolutions as listed in Table 2. The normal configuration is to have the Low, Medium/Blue and High dispersion grisms in the wheel, with the remaining 3 places taken by the Hartmann masks HU and HD, and a clear position.

Up to 7 filters can be mounted in the filter wheel at once. Three broad-band filters (the BVR Harris set as used by NOAO) are supplied for direct imaging. For information on the Harris prescription BVR filter set, see NOAO Newsletters 11, 12 and 14. Three other filters are available which have been designed for use in spectroscopic mode for spectroscopic order selection and wavelength isolation. All these filters have been antireflection coated, and are specified to be flat to 2λ with surfaces parallel to 1 arcmin. Their overall thickness is held to +0.1mm, -0.2mm. These are detailed in Table 3, and the throughputs plotted in Appendix G.

Additional filters in the A&G unit can be used using the ICL commands MAINFILTC and MAINFILTND, but these give an unvignetted field of only 9 arcmins. RGO also have some neutral density filters which can be installed in the LDSS-2 filter wheel. Note that separate neutral density filters are provided in the comparison lamp system.

Observers may supply their own filters. The specification is that the diameter must be 100mm ($\pm$0.1mm) and the thickness less than 8mm. In the case of user-supplied filters, staff should be notified in advance to give time for any additional spacers to be manufactured.

Table 2: Grisms

Grism name	ruling density (/mm)	blaze wavelength (nm)	central wavelength (nm)	peak efficiency	dispersion (Å/pixel)	nominal resolution (Å)
Low	150	550	550	0.82	11.3	28.3
Med/Blue	300	500	550	0.76	5.3	13.3
Med/Red	300	600	550	0.74	5.3	13.3
High	600	500	420	0.64	2.4	6.0

Table 3: Filters supplied

Name	Prescription	Function
PB	1mm BG12, 2mm BG39, 1mm GG385	Harris broadband B
PV	2mm GG495, 2mm BG39	Harris broadband V
PR	2mm OG570, 2mm KG3	Harris broadband R
S1	3mm GG375	blocks 2nd order
S2	3mm GG420	blocks 2nd order
S3	1mm BG25, 1mm BG39, 1mm WG280	transmits passband around 400nm

Table 4: Summary of throughput for LDSS-2 with the Med/Blue grism and the Tektronix 1024 CCD.

Wavelength (nm)	Optics	Grism	CCD	Atmosphere	Telescope	Total	Measured
370	-	0.32	0.40	0.69	0.72	-	0.17
400	0.58	0.52	0.58	0.76	0.72	0.10	0.08
450	0.73	0.67	0.63	0.85	0.72	0.19	0.16
500	0.77	0.71	0.63	0.89	0.72	0.22	0.20
550	0.76	0.78	0.67	0.91	0.72	0.26	0.21
600	0.70	0.84	0.69	0.92	0.72	0.27	0.22
650	0.64	0.80	0.70	0.95	0.72	0.25	0.19
700	0.57	0.68	0.69	0.97	0.72	0.19	0.14
750	0.48	0.51	0.64	0.98	0.72	0.11	0.09
800	0.43	0.37	0.56	0.99	0.72	0.06	0.05

Data:	
Optics	Lab measurements by RGO
Grism	Lab measurements by RGO and Milton Roy for Med/Blue grism
CCD	Laboratory measurements by RGO
Atmosphere	RGO Technical note by D. King assuming 1 airmass
Telescope	Assumes 2 reflections each of 85% efficiency
Total	Total throughput estimated from the above data
Measured	Throughput derived from observations of spectrophotometric standard BD +25 3941 slit by Graham Shaw (Durham) - these were done with a wide slit to include all the light

Note: For the Med/Red grism, the predicted and measured throughputs at 600nm are 0.28 and 0.23 respectively. This is in good agreement with the results for the Med/Blue grism.

1.4 Performance of LDSS-2

The throughput of the instrument is very high, peaking near 60% for a wide wavelength range as shown in Fig. 3 which summarizes the performance measured in the laboratory. The whole system including the atmosphere, telescope and detector efficiencies gives an overall throughput of around 20%, as shown in Table 4.

These figures mean that in an 1800 second integration with the medium grism, a galaxy with $b = 24$ will produce 63 detected photons per pixel in the wavelength direction near 450nm. The corresponding counts from dark sky will be 178 detected photons per pixel, so the sky noise dominates the read noise. Assuming that all of the light from the object goes through the slit and is spread over two pixels in the spatial direction, the signal to noise will be 3 per pixel in the wavelength direction. In practice it has been found that a total integration time of 4 hours will give signal to noise adequate to measure redshifts for 80% of a sample of field galaxies with $23 < b < 24$.

Note that acquiring a field is a relatively complex and time-consuming process, and even with the aid of the LEXT package will take about 20-30 minutes for each new mask. This overhead means that it becomes inefficient to use the instrument for total integrations much shorter than 60 minutes.

Figure 3: Laboratory measurements of the efficiency of, (a) the main optics (camera and collimator), (b) the grisms and (c) the CCD as labelled (courtesy of Paul Jorden and Paddy Oates (RGO).

2 LEXT

The LEXT software package is an integral part of LDSS-2, in that it enables the complex operations required to observe with multislit masks to be carried out quickly and efficiently. The program performs three essential functions: it allows the observer to design the masks; it enables rapid acquisition of the target fields by calculating the telescope offset required to map the slits onto the targets; and it simplifies the data reduction. It also offers many general data processing tools. The present version has been developed for LDSS-2 but should work equally well for LDSS-1. The original LDSS-1 version was written by Richard Hook with modifications by staff at AAO.

LEXT is a Starlink-compatible program which runs on a workstation at the telescope but can also be used at Starlink nodes. Thus you can use it at your home Starlink node to design the masks before the observing run and afterwards to reduce your data. The complete package includes the executable image, source code, help files, LEXT procedures and DCL command procedures (for VMS) or make files (for UNIX) to maintain the software. The software is predominantly written in Fortran, and depends on several Starlink ADAM and FIGARO subroutine libraries. Refer to the *LEXT Installation Guide* for details of installation.

It should be noted that LEXT is resource-hungry and will probably need special quotas. Extended use for long periods (for example at the telescope) may eventually cause problems with virtual memory resources since the DSA library, which LEXT uses, appears to be a little careless on occasions about freeing virtual memory. If this happens, the solution is to exit from LEXT and restart. For this reason, and as a normal wise precaution, you should make sure that important intermediary data sets are saved to external disk files.

The following section gives a general introduction to the LEXT package. More specific information about using LEXT is given in: Section 2.2 for preparing masks; Section 4.8 for calculating image distortion corrections; Sections 5.3 and 5.4 for acquiring fields; and Section 6 for reducing data. These sections should act as a user guide, and hopefully contain the essential information required to run LEXT for most observing programs. A more comprehensive description of the functions available in LEXT is presented in the *LEXT Reference Manual*, (Appendix A). Much of this information is also available in the large on-line HELP library which can be accessed from within the package.

2.1 Startup and basic concepts

LEXT is a monolithic program which is essentially a tool-kit to support multiobject instrumentation. Although experienced users can gain the most from its powerful features, inexperienced users can carry out sophisticated target acquisition operations with ease by making use of several special *procedures* written especially for LDSS-2. There are procedures to carry out all the essential functions of LEXT, and for most observers they will provide the easiest way to use LEXT. A list of the most useful procedures is given in Table 2.1.

Several logical names and symbols must be set up to run LEXT and there must also be some start-up files in your LEXT directory. The details of what is required are given in the LEXT manual. At the telescope, you will access LEXT from the account LEXTOBS, most conveniently run from the LPVS3 VAXstation. This account automatically sets up the relevant logical names and symbols, and LEXT can be invoked from DCL by simply typing:

$ LEXT

After some startup messages, you should arrive at a command line prompt:

LEXT – IMAGE 1 >

From here you can invoke any of the LEXT functions; a good one to start with being:

LEXT – IMAGE 1 > **HELP**

The on-line help facility uses the Starlink portable HELP facility which is different in some respects from the VMS HELP facility. In particular, if you request help on a command *and* its qualifier on the command line, you should leave a space between them. For example: **HELP MAKEFF /PLOT** will work but **HELP MAKEFF/PLOT** will not. Alternatively you can type **HELP MAKEFF** and then type **/PLOT** in response to the HELP facility prompt for the MAKEFF topic.

LEXT operates in two modes: IMAGE mode for handling image data such as acquisition images and the 2-d spectra; and LIST mode for handling tables of data, such as a list of object positions. There are several special types of LIST used by different LEXT functions. For example a MASK list contains details of the mask configuration and a BOXES list holds information on the predicted extent of the spectra for a particular observing configuration.

The user can toggle between working in LIST and IMAGE mode simply by typing **LIST** or **IMAGE**. The current mode is displayed within the command line prompt. LISTs and IMAGEs can be read in, using the READ command, to internal *slots*. There is a *stack* of slots for IMAGEs and one for LISTs. Subsequent processing takes place on these slots, and when they require saving they can be written back to disk files with the WRITE command.

There are a number of LEXT commands which simply deal with the bureaucracy of the stack system. For example DIRECTORY shows the currently used slots in the stack, NEXT, BACK and USE allow the user to move the current slot pointer. The relevance of this is that many other commands work, by default, on the current slot. However, many commands will search the stack for LISTs of the right type and warn you if there is more than one list of the correct type present.

Many of the simple commands (see the on-line HELP for full details) can be used on both LISTs and IMAGEs but with different results. For example, in LIST mode, typing:

LEXT – LIST 3 > **READ ALIST**
LEXT – LIST 4 > **ADDC**

will first read in a list called ALIST and will then prompt the user for a constant to add to a given column of the LIST (which is also prompted for) in the current slot. Note that, in this example, we start by pointing at LIST 3. The slot pointer is changed to 4 as ALIST is read into the next available slot which happens to be 4. The old data values will be over-written. In IMAGE mode, typing:

LEXT – IMAGE 2 > **ADDC 6.3**

will add 6.3 to all the data values in the current IMAGE held in slot 2. Notice that here we have specified the parameter on the command line, which is an alternative to allowing the program to prompt.

There are also a selection of more sophisticated commands to perform LDSS-2 specific tasks. Many of these require standard information, such as the pixel scale, the dispersion of the grism etc. This information is stored in a large set of internal parameters, which are then used as required by each routine. A list of some of the most important parameters is shown in Appendix D. To see what the current settings are type:

LEXT – LIST 2 > **SHOW/ALL**

This works in both modes, as do all the remaining examples in this section.

Internal parameters may be changed individually using the command

LEXT – LIST 2 > **SET** *parameter value*

The currently SET parameters may be output to an external ASCII format file using the command SAVESET. By default the saved file is called LEXT.SET, but any name can be specified on the command line. Files with can be read back by simply typing their name, e.g. to set the parameters in MYFILE.SET type:

LEXT – LIST 2 > **MYFILE.SET**

These files are examples of LEXT *procedures*, which are basically lists of LEXT commands to be executed one after another (see the example file in Appendix D). In the case of LEXT.SET all these commands are simply to SET internal parameters.

There are also several other procedures which have been written to facilitate the tasks of mask design, field acquisition etc. These reside in a directory with logical name LDSS_PROC and are invoked by typing the procedure name. LEXT searches LDSS_PROC as well as looking in the current directory for the specified procedure file. Thus both the procedures RUMBA.PROC in LDSS_PROC and RUMBA.PROC in the current directory could be invoked by typing:

LEXT – IMAGE 4 > **RUMBA**

If both procedures were present, LEXT would preferentially use the one in the current directory.

Several procedures are discussed in the appropriate sections of this manual, including PREDICT_SPECTRA, EDIT_MASK, OPTIMIZE_MASK and DRAW_MASK to help in designing masks, and FIND_TWEAK to help acquiring fields with the telescope. A list of procedures is shown in Table 2.1.

Procedure	Action
SET_GRISM	sets parameters for the different grisms
COORDS_MASK	Creates a MASK list from LDSS image coordinates
PREDICT_SPECTRA	Calculates the predicted extent of the spectra on the detector and plots the boxes
EDIT_MASK	Allows interactive adjustment of slit parameters in a MASK list
OPTIMIZE_MASK	Attempts to maximise the slit lengths for each object
DRAW_MASK	Draws a plot of slits and holes on a mask
PLOT_SPEC	Plots the predicted extent of the spectra on the detector
ANALYZE_MATRIX	Maps the LDSS distortion using an image of the matrix mask
ANALYZE_MASK	Used to measure the exact positioning of a target mask
FIND_TWEAK	Calculates small adjustments to centre the fiducial stars in their holes

Table 5: Some useful LEXT Procedures

2.2 Preparation of mask data

The multiaperture mask in the focal plane of LDSS-2 must have an accurately positioned slit for each target object, and also 3 or more larger holes to allow accurate alignment of the mask and the target images. LEXT has facilities which make it relatively simple to design a mask either from direct images of the target field or from previously measured image positions. Once the design of a mask has been completed, LEXT writes out a file which describes the position and size of the slits and fiducial holes. Observatory staff can then use the file to manufacture the mask with a computer controlled milling machine.

Note that it is essential to save the catalogue files and have them accessible to the LEXT package at the telescope so that the fields can be acquired.

2.2.1 Creating the input catalogue

In order to design masks which will allow the targets to be acquired accurately, you must provide good astrometric data for each potential target and for a number of fiducial stars that are required to help acquire the target field. Specifically, you must provide:

- Positions for each potential *target object*. These should be accurate relative to each other to a small fraction of the slit width. If the random positional errors are large then a large fraction of the useful light from the targets will be lost.

- Positions for *fiducial stars* which will be used to align the telescope with the target field. These should be accurate relative to the positions of the targets to a fraction of the slit width. At least 3 of these are required, preferably 4 or 5. There is an optimum brightness range for the fiducial stars: if they are too faint, they will be hard to see in the direct exposures required for target acquisition; if they are too bright, the acquisition algorithm will not be able to determine their positions securely and they may lead to charge bleeding during spectroscopic exposures which may obscure the spectra of the programme objects. Stars of between 15 and 17th magnitude in V work well.

- A position for a single, bright fiducial star used for locally recalibrating the telescope pointing model, the *pointing recalibration star*. The star must be bright enough to be easily seen by the telescope direct TV system, and it's position must be known accurately relative to the positions of the targets and other fiducial stars. This star should be as close as possible to the target field and, usually one of the fiducial stars within the field can be used.

The common coordinate system for these objects should be aligned with the celestial coordinate system to an accuracy of about $0.5°$ otherwise the rotation could be large enough to make the fiducial stars miss the holes in the mask. The *absolute* position of the field centre is not important since the pointing model will be locally reset but it should be good enough so that the pointing recalibration star can be easily identified with the direct TV system, i.e. ≤ 10 arcsec.

Coordinates derived from CCD exposures and scans of photographs should be converted carefully to celestial coordinates using astrometric standards to avoid errors due to incorrect calibration of the pixel scale or field rotation. Coordinates derived from direct images taken with LDSS-2 can be used directly since the the same coordinate system is used throughout.

All these positions are entered into a *catalogue file* with a name of the form *name*.CAT. The file must also contain global information about the target field. Detailed instructions on the file format and examples are given in Appendix E. The most important global parameters are:

- Position of the field centre
- Equinox
- Epoch
- Position angle of the slits

The entry for each object (both target and fiducial objects) must contain:

- The ID of the object
- The celestial position (RA and Dec)
- A *weight* which, if positive, indicates the importance of the target for subsequent optimization of the mask or is zero for fiducial stars

A number of other parameters relating to the slit configuration can also be entered for each object to override the default values derived from LEXT's internal parameters. These slit-related entries may be modified during subsequent processing by LEXT.

The catalogue file can be read into LEXT using the command

READ/CAT *name*

where *name* is the first part of the catalogue file name (*name*.CAT). The representation of a catalogue file inside LEXT is a MASK list. Initially this contains the same information as in the catalogue file with additional default values for slit parameters supplied from the values of some of the LEXT internal parameters. These will probably be altered during the mask design phase. The command WRITE/CAT will output to a disk file the same information as you input (plus any subsequent changes) with extra information about the mask configuration.

2.2.2 Generating relative astrometry from LDSS-2 images

It is possible to generate the astrometric information from positions measured on a direct image taken with LDSS-2. This is most likely to be of use when you are at the telescope and wish to improve on astrometry obtained by other means. The main complication with data obtained this way is that the optical distortion in LDSS-2 must be accounted for in transforming from the detector focal plane to the telescope focal plane. This means that the procedure should not be used with image data obtained with other instrumentation unless the distortion is recalibrated within LEXT.

This method is discussed here although it is unlikely that you will be in a position to do this before you get to the telescope. The main steps are as follows.

- Take a direct image with LDSS-2 though a filter for which you have already worked out the distortion correction from a matrix mask exposure (see Section 6.1). You will need to record the position of the field centre and the position angle used for the original direct image since this information will be used for re-acquiring the field for spectroscopy.
- Use LEXT procedure COORDS_TO_MASK to generate a MASK list. COORDS_TO_MASK can take input either as a list of coordinates produced by a previous WRITE command or an LDSS-2 direct image. If an image is used as input, the coordinates are derived interactively in the procedure using LEXT's graphical editing/selection capability. The relevant distortion correction data derived from matrix mask observations must be available (see Section 6.1). The output is a MASK list containing the relative positions of the targets. Optionally a field centre in celestial coordinates may be provided. If so, the MASK list produced will include the assumed RA and Decs of the positions in addition to the relative sky coordinates in arcsec.
- Generate a catalogue file from the MASK list and edit as appropriate. This MASK list is the internal representation of a *catalogue* file. You can then either proceed with the mask design or output the MASK list to a catalogue file with WRITE/CAT for further processing.

2.2.3 Designing the masks

Once you have created an astrometric catalogue file, LEXT provides facilities to design and optimize the slit positions and sizes for the actual mask. The main stages here are:

1. Set the lext parameters which describe the dispersion and wavelength range relevant for the grism that you intend to use.
2. Display where the direct images of the targets will fall on the detector surface to identify obvious overlaps
3. Edit the MASK list (graphically) to remove supernumary targets
4. Display where the spectra will be on the detector to identify remaining overlaps
5. Edit the MASK list again to fine-tune the slit parameters
6. Optimize the slits to maximize the slit length for each object

7. Display once more to verify the optimized slit parameters and, if necessary, edit again to fine-tune the parameters of individual slits

Finally, you will need to output a file containing the manufacturing instructions as described in the next section.

This can all be done with standard LEXT functions but it will probably be easier to use the LEXT procedures SET_GRISM, PREDICT_SPECTRA, EDIT_MASK, OPTIMIZE_MASK and DRAW_MASK as described below.

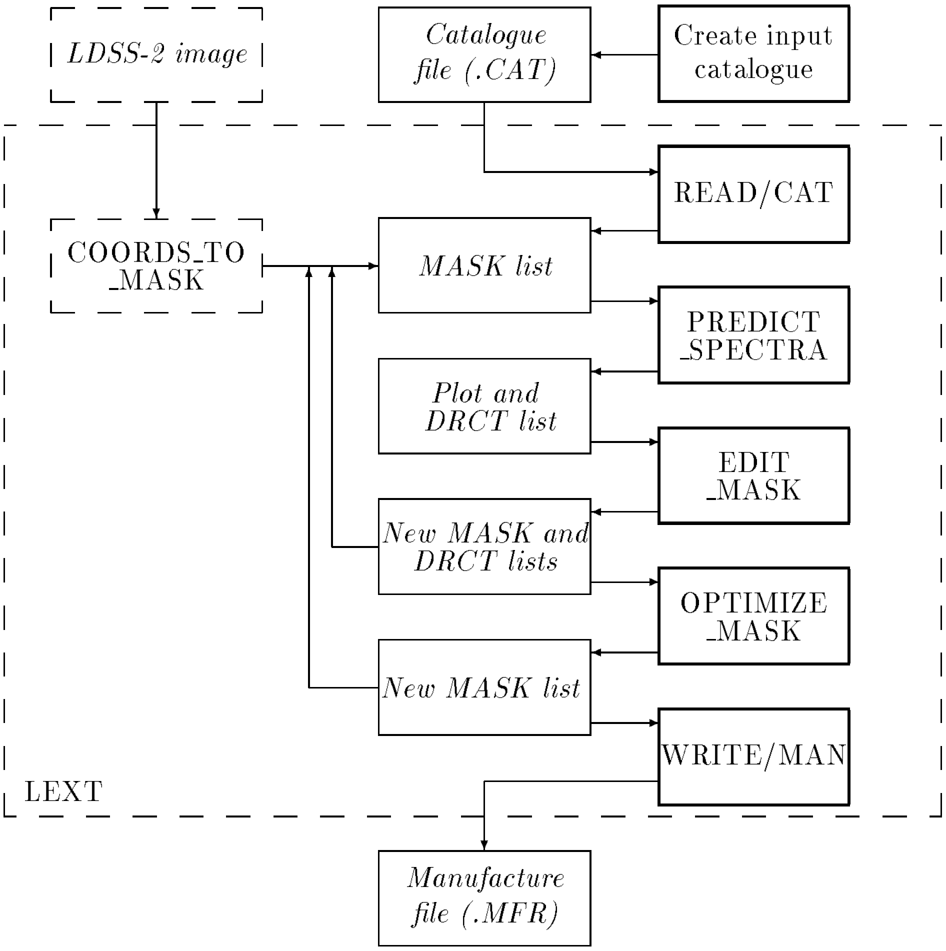

Figure 4: Summary of the generation of mask data from an input catalogue (or optionally from an LDSS-2 image) using LEXT procedures.

SET_GRISM. This simply reads a .SET file corresponding to the relevant grism.

PREDICT_SPECTRA. This plots the predicted position of the direct images of the targets and the position of the currently defined slits as they would appear on the detector. Each target is shown as an open circle with the current slit assigned to it superimposed. The fiducial stars are shown as open circles within larger circles which indicate the size of the fiducial hole. Each target is labelled with the ID number from the catalogue file. Optionally, the location of the spectra will also be shown but this can be confusing if you have a lot of supernumary targets at this stage. The user can decide whether to display the whole detector surface or just the area in which the targets are located. The input is either a user-specified catalogue file (see Section 2.2.1) which will be read into a MASK list or an existing MASK list (which may have been modified already). Fig 5 shows an example of the output. The coordinate system used by LEXT is shown in Fig 6. The procedure also produces a new list of type DRCT, which, together with the MASK list is updated by the EDIT_MASK procedure.

Figure 5: An example of the output from LEXT procedure PREDICT_SPECTRA showing the predicted positions of the direct images of the target objects and their corresponding slits.

EDIT_MASK. This uses the plot created by the procedure PREDICT_SPECTRA to *graphically* edit the MASK list by pointing to the appropriate direct image of the target with the cursor and deleting or editing it by pressing the appropriate number on the keyboard. If the target is deleted (press 1), it is removed from the plot (the label will remain). If the target is to be edited (press 2), the user is prompted for the parameters describing the current slit. These are:

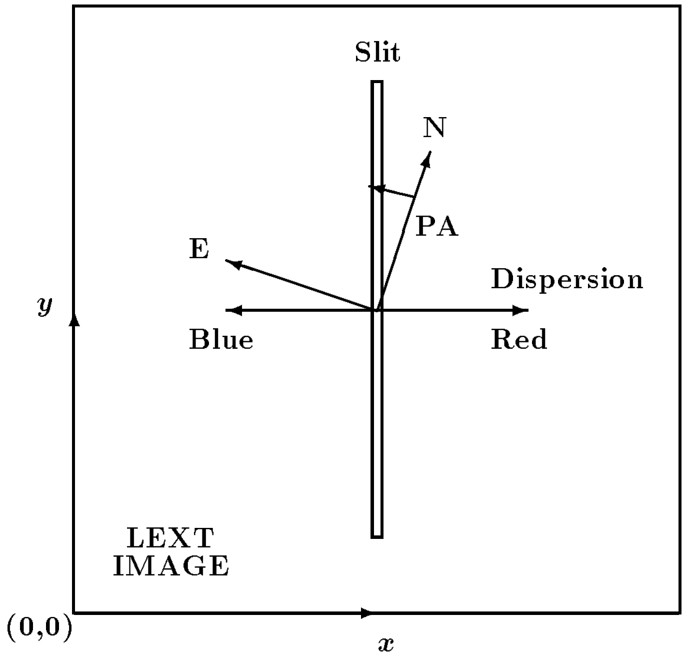

Figure 6: The LDSS-2 coordinate system showing the relationship with the sky when the slit is at a non-zero, positive position angle. This assumes that the image has been read into LEXT in the correct orientation.

- Displacement of slit in Y (pixels): A positive value here will move the whole slit upwards
- Length of slit (pixels): Set the value you require
- X position of object (pixels): you should not normally change this
- Y position of object (pixels): you should not normally change this
- Y extent of object (pixels): changing this may affect how the slit is subsequently optimized

In each case, the current value is offered as a default. The initial values of the global slit parameters are set internally (see below). After this, the display is updated to indicate the alterations. You can edit as many targets and their slits as you like, finishing by hitting key 4 while the cursor is within the display area. This procedure updates both the MASK and DRCT lists so that a subsequent PREDICT_SPECTRA will show the new configuration.

OPTIMIZE_MASK. This allows the user to optimize the mask design by increasing the length of the slits up to the point where there is an overlap with a neighboring slit. It is important to realize that this optimization will not extend beyond the currently displayed region of the detector unless the user specifies a larger area. As well as updating the MASK list, this procedure creates a new list of type BOXES. Note that the fiducial objects must be given weight zero, otherwise the position of the holes may be changed by the procedure.

These procedures can be repeated in sequence until the optimal configuration is obtained. The whole process is summarized in Fig. 4. It is possible to modify these procedures for your own use; they can be found in the directory LDSS_PROC. Alternatively, you can use any of the specialized LEXT *functions* for the same purpose: PLOT/DIRECT, PLOT/BOX, GROW, CURSOR/EDIT.

It would be wise to save intermediate versions of the MASK list using WRITE/CAT in case anything goes wrong.

Once the mask design has been finalized, a file containing the manufacturing instructions for the observatory's mask manufacturing facility can be generated using the command:

WRITE/MAN *file*

This will produce a file named *file*.MFR which can be sent to the observatory for use in physically making the masks.

The procedure DRAW_MASK produces a drawing of the mask which (if reproduced on a suitable high resolution plotter) could be used for alternative fabrication methods. An example is shown in Fig. 7. This output can be used to double check the target distribution and the final mask.

2.3 How to get the masks made

There are two methods that have been used to physically make the masks. The mask manufacturing facility operated by the observatory; and an industrial photoetching technique (masks have been this way for LDSS-1).

You are *strongly* advised to use the observatory facility rather than alternative methods since:

- It produces high quality slits
- The lead time is much reduced (as little as 30 minutes provided that the necessary technical staff are available)
- The positions of slits are reproducible (i.e. two masks made from the same data should be identical) since the masks are machined within their cells
- The masks are stiff so that they won't sag under when mounted in the instrument.

You should only need to consider alternative methods if the observatory facility is not available or if you require a very unusual slit configuration that cannot be provided by the observatory (eg very narrow slits). In this case you will be entirely responsible for getting the masks made at your own expense.

2.3.1 Observatory mask manufacture facility

A numerically controled Bridgeport INTERACT-4 milling machine is used to cut the slits and acquisition holes in a brass disk mounted on a special jig on the X-Y machine table. The cutting head consists of a cutting tool held in a chuck on a rotating spindle which moves in the Z direction. The slits have a V-shaped profile which avoids defocussing at the slit edge. The nominal width is 320μm which corresponds to about 1.5 arcsec on the sky. In principle, the width of the slits can be varied by altering the depth at which the cutting head is set, however there is no guarantee that the quality of the slit edge would be optimal for these other slit widths. The slits have rounded ends with radius equal to half the slit width. A reproduction of

Figure 7: An example of a plot of a mask produced with LEXT procedure DRAW_MASK

a slit made with INTERACT-4 is shown in Fig 8. The mask is machined as a unit within its cell so that no positional uncertainty is introduced by mounting the mask in the cell at a later stage.

Curved slits can be made by connecting short slits between a number of user-specified points. However, this will not, in general, result in a constant slit width in the dispersion direction. *Please note that the interface specification for INTERACT-4 (as used in the .MFR files) does not have provision for specifying curved slits so it would be necessary to make special arrangements with the observatory.*

To get the masks made, check with the observatory for details of when they want the files and the desired physical format of the data. They will require the .MFR file produced by LEXT using the WRITE/MAN command. Since this is in ASCII format, it may be E-mailed to the observatory or sent by any other means appropriate to the transfer of ASCII data.

The elapsed time to make a mask depends on the availability of trained staff at the observatory and reference should therefore be made to the technical staff via your Support Astronomer. The system has been designed with the aim of producing masks within 30 minutes of generating the .MFR file.

Figure 8: An enlargement of a slit made with INTERACT-4. The width is 320 μm.

2.3.2 Alternative methods

A company which has produced masks for LDSS-1 and LDSS-2 is:

Photofabrication (Services) Ltd.
Chemical Milling and Graphic Services,
14, Cromwell Rd, St Neots,
Cambridgeshire PE19 2HP,
Telephone: (0480) 75831 Fax: 75801

(Contact: J. McGarrey). In the past, they have worked from either high quality plots of the masks required or from data describing the positions of the slits (and fiducial holes), fixing holes and the outer diameter of the mask.

In general, they will only be able to supply adequate quality slits in *thin* stainless steel. This means that there is a risk that the mask will sag when mounted in a cell, especially if the mask contains long slits spanning a significant fraction of the mask diameter. Since the masks will not be made as an integral unit with their cells, there will be a positional uncertainty in the way in which the masks are fixed into the cells.

3 Control systems

3.1 Overview

There are several different systems which the observer needs to know about and operate, as summarized below. In general these are the same as for observing with any other instrument such as ISIS but with the addition of the LEXT software package running on a separate computer. More detailed descriptions are presented in the relevant sections, and there are also separate manuals for the systems not specific to LDSS-2,

Instrument Control System: This is the control system for the instruments and related sub-systems. It consists of a number of ADAM D-Tasks which handle communications with the instrument sub-systems and a user interface running ICL which accepts simple commands. The observer interacts with the system via a VAXstation which also runs a multipage MIMIC display to show the status of the telescope and instrumentation. The following functions may be controlled:

- Instrument control (see Section 3.2 for LDSS-2)
- Data acquisition and detector configuration.
- Acquisition and Guidance unit (comparison lamps/filters and autoguider probe positioning)

Detector Memory System (DMS): This controls the detector system and is run from a window on a Sparcstation in the console area. It is operated by the observers. The main functions are:

- Monitoring of the CCD
- Inspection of the raw CCD data through interaction with an image display
- Hartmann tests for focus/tilt and rotation checks (see Section 4.6)

LEXT software: This runs on a dedicated VAXstation in the control room. The system is operated by the observers and runs in an account called **LEXTOBS**. See Section 2 for further information.

Telescope Control System (TCS): This system is used to control the telescope and associated sub-systems. It is run through a VMS-style user interface by the Telescope Operator.

Acquisition TV system: This is a Forth-based system controlled by the Telescope Operator.

Autoguider Control System: The CCD autoguider is run by a FORTH based system which is controlled either by commands from the ICL interface, or through a terminal interface to the system, usually used by the Telescope Operator. The operation of the CCD autoguider, and the commands available from both interfaces, are described in more detail in the ISIS User's manual. Control of the Autoguider probe positions is through the ICL interface,

Data Archiving: Data are formatted and saved to disk on the system computer by the Data Acquisition system. Data are recorded on disk in .NDF format, and should be archived to tape (usually on a Digital Audio Tape), using the procedures FITSINIT and WRITE_FITS.

3.2 ICL and LDSS-2 start-up

The LDSS-2 control system runs under ICL on the instrument control computer. The commands specifically for LDSS are summarized in Table 6, and some other useful commands are shown in Table 7. The following steps are necessary to start up the system, and you will probably need to do this every day before starting to observe. It would be very wise to do this during the afternoon while there are technical staff around to correct any problems.

1. First make sure that both the system computer and the VAXstation used to provide the user interface are running. Then log on to the VAXstation using the OBSERVER account and start up ICL by simply typing **ICL**. This will give you a menu of instrument combinations from which you choose LDSS. During the course of the setup, you will be asked to supply the reference focus *position* with respect to which all focus *offsets* are made (see commands LFILTER etc. below). The *position* must be given as an integer in the range: 0 – 767. If in doubt, set it to the centre of the allowed range, i.e. around 380. When this has finished you should have the ICL> prompt. (If for some reason the TCS was not running when ICL was started up, you will have to start up the relevant tasks with the command TEL_LINK_TO_TCS.)

2. Normally all the LDSS-2 mechanisms are initialized automatically during the course of the startup procedures but you may need to know how to initialize LDSS-2 mechanisms in the event of problems or after loading a wheel. There are two ways to initialize LDSS-2 mechanisms depending on whether the wheels are located in a clamped position or not. After normal use they will be in such a position, but if the wheels have been loaded up recently, it is possible that they will be in an unclamped position. The significance of being in an unclamped position is twofold: (1) the position is undefined and (2) the wheel might freewheel if the telescope is not parked at the zenith which could lead to damage to some wheel-mounted components. The two ways of initialization are:

   (a) If you are sure that each wheel is in a clamp position, type **LDSS_INIT**. This will initialize each wheel in turn. On the LDSS page of the MIMIC, you should see all mechanisms turn from red to blue to green as each is initialized.

   (b) If you are *not* sure that each wheel is in a clamp position, you will need to initialize each wheel separately. Wheels which *are* in the clamp position may be initialized using LAPERTURE_INIT, LFILTER_INIT or LGRISM_INIT. Wheels which *are not* in the clamp position *must* be initialized with:

      SEND LDSS OBEY *mechanism* **GINIT**

   where *mechanism* is one of APERTURE_WHEEL, FILTER_WHEEL or GRISM_WHEEL. You must make sure that the telescope is in the zenith position otherwise there is a risk of the wheel losing registration. You can monitor progress by watching the MIMIC display.

3. Define the contents of each wheel using:

   LAPERTURE_SETUP for the aperture wheel. You will be asked for the name of the mask to be associated with each position in the wheel.

   LFILTER_SETUP for the filter wheel. You will be asked to supply the filter name and the focus *offset* from the reference position, i.e. if you specify a focus offset of 0, the focus used will be the same as the reference value specified in LDSS_BEGIN or LFOCUS_SETUP *unless* you alter the focus independently using **LFOCUS** *position*.

Table 6: Summary of LDSS-2 Instrument Control ICL Commands

Command	Parameter	Description
Routine operation		
LAPERTURE	*position*	Move aperture wheel to specified *position* = 0-7
LFILTER	*position*	Move filter wheel to specified *position* = 0-7 and adjust focus by corresponding offset
LGRISM	*position*	Move grism wheel to specified *position* = 0-5
LFOCUS	*position*	Move camera focus to specified *position* = 0-767
LDOOR	*state*	Lock (*state* = *1*) or unlock (*state* = 0) access doors
Definition of wheel contents		
LAPERTURE_SETUP		Define contents of aperture wheel
LFILTER_SETUP		Define contents of filter wheel and focus offsets
LGRISM_SETUP		Define contents of grism wheel
Wheel loading		
LDSS_CLAMP	*wheel*	Clamp *wheel* = aperture/grism/filter
LDSS_UNCLAMP	*wheel*	Unclamp *wheel* = aperture/grism/filter
SEND LDSS OBEY *mech* **GINIT**	*mech*	Initialize *mech* = APERTURE_WHEEL etc. from unclamped position
Initialization		
LAPERTURE_INIT		Initialise aperture wheel
LFILTER_INIT		Initialise filter wheel
LGRISM_INIT		Initialise grism wheel
LFOCUS_INIT		Initialise focus mechanism
Startup		
LDSS_INIT		Initialise *all* LDSS mechanisms.
LFOCUS_SETUP		Define focus reference value
Software setup		
LDSS_BEGIN		Startup LDSS software.
LDSS_LOAD		Load LDSS D-task
LDSS_DEFINE		Load all LDSS ICL procedures

LGRISM_SETUP for the grism wheel. You will be asked for the name of the grism to be associated with each position in the wheel.

Once initialized, each *wheel* may be moved to a new position using the commands **LAPERTURE** *position*, **LFILTER** *position* or **LGRISM** *position*, where *position* is the position desired as given on the MIMIC. In principle, the *name* of the position as listed in the relevant **..._SETUP** commands may be used, e.g. **LAPERTURE 4C3729A_L1** but caution needs to be exercised since if the *name* is the same as a parameter name defined internally by ICL an error may result. It is safest to use the position number.

The camera *focus* may be changed using **LFOCUS** *position* where *position* is an integer in the range 0 – 767 which gives the desired focus. In normal use, the focus will be changed automatically using the focus *offsets* stored by LFILTER_SETUP and the fiducial focus set with LDSS_BEGIN and/or LFOCUS_SETUP.

The doors are controlled with **LDOOR** *state* where *state* is either **1** for *locked* or **0** for *unlocked*.

In each case the selected mechanism is indicated on the MIMIC by highlighting the selected position or displaying the chosen value.

3.3 Data acquisition

The detector and data acquisition are controlled via ICL from the same VAXstation that controls the instrument. The most common commands are listed in Table 7.

Data are formatted and saved to disk on the Vax 4000 system computer by the Data Acquisition System, which is described in detail in "The Data Acquisition System", by G.T. Rixon and S.W. Unger. In ICL, normal integrations are started using the command RUN. On completion a RUN will read the data into the DMS, and then automatically copy it to a file in .NDF format on the VAX in a new directory for each night of observing, e.g. DISK$WHTDATA:[OBSDATA.01-JAN-1992]. These files can be examined from any of the data reduction VAXes. Of particular importance when observing with LDSS, they can be read by LEXT running on LPVS3.

The DMS stores only the most recent readout, whereas a new VAX file is created for each run. The file names are generated using the automatically updated run number. For test and set-up frames which you don't want to save, it is possible to use the command GLANCE, which does an integration, but writes the data only to the DMS; no VAX file is created and the run number remains unchanged.

The data should be archived to tape (usually on a Digital Audio Tape), using the procedures FITSINIT and WRITE_FITS. These procedures can be run from any Vax in the cluster which is connected to the relevant peripheral device, but the normal procedure is to use the OBSERVER account on the data reduction Vax LPVE. It is the responsibility of the observer and the support astronomer to produce the FITS format archive tape, or D-tape; the observers copy, or C-tape, can be produced either in FITS format or using the VMS BACKUP utility by the observers, or as a direct copy of the D-tape by operations staff.

Data in any of the DMS buffers can be also be transferred to the Sparcstation connected to the DMS, but this is not done automatically. The Sparcstation is useful for some set-up procedures where the IRAF package can be used to inspect the data, so it is worth setting it up to get data from the DMS. To do this you must use the mouse on the Sparcstation to select the DMS buffer being used by LDSS. The buffer number being used should be written on the whiteboard in the WHT control room (note that it may not be called LDSS in the DMS window on the Sparcstation). Then, once an integration has been read into the DMS buffer, the mouse on the Sparcstation can be clicked on the relevant button to copy the DMS frame into an IRAF file. There are several options for naming the IRAF file, including one which takes the currently active run number. In this option it is important to realize that if you get the data from the DMS after you have started the next run, the IRAF file will have the name corresponding to the run in progress, not the run that has just completed which corresponds to the data in the DMS.

3.4 Acquisition and Guidance unit

The acquisition and guidance unit contains the autoguider probe and the comparison lamps for calibration data. The calibration lamps, filters and comparison mirror and the autoguider probe are controlled by ICL commands in the same way as the instrument. The most commonly used commands are listed in Table 7.

The autoguider probe must be positioned by commands from ICL, but the the CCD autoguider itself can be controlled either by commands to the Autoguider D-task from the ICL interface, or through a terminal interface to the FORTH based autoguider control system. The terminal interface is usually used by the Telescope Operator. The operation of the CCD autoguider, and the commands available from both interfaces, are described in more detail in the ISIS User's manual.

The acquisition TV is controlled by a Forth-based system and is normally run by the Telescope Operator.

Table 7: Some useful basic ICL Commands

Command	Parameter	Description
Data acquisition		
RUN LDSS	*type n*	integrate for n secs, store data in DMS and copy it to a file on the VAX. The parameter *type* specifies the image type which can be FLAT, BIAS, ARC, TARGET, DARK
GLANCE LDSS	*type n*	integrate for n secs and store data in DMS
KEEP		save the last glance to the VAX, using the next run number
ABORT LDSS		stop current integration and don't save any data
FINISH LDSS		stop current integration and save the data
WINDOW LDSS		change the readout window of the ccd
DISABLE_WINDOWS LDSS		reset the readout window of the ccd
Calibration Lamps and Filters		
AGCOMP		move mirror to view calibration lamps
AGMIRROR OUT		move mirror to view the sky
COMPLAMPS	*lamp*	turn on calibration lamp. The parameter *lamp* can be W, CUAR, FEAR, OFF
COMPFILTA	*filter*	put filters in front of calibration lamps. The parameter
COMPFILTB		*filter* can be either the filter position number *1 -6* , or the name of a filter (eg *GG395*)
MAINFILTC	*filter*	put 9' filters in main beam, ie both sky and calibration beams. The parameter
MAINFILTND		*filter* can be the position number or the filter name (eg *ND3.0*) etc.
Autoguider and Acquisition TV		
AUTORADIAL	r	position autoguider probe in r
AUTOTHETA	θ	position autoguider probe in θ
AUTOFILT	*filter*	put filter in autoguider beam
FIELD		make the autoguider scan for a star
FOLLOW	*state*	make the autoguider start (*state* = ON) or stop (*state* =OFF) following the star (abbrev FON or FOFF)
ACQINT	*time*	set the autoguider acquisition time in millisecs
GUIINT	*time*	set the autoguider guiding time in millisecs.
TVFOCUS	*value*	set the acquisition TV focus to *value*
TVFILT	*filter*	put a filter in front of the TV
TVSCALE	*scale*	set the scale at the TV camera to 4.5 or 12 arcsecs/mm. *scale* can be 5 or 12

4 Setting up the Instrument

This section deals with the the things you need to do after you arrive at the telescope but before you start observing. It details the procedures you need to go through and the systems you need to interact with to ensure the instrument produces high quality data. Most of these checks will have been carried out by your support astronomer.

4.1 Checklist

- Check that the detector is correctly installed, cooled and functions electrically
- Install the test masks and initial programme masks in LDSS-2
- Check that the required filters and Hartmann masks are installed
- Check that the required grisms are installed
- Check focus, tilt and rotation by Hartmann tests
- Take distortion exposures of the matrix mask through each filter
- Do the positional calibration of masks
- Take dispersed flatfields through each mask for each grism

4.2 Detector

LDSS-2 should work with any standard La Palma detector system. For the purposes of this document, it is assumed that the Tektronix 1024 CCD which was used during commissioning will be used. Table 1 gives the parameters for this CCD.

It is wise to carry out some checks to ensure that the CCD is working as expected. These can be carried out using the DMS to inspect test images and calculate simple statistics. The DMS is currently run from a window on the Sparcstation, and there are also menu options accessed with the mouse attached to the DMS display. Also data in any of the DMS buffers can be transferred to the Sparcstation (see Section 3.3). This allows image inspection using more sophisticated software such as IMEXAMINE and other IRAF routines.

The ICL computer should be used to set up the correct windowing so that the required part of the CCD is read out. Some CCDs also have a fast readout mode which reduces the readout time at the expense of increased noise. Normally you will need the full CCD area and the slow readout mode to minimize noise, but there are times during certain setup operations when it is useful to have a small window and/or fast readout so that the total elapsed time to readout the CCD is reduced.

The following aspects of the CCD detector need to be checked.

- **Noise levels:** Take a bias frame (zero exposure) and do statistics on the image using the DMS menu functions. The noise level recorded should be close to the expected readout noise (see Table 1).

- **Uniformity and cosmetics:** A bias frame should not show significant structure. Ramps over one dimension of the chip probably indicate the presence of dark current. If you see this, first check that the CCD is at the correct operational temperature. You can also check for anomalous rows or columns and individual pixels. These can also be a symptom of incorrect operating temperature since traps are temperature dependent.
- **Charge transfer efficiency:** The most practical way of checking this at this stage is to examine cosmic ray events. By taking cuts through them in the X and Y directions (use DMS functions X-CUT, Y-CUT, X-PROF, Y-PROF), you can see if there is any evidence for trailing or asymmetry in the charge distribution. If so, this may indicate problems with charge transfer efficiency but first check several cosmic ray events since some events are intrinsically asymmetric! A better check would be to examine unblended lines in a wavelength calibration exposure (Section 5.5.2).

Throughout the night, be sure to check the temperature of the CCD from time to time and make sure that the dewar has been filled at the start of the night.

4.3 Aperture masks

The aperture masks for the programme should have been manufactured well before the start of the run, and should be installed during the afternoon before the first night of observing. The focus and matrix masks (see Section 1.2) are required for some setup operations. *Loading the aperture wheel is a task for qualified personnel only.* However, it is useful to know the general procedure and the observer may need to perform some of the non-critical items in this sequence

- Take the telescope to the zenith
- Unlock the doors using **LDOOR 0**
- Unclamp the aperture wheel using **LDSS_UNCLAMP APERTURE**
- Go out to LDSS-2 with new masks and open the doors
- Manually release the spring clamp and turn the aperture wheel by hand to the desired unloading/loading position, letting the clamp relocate to hold the wheel in the new position
- Remove the old mask by turning each of the three spring-loaded clips and lifting out the mask. Take care not to touch the underside of the mask, since this could damage the slit edges.
- Place the new mask in the holder so that it seats down flat; the three locating points on the cell are such that it will fit properly only in the correct orientation and the right way up.
- Make sure that the mask cell is held tightly against the locating points while you lift and turn the three clips to hold it in place. Check that the cell has been clamped firmly up against the locating points by trying to slip a piece of paper between the cell and each of the three pins (this is the most difficult part).
- Once satisfied that the mask is correctly installed, unclamp the aperture wheel and move it ready to change the next mask, making sure to note which mask is in which position

- Close the doors and return to control room taking old masks with you
- Lock the doors using **LDOOR 1**
- Reinitialize the wheel from an arbitrary position using
  SEND LDSS OBEY APERTURE_WHEEL GINIT
- Use **LAPERTURE_SETUP** to redefine the contents of the wheel.

4.4 Filters

The standard filters for use with LDSS are listed in Table 3. Observers may supply their own filters. The specification is that the diameter must be 100mm (±0.1mm) and the thickness less than 8mm. *Filters should only be installed by qualified personnel.* In the case of user-supplied filters, staff should be notified in advance to give time for any additional spacers to be manufactured.

4.5 Grisms

The choice of grisms is summarized in Table 2. Three of the four may be mounted in the grism wheel at any time. Two of the remaining three positions in the wheel are taken by the left and right Hartmann masks, and the final position is empty. *Changing a grism is an operation that should only be carried out by qualified personnel.*

4.6 Rotation, tilt and focus

The detector should be mounted on LDSS-2 and set to the correct back focal distance and orientation by technical/support staff. The detector position and orientation is determined with the aid of three micrometer heads which measure the distance between reference surfaces attached to LDSS-2 and the detector. A fourth micrometer head measures the rotation about the optical axis. This set of four micrometer readings uniquely defines the correct position of the detector. Thus, once these numbers have been determined, it should be possible to reposition each detector correctly without having to redetermine the correct position using optical tests each time it is interfaced to LDSS-2. However, in practice it is necessary to check that the positioning is correct every time a detector is interfaced to LDSS-2.

The optical system and detector must be aligned so that

- the optimum *focus* position is within range of the focus adjustment on the camera
- the detector is not *rotated* with respect to the slit and dispersion directions (i.e. the columns/rows of the CCD are aligned with the slit/dispersion direction)
- the detector is not *tilted* with respect to the focal surface (i.e. the focus is uniform over the full extent of the detector)

To check the alignments, direct images of the focus mask illuminated by the Tungsten calibration lamp are analysed using routines on the DMS. When satisfied with these adjustments, the best focus must be determined for both spectroscopic observations and for direct imaging. For spectroscopy the focus must be chosen to give the best compromise over the full spectral range required. For photometry the focus should be optimized to give the best images for a particular filter.

The optimum order to do these tests is as follows:

1. Set LDSS-2 to use the focus mask with white light illumination and the filter that you will use to determine the reference focus position
2. Set the camera focus to the default value (LFOCUS 380).
3. Check the rotation of the detector (single exposure with no Hartmann mask selected)
4. Setup the sampling windows for the DMS Hartmann routines.
5. Check that the focus is not out of range (Hartmann test)
6. Check the tilt (Hartmann test)
7. Determine the best overall focus for the reference filter (Hartmann test)
8. Determine the best focus for the other filters that you will be using (Hartmann test)

The following sections deal with the determination of rotation, tilt and focus in more detail.

4.6.1 Rotation

If the rows and columns of the CCD are not parallel to the dispersion and slit directions, both the acquisition of the target fields and the subsequent reduction of the data are complicated. Therefore the rotation between the detector and the optical system must be checked, and adjusted if necessary.

The rotation of the CCD with respect to the focal plane can be checked by measuring the X position of the ends of the slit on an image of the focus mask or a long slit with the grism wheel in the clear position. This should be illuminated with a white light source from the calibration system (i.e. a Tungsten lamp) with appropriate neutral density obtained using the ND filters in the comparison system. Note that some DMS routines are confused by pixel values >32000, so ensure that the maximum count is less than this. Typical exposures through a ND5 filter should be roughly 10s in V, and 5s in R. The X position of each end of the slit image can be measured with the DMS routine X-FIND.

The amount of rotation found in a particular exposure depends on BOTH the rotation of the detector with respect to the LDSS-2 optical coordinate frame AND any rotation introduced by incorrect installation of the mask. It has been found that it is possible to reinstall a given mask to an rms accuracy of 0.014° which, for the Tektronix 1024 CCD, is equivalent to 0.24 pixels (0.14 arcsec) over the full extent of the detector. The *maximum acceptable* rotation error is much larger than this, but it is not difficult to align the CCD such that the slope of the slit image is less than 0.5 pixels from top to bottom. If the slope is greater than this, then the CCD mounting ring should be rotated with respect to LDSS.

The CCD mounting ring is fixed to the mounting ring on LDSS by seven 6mm Allen screws which pass through curved slots in the CCD mounting ring into the spectrograph mounting ring. **There are two further Allen screws which hold the LDSS mounting ring to LDSS, these lie on a line through the centre of the mounting ring, and are recessed more deeply than the seven other screws. These two screws should not be loosened.** If the seven screws are loosened the cryostat and mounting ring can be rotated by a small amount, the limit is set by the length of the slots in the CCD mounting ring. There is a micrometer gauge fixed to the CCD mounting ring, which can be brought against a block which is fixed to the LDSS mounting ring to give a measure of the relative position angle of the two rings. The cryostat should be rotated by backing off the micrometer; loosening the screws; rotating the cryostat manually; tightening at least three of the screws; then measuring the position angle with the micrometer. The micrometer gauge should not be used to push the cryostat around.

A 1 pixel slope from end to end of the slit will require a movement of the cryostat position angle equivalent to around 0.1mm on the micrometer. The direction of the shift will depend upon which CCD on-chip amplifier is being used, and so will have to be established by trial and error.

4.6.2 Hartmann tests

The best method for determining focus is to use Hartmann masks. These work by blocking off alternate halves of the pupil. If the optics are perfectly focussed onto the detector, the image of a point source will be the same when either Hartmann mask of a complementary pair is employed. The size of the relative image shift between each Hartmann pair is a measure of how far away the best focus is. A number of routines are available on the DMS to calculate the Hartmann shifts from pairs of exposures employing alternate Hartmann masks.

LDSS-2 is equipped with Hartmann masks located in the filter and grism wheels (Table 8). They have the same mounting arrangement as the filters so that they can be mounted anywhere in the filter wheel or in the round holes in the grism wheel.

Table 8: Hartmann masks

Name	Description	Normal location
HL	Left	grism wheel position 2 (blocked half towards hub)
HR	Right	grism wheel position 4 (blocked half towards rim)
HU	Up	filter wheel position 1 (blocked half on door 2 side)
HD	Down	filter wheel position 2 (blocked half on door 1 side)

Up/down etc. refers to the half of the aperture which is obscured in the coordinate system of the detector. Up = positive Y direction, Left = negative X-direction etc. (+X is the red end, +Y is north on the sky for PA=0). See Fig. 6 for details of the coordinate system.

Although the Hartmann masks may be mounted in any available position within the filter and/or grism wheel, there is a particular arrangement which is strongly recommended. HL and HR should be mounted in the grism wheel so that they can be used to provide information in the dispersion direction for a particular filter. If desired, HU and HD could also be mounted in the filter wheel to provide information in the cross-dispersion direction in conjunction with a pin-hole mask and grism.

To do Hartmann tests for focus determination in the dispersion direction, you will need to use the *focus mask* (Section 1.2) which consists of three parallel long slits. This should be illuminated with white light from the calibration system with appropriate neutral density obtained using the ND filters in the comparison system. Note that some DMS routines are confused by pixel values >32000, so ensure that the maximum count is less than this in your focus images. Typical exposures through a ND5 filter should be roughly 10s in V, and 5s in R.

The DMS focus routines require sampling regions to be defined within each image. The regions are set up with the following DMS commands, typed in the DMS window on the Sparcstation:

```
25 50 75 VERT 1 SET-LINE
FOCUS
```

The first command defines three positions in the Y-direction (i.e. along the slit) where the direct image of the slits will be sampled. On Figure 9 these positions are labelled A,B, and C. They should be well spaced to sample the full length of the slits symmetrically about the fields centre. In the example given these positions are 25%, 50% and 75% of the extent of the detector in the Y-direction which suits the length of the slits quite well. The second command allows the user to interactively define where the three slits are in the X-direction.

Make sure that the exposure in the DMS was taken with the HL mask in beam, and enter the DMS command FOCUS-LEFT. This will determine the centroid of the slits averaging over the X-direction at the specified Y positions. Then put the HR mask in the beam, take another exposure and type FOCUS-RIGHT in the DMS window. This will again determine centroids for the slits and compare to the HL values to give Hartmann shifts for each of the three positions on the three slits. This gives a total of 9 Hartmann shifts which sample the on-axis position and 8 off-axis positions symmetrically disposed around it. Fig. 9 shows the geometry of the situation, and Table 9(a) shows some typical results for the case where both the focus and tilt are wrong. Experience has shown that the Hartmann shifts have an associated uncertainty when measured in this way of about ± 0.1. Note that you must use the FOCUS command before FOCUS-LEFT and FOCUS-RIGHT for each pair of Hartmann images.

4.6.3 Tilt

If the detector surface is tilted with respect to the focal surface of the camera, images will not be in focus over the full field of view. The tilt of the detector can be changed by adjusting three capstans labelled A, B and C on the dewar. To check for tilt you need to carry out a Hartmann test with the HL and HR Hartmann masks using the DMS routines FOCUS-LEFT and FOCUS-RIGHT after the appropriate exposure. Make sure you run FOCUS first. The slight curvature of the camera focal plane will mean that there will be a small difference in focus between the centre of the field and the outer positions. However the pattern of Hartmann shifts should be symmetrical about the on-axis position. It will not be exact because the detector may not be precisely centred on the optical axis.

Some typical results for the case where both the focus and tilt are wrong are shown in Table 9(a). Table 9(b) shows the situation after correction for both focus and tilt. You should aim to achieve similar figures after correcting for tilt although a constant will be added to the values shown if you have not yet corrected the focus.

The amount by which you need to move the capstans is indicated by an empirical relationship

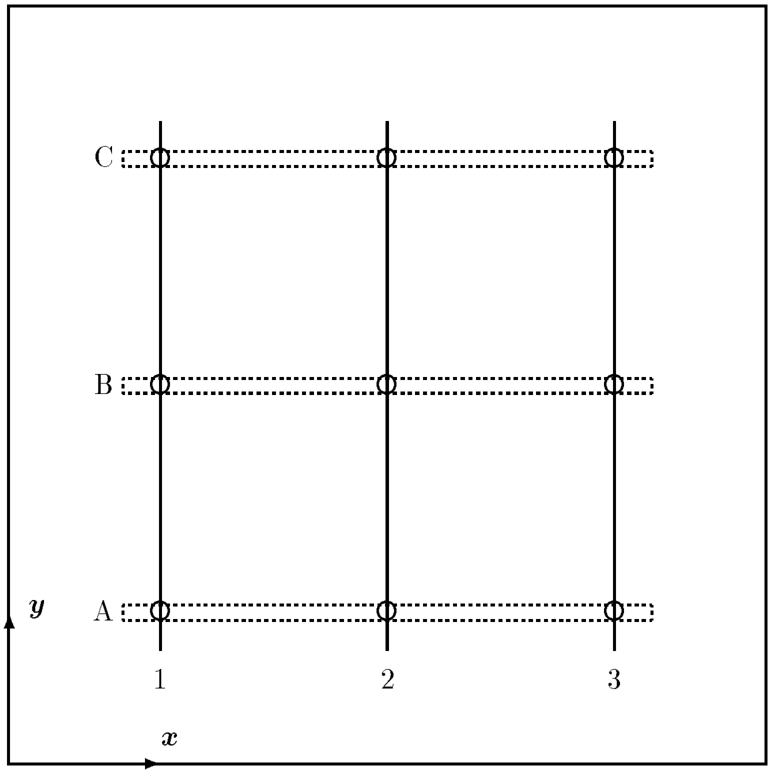

Figure 9: Schematic diagram of an image showing the the slits in the focus mask (1-3) and the sampling windows chosen for the Hartmann tests (A-C). The resultant Hartmann shifts indicate the focus value at the 9 points marked by circles.

Table 9: Examples of Hartmann shifts (a) when out of focus and with uncorrected tilt and (b) when in focus with tilt corrected

(a) Uncorrected			
	Left	Centre	Right
Top	-1.69	-1.97	-2.07
Centre	-1.70	-1.96	-1.94
Bottom	-1.33	-1.47	-1.56

(b) Corrected			
	Left	Centre	Right
Top	0.03	0.00	0.08
Centre	-0.11	-0.17	0.01
Bottom	0.02	0.10	0.14

Table 10: Example of Hartmann shifts with tilt, and orientation of capstans under CCD.

	Left	Centre	Right
Top	0.28	0.08	-0.3
Centre	0.10	-0.30	-0.5
Bottom	0.20	-0.20	-0.3

A		C
	B	

between Hartmann shift and the physical displacement of the camera. As an example consider the values in Table 10. These show a differential shift from left to right of 0.5 pixel, in the sense that the right hand values are negative. Assuming the exposures taken with the grism wheel in position LH were analysed with FOCUS-LEFT, and those taken with the grism wheel in position LR by FOCUS-RIGHT; then this shift can be corrected by rotating capstan A 0.5 turn clockwise, and capstan C 0.5 turn anticlockwise. To correct a differential shift of 0.5 pixels from top to bottom, in the sense that the lower values are positive, requires that capstan B is rotated 0.6 turn anticlockwise, and A and C each 0.3 turn clockwise. To lower the correct LFOCUS position by 300 units requires that all three capstans are rotated 0.5 turns clockwise.

Table 11: Information on focus and tilt correction

Pitch of capstan screws on detector interface Micrometer readings *decrease* as detector is *lowered*	640μm/turn
Relationship between Hartmann shift and camera position To correct a *positive* Hartmann shift, *lower* camera	0.93 shift/100μm
Relationship between LFOCUS units and camera position To *raise* camera, *increase* LFOCUS value	1.0 units/μm
Relationship between LFOCUS units and Hartmann shift To correct a *positive* Hartmann shift, *decrease* LFOCUS	108 units/1.0 shift
Target LFOCUS for reference filter	380

4.6.4 Focus

The optimum focus is a function of wavelength since LDSS-2 has a dioptric optical system in which the lenses introduce longitudinal chromatic abberation that cannot be perfectly corrected. Also the camera focal surface is not quite planar and there is some chromatic distortion which increases with off-axis angle, so there will be some slight degradation of focus as you go off axis. It is therefore necessary to determine the best focus for each filter that you wish to use. This will give you the best focus for direct imaging in the appropriate band and will also indicate the focus value to choose in spectroscopic mode. For example, if you want your spectra to have the best (spatial) focus at 6000Å, you would be wise to choose the focus appropriate for the V filter which has a central wavelength around 5600Å. For this reason, it would be wise to determine the optimum focus for the B, V and R broad band filters even if you do not plan to use all of these for direct imaging.

If LDSS is focussed for best imaging at V, then the image spread at B due to longitudinal colour terms is 125μm, and at R it is 30μm. The spatial resolution of the instrument when used in spectroscopic mode over a wide wavelength range is severely wavelength dependent.

The camera focus is adjusted using the command LFOCUS on the instrument control system. A Hartmann test with a given filter selected, should produce Hartmann shifts close to zero, but these numbers will never all be zero because of the residual curvature of the camera focal surface. The observer has to choose whether to optimize the focus for the on-axis position or for the whole field. An example of satisfactory Hartmann shifts is given in Table 9(b). Each shift has an associated uncertainty of about ± 0.1.

The relationship between Hartmann shift and the units used by LFOCUS is shown in Table 11. Thus a Hartmann shift of +1.5 can be corrected by *reducing* the focus by about 160 units.

Examples of focus values obtained for the broad band filters are shown in Table 12. The offsets can be loaded into the instrument control system using the LFILTER_SETUP command so that they will be automatically applied when the appropriate filter is selected using the command **LFILTER** *filter*.

Table 12: Typical LFOCUS values for broad band filters

Filter	LFOCUS value	offset from PV
PB	135 (110)	-250 (-255)
PV	385 (365)	0
PR	355 (305)	-30 (-60)

From all these data, it can be seen that if Hartmann shifts are more positive than +1.2 units or more negative than -3.5 units when LFOCUS is set at 380 for the V filter, then there is a risk that the optimum focus will be out of range of the camera focus drive for some passbands.

4.7 The optical centre of LDSS

For easy target acquisition it is important to determine the optical centre of LDSS-2 in the LEXT coordinate system. By convention this is taken as the position of the centre hole in the matrix mask (Section 1.2). To determine this position, take a direct exposure through the mask with a calibration light source and then use the CURSOR/GFIT command in LEXT. Though it is possible to use the DMS or Sparcstation to determine the LDSS-2 centre, it is then necessary to convert this to the coordinates as measured by LEXT — they are not the same and will depend on the options used with the LEXT *READ* command.

4.8 Distortion

The optical system produces small radial distortions amounting to approximately 2% of the radius at the field edge. This is important if you want to derive coordinates for mask manufacture since these must refer to the focal plane of the telescope which, to first order, is undistorted.

The distortion map is obtained using the *matrix mask* (see Section 1.2) which contains small holes spaced on a regular square grid. The mask should be observed without a grism with white light from the calibration system (plus neutral density filters to avoid saturation of the CCD). It is important that this should be done with a broad-band filter so that the image of each hole is not blurred by chromatic distortion effects.

Exposures should be taken through each broad-band filter (or custom filter) that you intend to use so that the chromatic component can be accounted for although this may be small enough for you to ignore.

The exposures should be analyzed using the LEXT procedure ANALYZE_MATRIX which does the following:

- Reads the user-specified matrix mask image which would normally be the raw data from the directory DISK$WHTDATA:[OBSDATA. *date*]
- Reads a user-specified file containing the positions in mm of the holes in the matrix mask. For the matrix mask in use in 1992, this file is **MATRIX_MM** (.DST or .SDF) in the directory **LDSS_PROC**.
- Predicts the location in the image plane of the matrix mask holes and calculates the hole centroids in the actual image. A comparison of the two is displayed as vectors joining the predicted and actual positions (multiplied by a large factor for clarity). At this stage, bad vectors can be edited out graphically.
- New values are calculated for: the position of the matrix mask centre in pixels; the rotation of the mask (clockwise) with respect to the detector in degrees; and the focal reduction factor between the telescope focal plane and the detector focal plane (approximately 11/2). You can then choose to use these values of the global parameters in preference to the original values and optionally store them in a new .SET file for subsequent use.
- A bicubic spline is fitted to the distortion data and stored in files FTRANS and BTRANS *or* in file names set earlier using the commands **SET FTRANS** *ftrans_file* and **SET BTRANS** *btrans_file*. These files contain the FORWARD and BACKWARD transformations respectively.

If the matrix image is too far from the nominal position, the automatic centroiding may fail. The simplest remedy is to manually set the parameters X_CENTRE and Y_CENTRE to approximately the correct values. Then re-run ANALYZE_MATRIX.

The new global parameters, and BTRANS and FTRANS files are required to generate mask data from direct LDSS-2 images using the LEXT procedure COORDS_TO_MASK.

4.9 Positional calibration of masks

Mounting the aperture masks is not a straightforward operation and it is possible for a mask to be installed so that the centre of the mask is shifted with respect to the centre defined by the matrix mask. If the masks are not made with the milling machine at the telescope, it is probable that the centre of the mask will be a considerable distance away from the correct position.

It is therefore desirable (essential in the case of masks not made by the on-site facility) to calibrate the positions of the masks. This can be done by taking a direct exposure through the appropriate mask with white light from the calibration system, using the same filter as for the master distortion exposure that you wish to relate everything to.

The LEXT procedure **ANALYZE_MASK** will calculate the relationship between the mask positions in the exposure and the predicted position from the catalogue file. This information will be stored in a new .SET file which can be used subsequently for all target acquisition operations with this mask.

5 Observing procedure

By now you should have set everything up and be ready to go. This is how you carry out the observations.

5.1 At the start of the night

Before you acquire the first of your targets, you need to do the following.

- **General system setup**

  Before dinner, ensure the DMS, CCD system, autoguider and system computer are running properly (see Section 3.2).

- **Setup the CCD readout mode**

  The CCD should be set up with the correct windowing so that the required part of the CCD is read out. Some CCDs also have a fast readout mode which reduces the readout time at the expense of increased noise. Normally you will need the full CCD area and the slow readout mode to minimize noise.

- **Setup up the Telescope Control System**

  Check with your Support Astronomer and Telescope Operator that the correct version of the TCS software has been loaded. The TCS needs to know that the instrument being used is LDSS-2 so that it sets up the correct coordinate transformation matrices internally - in particular it needs to know the offset between the zero points of the LDSS-2 and telescope rotation systems, i.e. which telescope rotator position puts the LDSS-2 slit direction at PA=0. Normally this would be done by a command such as INSTRUMENT LDSS.

- **Determine the telescope rotator centre**

  As part of the normal startup duties, the Telescope Operator will determine the rotator centre of the telescope. This is the projection of the centre of rotation of the Cassegrain rotator on the sky. To determine this, a bright star is selected and the rotator moved through 180°. The rotator centre is at the middle of the line joining the before and after positions of the star on the direct TV. The Telescope Operator will write in the log the position of this centre in terms of the *TV coordinate system*. It is vital to realize that *this coordinate system is changed if the reverse scan switches on the TV system are altered* to make the TV image invert left-right or up-down so make sure that the same switch settings on the TV system are used throughout.

  This is an important step since the field of view of the telescope, by default, will rotate around the rotator centre. If the rotator centre is incorrect, stars will appear to gyrate in position with the sidereal period when the rotator is tracking the sky.

- **Refine the telescope pointing model**

  Another standard startup procedure for the Telescope Operator is to determine an update for the global telescope pointing model by a sequence of observations of positional reference stars. This is initiated with the TCS command CALIBRATE. An alternative option is to use a previous pointing model (CALIBRATE/LAST) but this is not recommended, especially for the first night that LDSS-2 has been put on the telescope. In general, it is always best to go through the positional calibration sequence in case something has changed from the previous night. The more time you spend now to get the telescope pointing right, the less problems you will have later on acquiring your fields. The Telescope Operator will examine the residual pointing errors. They should be within accepted bounds.

Now check that this all works correctly by acquiring a positional reference star to make sure it comes in close to the rotator centre.

- **Focus the telescope onto LDSS-2**

  The telescope must be focussed onto the plane of the mask which is coincident with the input focal surface of LDSS-2. You will already have setup, or checked the best *internal* focus for LDSS-2 using Hartmann tests (Section 4.6). Make sure that the *reference* filter which you used to setup the reference focus value is selected and check that the correct focus value is in operation (**LFILTER** *filter* should be all you need to do).

  Then set the focus to the approximate value using records of previous satisfactory values. The Telescope Operator should be able to find these in the log. The telescope should be pointing at a field with stars of about 14th magnitude (with the field of view of LDSS a random patch of sky will do).

  The telescope can then be focussed onto the detector using the ICL procedure FOCUSIMAGE. At the ICL interface type:-

  FOCUSIMAGE

  The procedure will ask a number of questions, then do a number of short exposures, stepping the telescope and the telescope focus between each, and finally read out the CCD frame. The star images can then be analysed for the smallest image, and thus the best focus position, using any of the following options: the X-FIND and Y-FIND procedures on the DMS; imexamine in IRAF on the Sparcstation; or LEXT on the Vaxstation. As a guide to the parameter values: the initial focus should be set to about 0.3 mm below the estimated focus for this instrument; the focus step should be about 0.1mm; and the telescope step around 20 arcseconds. The procedure inserts a double length telescope step between the first and second focus positions.

  At this stage it would be a good idea to adjust the direct TV focus to give the sharpest images for this telescope focus value so that you can assess the seeing and/or focus easily by examining the images on the direct TV system. The TV focus is changed from the ICL VAXstation using the command TVFOCUS.

- **Determine the LDSS-2 centre**

  It is necessary to relate the LDSS-2 centre as measured from the matrix mask to the position of the rotator centre. So far the Telescope Operator has determined the rotator centre with respect to the TV coordinate system and it is necessary to relate this to the LDSS-2 coordinate system. This is accomplished by putting a brightish star on the rotator centre as accurately as possible. Then take a short direct image with no mask and measure the centroid of the star, preferably using CURSOR/GFIT in LEXT. The position of the star gives you the position of the telescope rotator centre.

- **Setup the acquisition reference position**

  The acquisition reference position is the point on the TV system display that the Telescope Operator uses for acquiring a target. After acquiring the target blindly (using GOCAT etc..), the Telescope Operator will use the handset to position the target onto the acquisition reference point.

The acquisition reference position should be the centre of field rotation. Ideally it should correspond to the LDSS centre (as determined above) rather than the physical rotator centre determined initially. The amount of mismatch that can be tolerated is determined by the size of the reference star holes in the mask. If the offset is much less than the hole size (default 10 arcsec diameter), say 2 arcsec, you can use the rotator centre as the acquisition reference position.

If the offset is larger than this, it is probably worthwhile asking the Telescope Operator to set an APERTURE OFFSET on the TCS. This will set the telescope to point at the correct LDSS centre, and more importantly, if the position angle is changed, the field will rotate about the aperture centre rather than the real (physical) rotator centre. The TCS command used is

ENTER APERTURE 0 Δx Δy

where (Δx,Δy) is the offset *in TV system coordinates*. To determine how the TV system and LDSS-2 coordinates are related, ask the Telescope Operator to use the Handset in RA-Dec mode to move the telescope by the RA and Dec offset calculated from the position of the rotator centre in the LDSS-2 coordinate system. The handset display will then give the equivalent offset in APOFF coordinates. It this which the TCS needs as the last two arguments of the ENTER APERTURE command. It's best to do all this at PA=0 to avoid confusion.

This position defines both the LDSS-2 centre and the acquisition reference position, and the Telescope Operator should mark it on the TV system display with a cursor so that there is a visual reference mark on which to acquire your targets.

5.2 Direct imaging

The procedure for direct imaging observations is the same as for ordinary imaging instruments.

- Select the position angle required on the telescope rotator
- Acquire your target on the acquisition reference position using the direct view TV.
- Find a guide star and start autoguiding
- Select the required filter
- Expose

5.3 Target acquisition with a multiaperture mask

Acquisition of the target fields, although harder than for longslit spectrographs with slit-viewing optics, is quite straightforward and usually reliable. The LEXT procedure FIND_TWEAK is essential for the acquisition, and requires copies of the catalogue files used to produce the masks. The special case of acquisition with a longslit (without fiducial holes) is dealt with in Section 5.4.

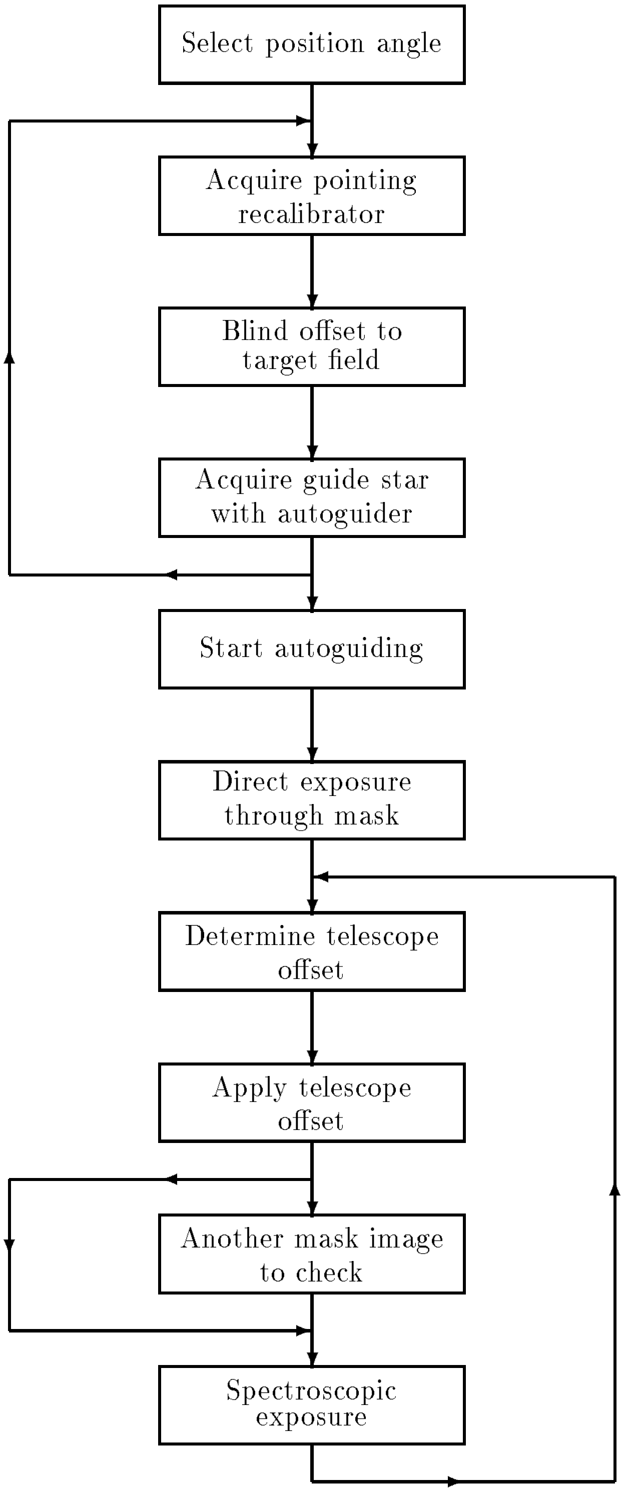

Figure 10: Standard target acquisition procedure

5.3.1 Standard technique

The standard procedure is summarized in Fig. 10.

1. **Select the required position angle**

   The first thing to do is to select the position angle that you require which should obviously be the same as you specified when designing the mask. The Telescope Operator will use the TCS command ROT/SKY to set this up. If the TCS has been setup correctly for LDSS-2, it will put the telescope rotator at the angle which puts the LDSS-2 *slits* at the position angle requested.

2. **Local calibration of the pointing model with a fiducial star**

   The acquisition procedure requires the telescope to point to an accuracy that is a small fraction of the size of the reference star holes in the mask. Since there may be an offset between the coordinate system of the telescope (FK5) and that of the target positions, it is very wise to *locally* refine the pointing model by moving the telescope to a star near (or in) the target field which has astrometry from the same solution as your target objects — the pointing recalibration star defined in Section 2.2. This star should be loaded into the TCS catalogue and acquired using GOCAT, and then moved using the handset onto the acquisition reference position marked on the TV display.

3. **Blind offset to the target field**

   The TCS command **BLIND_OFFSET** *target* will move the telescope to the position of *target* on the assumption that the position of the original star is perfectly known. In other words it locally refines the pointing mode. In all likelihood the telescope will move to *target* with sub-arcsecond accuracy, provided that the local reference star was very close to the target field. Usually this reference star will be one of the reference stars in the target field.

4. **Acquisition of the guide star**

   Now that you are on the target, it is time to find a guide star. The simplest way is to use the GSS software on LPVS3 which will provide a list of suitable stars with the required guide probe positions. Once a star is found, don't start guiding yet but repeat the blind offset sequence (i.e. GOCAT to your positional reference star, centre up and do the BLIND_OFFSET again) to make sure that telescope has not wandered while you were finding the guide star. Start guiding immediately you have done the blind offset, and as soon as you are sure that the autoguider is tracking the star, ask the Telescope Operator to make the telescope use the autoguider output for tracking corrections.

5. **Direct exposure through mask**

   Now take a direct image of the sky through the mask with no grism (a broad band filter is desirable but not essential). The image should show the reference stars in the appropriate holes in the masks, in general offset from the centres of the holes. If no stars can be seen: check the acquisition procedure so far — are you still autoguiding? — is the mask correct? An image of the target field without the mask will verify the field identification if in doubt. Measurements of the positions of the reference stars can be compared with the location of the holes in the masks to check for errors.

6. **Determination of the telescope offset required**

   The image can now be analyzed using LEXT procedure FIND_TWEAK n where n is the number of fiducial holes. This works out how much the telescope should be moved to place the fiducial stars bang in the middle of the fiducial holes. Read the comments as you go along for information about the things that happen. The main stages are:

   - Read in the acquisition image to analyze (if not already read in). Note that the correct read option must be used to get the correct image orientation. READ/1 worked last time, but it will depend upon which CCD on-chip amplifier is being used.
   - Read in the Catalogue file
   - Calculate the geometric centre of the holes. A threshold needs to be defined. Usually the defaults are acceptable.
   - Display the regions surrounding each hole in turn with the calculated centres marked. You will be prompted for the display thresholds. Normally the defaults are acceptable although you may need to define levels sensibly for the first hole.
   - Calculate the centroid of the fiducial stars.
   - Redisplay each hole with the centroid marked. Again the display levels are prompted for but can usually be defaulted.
   - Display the full image area with the vectors joining the hole centres and the star centroids shown (multiplied by a large number).
   - Edit these vectors graphically if desired, following the instructions given. If one vector is discrepant you may wish to remove it otherwise exit from the routine by pressing 4.
   - Output the x shift, y shift and rotation (Δx,Δy,$\Delta\theta$) in units of (arcsec, arcsec, degrees) required to move the stars to the centres of the holes. *Note these numbers down.* (Usually they will be less than 5 arcsec in x and y and $0.5°$ in rotation.)

7. **Application of the telescope offset**

   Give the offsets to the Telescope Operator who should use the TCS command:

   TWEAK Δx Δy $\Delta\theta$

   to move the telescope *while the autoguider is still locked on and the telescope continues to receive guiding signals.* During the set up procedures the Telescope Operator should have used the TCS command INSTRUMENT LDSS to enter the correct orientation for the offsets.

   Important note: At present, the TWEAK has to be broken down into steps of no more than 0.5 arcsec in x and y and $0.1°$ in θ. This is because the autoguider may lose lock if the telescope moves by amounts larger than this. The procedure is to break down the TWEAK into increments of this size and apply each one, waiting a few seconds to allow the autoguider to catch up. It would be wise to watch the autoguider display carefully to try and see if it loses lock. If it does, you could try (a) reducing the increment size and/or (b) selecting a brighter guide star. You should also take care that the guide star is not so near the edge of the autoguider field that it moves outside the area in which the autoguider can track it when the TWEAK is applied.

Example: TWEAK 1.3 0.7 0.4 should be applied as follows:

TWEAK 0.5 0.5 0.1
TWEAK 0.5 0.2 0.1
TWEAK 0.3 0.0 0.1
TWEAK 0.0 0.0 0.1

Doing the TWEAK with the autoguider in *closed-loop* should ensure that no positional errors occurs during the offset. If you need to apply a large TWEAK that cannot be done in closed-loop (for example, because the guide star would move outside the autoguider detector area), you can use TWEAK with the autoguider off (*open-loop*). However you would then need to take another direct exposure after restarting autoguiding to check the position of the targets before doing a smaller closed-loop TWEAK.

8. **Acquisition check**

   In general, this procedure will be sufficient to acquire the target field to an accuracy of around 0.1 arcsec but it must be checked. After performing the TWEAK, take another direct image through the mask. Before analyzing it, it is usually safe to put the grism in and start a spectroscopic exposure while the second direct exposure is analyzed. If there is a residual TWEAK to be done, this can be applied during the spectroscopic exposure (in closed-loop). If there is a large error in position, the exposure can be aborted and the whole procedure repeated. If this happens, you should first try and work out what has gone wrong.

From time to time, during a long sequence of spectroscopic observations on the same field, you may wish to check the acquisition. To do this, simply take a direct image of the sky through the mask and use FIND_TWEAK to check that the stars are still centred in the holes. Any fine adjustments can be made during the spectroscopic exposures.

5.3.2 Further refinements to acquisition

If you doubt your astrometry, or the location of the mask is uncertain, you can use another LEXT procedure REFINE_TWEAK to correlate the target objects found in a direct image of reasonable depth ($>$ 60s depending on the detector) with an image of the mask illuminated with white light or sky. This necessitates taking two extra exposures (a) a white light (or sky) mask image before the first of the direct images of the mask against the sky and (b) an image of the sky with no mask after the initial TWEAK. The residual TWEAK found using REFINE_TWEAK can be applied during the subsequent spectroscopic exposure. Note that you must first have done a positional calibration of the mask using ANALYZE_MASK (Section 4.9) to determine the fine details of the mask mounting before you run REFINE_TWEAK.

5.4 Target acquisition with a longslit

You need to consult this section only if you are using one of the supplied longslit masks (Section 1.2). If you are using a multiaperture mask that contains one (long) slit *which also has fiducial holes custom-made for the target field*, then you should use the multiaperture acquisition procedure in Section 5.3.

The procedure here is as follows:

(a) Follow steps (1)–(4) in the standard multiaperture acquisition sequence (Section 5.3).

(b) Take a direct image through the slit with white light (or sky) illumination (You may have prepared one earlier).

(c) Take a direct image of the sky with no mask.

(d) Use LEXT to work out the position of the target(s) and the position on the longslit where you wish to place the target (for example, using LEXT function CURSOR/GFIT.

(e) Calculate the distance you need to move the *target* to put it on the slit *in arcsec* (Δx,Δy) in the LEXT coordinate frame. For example, if x-positions measured on the Tektronix CCD (in pixels) are 567.4 for the slit and 578.2 for the target, the offset is $\Delta x = (567.4 - 578.2) \times 0.59 = -6.4$ arcsec.

(f) If you also want to adjust the position angle of the slit to place it accurately on two or more targets, you need to calculate the angle offset $\Delta\theta$ in *degrees* which is *positive* if you need to move the line joining the targets *clockwise* to align them with the slit direction. For example, if you want to place the slit on two targets with positions (571.9,606.9) and (570.7,315.6) , $\Delta\theta = -(180/\pi) \times (571.9 - 570.7)/(606.9 - 315.6) = -0.24°$.

    This assumes that the slit is precisely aligned with the columns of the detector. If it is not for any reason, you will need to include this misalignment in the angle calculation. Note that this also assumes that the targets are roughly symmetrically disposed about the centre of the field. If this is not the case, a small lateral displacement might be introduced when the angle is changed. To cure this you would need to solve for Δx and $\Delta\theta$ together rather than independently.

(g) Move the telescope using the command

    TWEAK Δx Δy $\Delta\theta$

    as described in step (7) in the standard multiaperture acquisition sequence (Section 5.3). Note that if you BLIND_OFFSET from a pointing recalibration star (step (2) of the standard multiaperture acquisition sequence) the TWEAK is likely to be small

(h) Repeat steps (c) and (d) to check that the target field is now correct. If not, repeat steps (e) to (g).

Complications may arise if the size of the required telescope offset is large because:

- the effect of optical distortion will need to be accounted for (Section 4.8) in which case it will be necessary *either* to undistort the coordinates of the slit and target (or the images themselves; Section 6.1) *or* to do the offset in two steps so that the last one is a small offset to account empirically for the effects of distortion.
- the telescope offset can only be done in open-loop in which case the offset should be done in two steps: an initial open-loop TWEAK followed by a small closed-loop TWEAK after the position of the target has been redetermined.

Putting these two effects together, it is probably better to do the offset in two steps rather than to attempt to calculate the size of the distortion and do it in one.

5.5 Calibration exposures

To calibrate your data, you will need to carry out the following types of exposure. The reduction of the calibration data is covered in Section 6. Distortion mapping exposures have already been covered in Section 4.8.

5.5.1 Flatfielding

Flatfielding spectroscopic data is not a straightforward procedure and it is recommended that observers experiment to find the optimum method that suits their data best. It should be noted that the optimum method will depend strongly on the nature of the detector, particularly if the CCD is subject to fringing.

It is important to distinguish between the different methods by which the detector is illuminated. For direct images through a filter, each part of the detector is illuminated with the same (limited) range of wavelength, whereas in spectroscopic observations, a particular point on the detector is illuminated by essentially monochromatic radiation whose wavelength depends in a complicated way on the position of the slit and on the grism used.

The point of flatfielding is to remove sensitivity variations in the detector (and/or optics) but these variations are likely to be wavelength dependent. If the detector is a dye-coated CCD or is thinned, there is the additional possibility of fringing effects caused by interference within the thin layer of the dye or depletion region. If such patterning is present, it may also be dependent on the slit width since increasing broadening the slit will increase the range of wavelength seen by a given pixel which may wash out the fringes. For this reason, it is strongly recommended that you take both types of flatfield described below.

(a) Direct flatfields

This is the same procedure as used for normal imaging data. Direct images are taken though the desired filters of a uniform source of illumination from (i) a calibration system which carefully mimics the telescope optical system, (ii) blank fields at dawn or dusk, when the signal level in the sky dominates the contribution from point sources. Experience suggests that the last method is best. If fringing is present, this may not flatfield out because the range of wavelengths present in the flatfield exposure does not match the wavelengths seen in real on-sky exposures, which is usually dominated by a few discrete night-sky emission lines. A possible solution here is to construct a 'true' sky flatfield by median filtering a stack of your on-target observations to remove discrete sources.

The images are processed to produce a flatfield by subtracting the bias level (using the bias strip or a separate bias exposure if it is believed that the bias frame has structure) and dividing through by the mean signal level in the exposure to provide a flatfield with mean signal level of unity.

(b) Dispersed flatfields

Here it is important to simulate the conditions under which the exposure to be flatfielded is taken as closely as possible. A flatfield should be taken for each mask/filter/grism combination with a continuum light source. Ideally this should provide high signal level at all wavelengths of interest but few light sources do this.

It is normal to use the Tungsten lamp (with appropriate neutral density) in the calibration lamp system. It would be a good idea to experiment with the different colour filters provided in the calibration system to try and equalize the illumination level at all wavelengths. Nevertheless, it may be necessary to take two exposures for each combination, one which avoids saturating the CCD anywhere and gives a high signal level at the peak of the illumination (in the red) and another which either overexposes the level where the signal level is highest so as to produce acceptable signal in the faint areas or one in which a filter is used to block regions of the spectrum where the signal is high — the broadband B filter is well suited for this. The resultant exposures may be combined in some suitable way for further processing.

Twilight sky can also be used to obtain flat-field frames. These have the advantage that the light path is identical to that of the actual observations. However, it may be difficult to obtain flat-fields for every mask because the sky rapidly changes in brightness during twilight. This means there are only short periods of time when it is possible to obtain useful twilight flatfields: just after sunset and just before sunrise. Also absorption bands in the atmospheric spectrum make the signal to noise in the flatfields highly dependent on wavelength. Therefore, even if twilight skys are taken, Tungsten flats are also worth obtaining since they will have a more uniform signal to noise.

It should be noted that because of flexure of the instrument during the course of a long exposure, dispersed flatfields should strictly be taken after every long exposure or at least once during the course of the sequence of exposures rather than before the start of observing when the telescope is usually at the zenith. Whether you choose to do this depends on how carefully you want to do the flatfielding.

5.5.2 Wavelength calibration

The relation between wavelength and position on the detector is not linear and it is necessary to determine this relationship through observations of wavelength calibration sources. The presence of optical distortion means that there will be small differences in this relationship between different spectra in the field so it is important to derive this relationship separately for each slit in the mask.

In addition, in common with all spectrographs, the instrument flexes slightly as the telescope tracks across the sky. The main manifestation of this is a slight shift in the position of spectral features during very long exposures. In general, it is good idea to break long exposures into several shorter sections of 1000–2000s to allow cosmic ray events to be removed, and this also allows the gradual shift in the wavelength-position relation to be monitored by taking exposures of wavelength-calibration light sources.

The *worst* shift in the position of a spectral line on the detector that was measured during flexure tests at RGO was found to be 6μm for a change of attitude of 15°. Measurements at the telescope confirm the test results. This amounts to about 0.25 pixel/hour in the *worst* case.

Wavelength calibration is quite difficult because of problems in finding a suitable arc lamp which provides enough unblended lines over the full spectral range of LDSS-2. After much experimentation, it was found that a CuAr lamp was the best even though the lines in the blue are very faint. As for the dispersed flat-fields, it may be worth using a colour filter to attenuate the red lines, or perhaps use a long exposure for the blue lines and a short exposure for the red. In order to aid the observer, an atlas of emission line identifications has been prepared (see Appendix F). Note that some of these lines have wavelengths which have been determined empirically.

5.5.3 Flux calibration

To put extracted data onto a scale of flux density, it is necessary to observe spectrophotometric flux standards. There is a compilation of suitable stars in a folder in the control room. Ideally, the standard should be observed through each slit in a mask since it is possible that the instrument sensitivity might be a function of position within the field. Since this is a time consuming and difficult operation, it is more sensible to use a single observation either through one slit in the mask (although it will then be necessary to calculate an offset for the telescope to put the target on the desired slit) or through a longslit. Two longslit masks are provided (see Section 1.2): one has a normal slit width (1.5 arcsec) as used by default with INTERACT-4 masks; while the other has a much wider slit of 10-20 arcsec designed for spectrophotometric observations where it is necessary to get all the light in the slit.

6 Reducing your data

This section gives a basic description of the LEXT functions that you will need to reduce your data. A more detailed description of LEXT is given in the *LEXT Reference Manual* (Appendix A) and detailed descriptions of individual functions are available in the extensive on-line HELP facility.

6.1 Distortion correction

6.1.1 Effects of distortions

The optical system of LDSS-2 produces small radial distortions amounting to approximately 2% of the radius at the field edge. We may distinguish two types of distortion:

- Non-chromatic distortion which is the amount by which the centroid of an image of a point source deviates from the position predicted in the absence of distortion. Generally the prediction is made by adopting the reduction factor appropriate for the centre of the field (given roughly by the ratio of the telescope to camera focal ratios = 11/2 = 5.5). This amounts to a maximum of 2% of the radius at the field edge.
- Chromatic distortion which is the amount by which the centroid of an image of a point source varies with wavelength. The largest distortion predicted from ray-tracing is 20μm (= 0.5 arcsec) at about 3 arcmin off axis.

For spectroscopic observations, the effect of these distortions can be accounted for by the extraction routines in LEXT.

The *non-chromatic* distortion will manifest itself as an additional non-linearity in the dispersion (in addition to that caused intrinsically by the grism) which will depend on the location of the spectrum in the field. The normal way to reduce LDSS spectroscopic data is to use a wavelength calibration exposure (Section 5.5.2) to determine the non-linear pixel-to-wavelength conversion separately for each spectrum. If the spectra are then resampled correctly, this source of distortion will be exactly accounted for. However, this effect can introduce a small error if an object is positioned far from the centre of the slit in the cross-dispersion (y) direction. In this case there will be a y offset between the object and the centroid of the slit which is where the wavelength calibration was determined. Since the wavelength calibration depends on position, this introduces a small error.

The non-chromatic distortion will also cause the centroid of the spectrum in the cross-dispersion direction to vary with position in the field, in addition to the variation in centroid caused by differential (i.e. wavelength-dependent) atmospheric refraction. This is normally accounted for in the reduction by the extraction software keeping track of the centroid shift as a function of wavelength.

The *chromatic* distortion merely adds additional distortion that is also dependent on the wavelength of the light that falls at that position. It can therefore be accounted for using the standard procedures mentioned above.

For spectroscopic data, it is therefore not necessary to remove the distortion explicitly. Indeed it would be undesirable to attempt this since it would mean resampling the data unnecessarily which always adds noise.

6.1.2 Distortion mapping.

For imaging data, removing the distortion explicitly may be necessary in order to derive coordinates for objects in true tangent-plane coordinates. This is important if you want to derive coordinates for mask manufacture since these must refer to the focal plane of the telescope which, to first order, is undistorted.

The distortion is mapped by taking an image through the matrix mask and then using the LEXT procedure ANALYZE_MATRIX as described in Section 4.8. This procedure calculates a set of spline functions which describe the forward and backward transformations. Here, the forward transform means distorting from the mask (i.e. telescope focal plane) to the detector focal plane, and the backward transform means distorting from the detector focal plane back to the mask. By default the forward transform is stored in a file FTRANS, and the backward transform in a file BTRANS.

To apply the distortion corrections use the LEXT command DISTORT:

DISTORT will apply a *forward* (mask to image) distortion correction.

DISTORT/BACK will apply a *backward* (image to mask) distortion correction.

Since the distortion is wavelength dependent, there will normally be a different pair of transformations for each filter used. To change the file names used by DISTORT, use the commands **SET FTRANS** *ftrans_file* and **SET BTRANS** *btrans_file*.

The distortions can be applied to *lists* or *images*. In the list case the data are treated as coordinates and the distorted coordinates will be output to a new list. In the image case, the whole image is distorted. In most cases, it is faster to derive coordinates from the original image and apply the distortion to the coordinates rather than to derive coordinates from the image after a distortion correction.

It is important to note the distortion correction does not account for the simple scale change between the telescope and detector focal planes. In each case the distortion is done in the same units, so if you are distorting a list of positions in CCD pixel units, the distorted values will also be in pixel units. If you wish to transform between mask and detector units (i.e. to just change the scale) you should use the command TRANSFORM:

TRANSFORM F for mask to image conversions (i.e. mm to pixels)

TRANSFORM B for image to mask conversions (i.e. pixels to mm).

This applies a linear transformation, using LEXT globals XPIX, YPIX, X_CENTRE, Y_CENTRE, FRED and ROTATION.

6.2 Flatfielding

Flat-fielding multi-object spectra is a complex procedure, and LEXT has a special routine MAKEFF which simplifies the process. LEXT has no specific facilities for dealing with undispersed flatfields since they may be conveniently reduced with standard image reduction software.

The dispersed flatfields are prepared by fitting the variation in signal level with wavelength separately for each slit and dividing the fit into the actual signal at each column. This is not a simple procedure since the result is undefined for regions which do not receive any illumination — the interslit gaps. The region of validity of the resultant flatfields must be carefully defined by the extent of the slit and the range of wavelengths over which satisfactory levels of illumination have been obtained in the contributing exposures. The resulting flatfields should be applied only in these defined areas. The preparation of the flatfields is time-consuming using standard software (e.g. Figaro) but the LEXT routine MAKEFF makes it a relatively easy operation.

The input data required is a *dispersed* flatfield obtained with a multiaperture mask illuminated with white light. Care should be taken to ensure that the exposure has high enough counts to make Poisson noise negligible in comparison with the size of the flatfield variations.

MAKEFF generates a flatfield by obtaining for the specified boxes, a smoothed representation of the data in each column and dividing it into the data values for each pixel in that column. The default is for the mean value to be used but the smoothed value can also be obtained from:

- the median over a user-specified filter width (option /MEDIAN)
- a Chebyshev polynomial fit (option /FIT)

The option /PLOT allows the user to observe what is going on. The range of boxes to be processed is specified on the command line, for example **MAKEFF/PLOT/FIT 1-3 8-13**.

6.3 Wavelength calibration

In order to find the relationship between pixel position, in a given spectrum, and wavelength we use one or more dispersed, multiaperture images of standard wavelength calibration lamps. The procedure is to identify strong lines of known wavelength in each spectrum and to use this information to fit a low order polynomial relating pixel position to absolute wavelength. In order to get a reasonably good fit, ten or more lines should be identified, ranging over the whole spectral range.

The facility in LEXT for doing this is ARC. When invoked from the command line, the user enters a sub-package from which a smaller number of ARC specific commands can be issued. The reader is advised to refer to the on-line HELP for full details, but here we consider the main steps.

Before entering ARC either the whole image, or the best box should be displayed on the image display. On entering ARC the first command to try is **HE**, which lists the available commands (the full HELP must be accessed from the LEXT prompt). The command **CP** takes the user through several options which determine the functioning of the algorithms used later, for example, the size of the search box used in centroiding a spectral line. Once these have been set up, the next step is to use the **CU** option to interactively identify several lines in one spectrum.

The cursor positioning is only to get a first approximation, and the software then searches for the centre of the line within the fitting box. For each line a value of the wavelength, usually taken from a table or plot of standard lines, must be input. This information is all stored in a LIST of type LIPOS.

Once several lines have been identified, the **FI** option is then used to perform the wavelength fit to these positions. The user is prompted for the order of the polynomial and the results are stored in a LIST of type COEFS. If this looks acceptable we are now in a position to perform the same procedure for all the spectra in the image. This is done automatically with the **FA** option, which uses the earlier results as a template for searching for lines. Usually this routine will find all the lines identified in the first spectrum, although the user should follow the progress, as shown graphically on the image display, and go back later to any dubious fits.

The wavelength calibration coefficients thus derived, and stored in the COEFS list, are then picked up automatically when using EXTRACT so that the final spectra are wavelength calibrated. Of course, if you are intending to perform extraction in a future LEXT session, then this list should be written to disk before exiting.

6.4 Flux calibration

Observations of spectrophotometric flux standards may be conveniently reduced using various functions in *Figaro* (try the VMS HELP facility command HELP FIGARO TECHNIQUES FLUXING after initializing Figaro). There are no special facilities in LEXT to do this since this is not a specifically multiobject technique. The resulting flux calibration as a function of wavelength can either be read into LEXT and used during extraction to flux the extracted spectra or applied to extracted spectra outside LEXT. Note that in the latter case, it will be necessary to ensure that the correct subset of the fluxing function is applied to the each of the extracted spectra.

6.5 Spectrum extraction

Once the data in the image frame has been preprocessed, and the required subsidiary data are available, the multiple spectra can be extracted and calibrated. The main routine for this purpose is called EXTRACT. This routine has a large number of options allowing most of the sophisticated reduction processing to be preformed with the one command, provided the necessary LISTs are present. The normal requirements would be a BOXES list, a COEFS list and an FSPEC list.

The minimum requirement is the availability of an appropriate BOXES list to define the expected positions of the spectra and objects. This list should have been produced by running PREBOX on the main MASK list for the field. The BOXES list itself can be updated in the light of the actual data using the UPDBOXES command. This allows the user to interactively identify the spectrum and object ranges from a summed spatial profile.

The syntax of the EXTRACT command is to have the box numbers specified on the command line:

LEXT – IMAGE 1 > **EXTRACT 2–5 6–10 15** or, if all spectra should be processed:

LEXT – IMAGE 1 > **EXTRACT ALL**

Prior to running EXTRACT the user must have set up a name for the field with **SET OBJECT** *objectname*. The extracted spectra are then written to 1D FIGARO spectrum files with file names formed by *objectname_boxnumber*. There are many options which can be specified with EXTRACT and full details of all of these are given in the on-line HELP. Here we consider the most pertinent ones.

By default EXTRACT subtracts the sky from behind the object and then makes a gaussian weighted sum of the counts in the object rows. If a COEFS list is present in the LIST stack, which is produced by ARC, then it is picked up automatically and used to resample the data on a linear wavelength scale. If an FSPEC fluxing function is available, and either the /FLUX or /DFLUX options specified, then the output spectrum will also be flux calibrated. The FSPEC list itself must be obtained from an LDSS observation of a standard star, whose spectrum is known from some other source.

The level behind the object is estimated by fitting to the rows of the spectrum which contain just sky. The user will probably want to specify the /INTER option, at least the first time through the data, so as to have some control over this. In fact polynomial fits are used, one to the blocked spatial profile and another to the residuals in each column after normalizing the blocked spatial profile. The idea is that the blocked profile gives good signal to noise for gauging the slit profile and gross features in the background, whilst the extra column fit can account for column to column deviations which might occur, particularly close to bright night sky lines. The user is prompted for the polynomial orders for both of these fits. Obviously if either of these is given as zero, then the fit becomes effectively either pure block fitting or pure column fitting.

The gaussian weighting scheme used in the extraction has been found to give fairly good results, although it can be over-ridden by the /OBJECT qualifier. Alternatively the HORNE routine can be used to provide more sophisticated optimal extraction, although this requires an already sky-subtracted image, such as can be produced by **EXTRACT/ALTER**.

A LEXT manual

LEXT REFERENCE MANUAL

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This DRAFT dated January 15, 1997

This document describes the LEXT software package developed to support the LDSS-2 instrument at the WHT. It provides facilities to design multiaperture masks, acquire the target field and reduce the resultant data.

This version differs from the original AAT LEXT (originated by Richard Hook) in several respects. Most notably, data access is now done using DSA routines, and hence both the FIGARO/DST and NDF/SDF images are now supported data formats. There are new routines to support the LDSS-2 convention for specification of masks, field acquisition procedure and data reduction. In addition there are a large number of minor enhancements, such as the propagation and use of FITS header information, improved arc-line fitting, improved sky-subtraction, more examination and filter options. Finally the LEXT procedure language has been enhanced to allow considerably more powerful procedures.

Contents

B Introduction

LEXT is a software package designed to provide facilities to aid the use of the *Low Dispersion Survey Spectrograph, LDSS-2* instrument at the *William Herschel Telescope.* It was written [1] for use with the LDSS multi-slit spectrograph, at the Anglo Australian Telescope. It is intended primarily as an aid to observations in the areas of mask preparation, target acquisition and fast data reduction. Nonetheless, it provides powerful tools for the extraction of the spectra, and is designed to interface to the Figaro system which offers extensive further facilities. It is implemented to run under VAX/VMS [2] and is partly incorporated into the STARLINK ADAM environment.

Thus, its functions can be considered to be in three categories:

- simple, general purpose, data processing routines. eg. adding two images
- more sophisticated tasks which deal with the extraction and calibration of the multiple spectra from 2D images.
- tools which are rather specific to the LDSS system, such as multislit mask design, and target acquisition.

The detailed working of these commands is the subject of this document. For a more general discussion of the common operations and procedures, and examples of their use, the reader is recommended to refer to the *LDSS-2 Observer Manual.*

Unlike many other software packages, such as FIGARO, LEXT is a monolithic program. External *images* are read into the package and stored in a stack, where they can be operated on *in situ.* There is also a stack for tabulated information, called *lists*, which are used to store and communicate data such as slit positions etc. (see Section D). A large number of internal parameters control aspects of the interface, such as graphics pen colour, and store standard instrumental data, such as the physical size of the detector pixels. Many of the more sophisticated commands rely on the presence of list information defining, for example, the approximate position of the spectra within the image. It is intended largely for interactive use, and provides no special facilities for batch processing.

C Description of the user interface

The prerequisites for running the package are outlined in the *LEXT Installation Manual.* Assuming everything is correctly set up, the package is invoked from DCL by typing:

```
$ LEXT
```

The startup file is executed (see section D.8 for description) and several status messages are written to the screen. The main prompt then appears:

[1] Originally by Richard Hook, with enhancements by several people, notably Mathew Colless and Keith Taylor

[2] A version of LEXT has also been produced which runs on a SPARCstation with only slightly reduced functionality.

```
LEXT - IMAGE 1 >
```

LEXT is command language driven, with a fairly sophisticated interpreter. The LEXT commands themselves, summarised in appendix A, have the familiar DCL format of verb (or command), nouns (or parameters), and adverbs (or qualifiers). The interpreter normally accepts the minimum unambiguous shortening for commands and qualifiers.

If the necessary information is not supplied on the command line then it is prompted for through the parameter system. When prompted the user can either supply the parameter value, or, if a default is offered, press `Return` to accept this . Alternatively the user can type `?` to get a brief help description of the input required, or type `!` or `!!` to exit the routine back to the command line. Some routines, which are likely to be a long time in execution, and which are reporting to the terminal, may be aborted using `Ctrl-C`, which should be trapped and returning you to the command line. This does not apply to, for example, graphical displaying.

The parameters are frequently slots which are the internal data storage objects, as described in section D. Slots are referenced by their number rather than the name of the object they contain. The command prompt includes the number of the slot currently in use and the current *mode*.

Most operations, by default, use the current slot as the source and the first free slot as destination. Some operations are specific to either list or image, whilst others may apply to both (eg. `COPY`).

C.1 LEXT procedures

LEXT has the facility of running commands from *procedure* files similar to DCL command files. These must consist of an ordered sequence of LEXT commands as they would have been entered on the command line, interspersed with control commands, which all begin with a colon.

The procedure file is invoked by typing its name on the command line. In rare cases where there might be confusion of the name of a procedure with one of the LEXT built-in commands, then the user can make it clear to the program that a PROC is desired by prefixing the name with `<`. The default file extension is `.PROC`. If the procedure file is not found in the default directory, then it is searched for in the directory pointed to by `LDSS_PROC`. The individual command lines are optionally echoed to the terminal depending on the state of the internal control parameter `ECHO`. Any necessary information not supplied within the procedure will be prompted for in the normal way.

If the procedure is interrupted, by a bad error status, `Ctrl-C` interrupt trap or answering `NO` to the `OK?` prompt, then it can be resumed by typing `CONTINUE` as a subsequent command. The only restriction on this is that no other *procedure* file should be run in the mean time.

A procedure can be generated using a utility started by the `PROC` command. This takes a file name as an argument, into which the procedure commands are to be saved. On entering this facility the prompt changes and the user types in each line of their procedure. A simpler method is to use a text editor to generate the file via `EDIT` or `$EDIT`.

The available procedure commands are:

- `:LABEL <label>` to label a line

- :GOTO <label> to switch control to a new line determined by the label
- :ONERR <label> causes the procedure to jump to the specified label if an error occurs. It will remain in effect until cancelled with : ONERR with no label specified.
- :LOOP <number> will come back to this point at the next :BACK command. It does this <number> times in total.
- :BACK ends a loop. Within a loop the current value of the loop counter can be used as an input parameter by denoting it $$$
- :QUERY simply prompts for *Yes or No*. If the response is *Y* then it executes the next line, if *N* the next line is skipped.

Procedures can take arguments which are simply used to replace any instances of $<n> in the procedure, where <n> is the number of the argument in the list. For example:

```
LEXT - LIST 7 > MOBY dick
```

will execute procedure MOBY and replace all occurences in that procedure of $1 with dick. Procedures may also be nested.

An example of a procedure is shown in Appendix C.

C.2 Access to the operating system

From the command line there is access to individual DCL commands by issuing them prefixed with a $, or OS. Thus:

```
LEXT - IMAGE mode > $ SHOW TIME
+ Creating DCL subprocess. Please wait...
  1-JAN-1999 12:52:48
```

Since DCL access is provided via a sub-process, DCL commands which are intended to refer to the parent process, such as SET DEFAULT, will *not* work. The subprocess , which is created the first time DCL is invoked, takes a few seconds to start up, but remains running so that subsequent commands are quicker.

C.3 On-line HELP.

There is an extensive HELP facility, based around the Starlink portable help system. This is entered by typing HELP from the command line. There are detailed descriptions of all commands and options, as well as some notes on more general matters, such as standard procedures.

There is also single line help available for some parameters by typing ? at the parameter prompt.

C.4 Ending a LEXT session

To finish a session in an orderly way, any of the standard commands will suffice, namely `END`, `EXIT` or `QUIT`. If any slots are flagged to be saved (see section D.6) then the user is returned to the prompt. To finish fast, without checking for whether slots require saving, type `KILL`.

The use of `Ctrl-Y` will also exit the program, but it is not recommended. Should the program finish by either a `Ctrl-Y` interupt, or due to some other 'dirty' exit, the images constituting the image stack will remain in the directory LDSS_STACK. If required, and assuming they are uncorrupted, these should be copied or renamed appropriately. The old image stack is deleted when LEXT is run again.

D The internal data stack

LEXT recognises two fundamentally different data structures; the *list* and the *image*. Lists are 2D tables of numbers, whilst images are arrays of discrete pixel values.

D.1 Lists

Much of the information required and generated by LEXT is tabular in nature. This may be information about objects, spectral lines, mask parameters etc. The generic name for these tables is the list. Since they can contain different things, lists are distinguished by their *type*. The *type* is held within the list data structure along with a descriptive *label*, the details of the number of columns and entries in the list, and, where appropriate, the column headers.

Some functions which can be performed on lists are *type* specific. In many cases there should be one LIST of a particular *type* corresponding to the particular observation being reduced. In these instances routines which require a particular such LIST will search the stack for it, and will report an error if they don't find precisely one. An attempt to produce more than one list of certain *types* (eg. MASK) will also result in an error for this reason.

LISTs which are created as output by LEXT commands, are usually given their *type*, and also their *label*, automatically.

The complete set of standard list *types* is given in appendix B.

D.2 Images

These contain the multiple spectra, and any further reduced data or calibration frames. One might also have direct images for use with target selection and astrometry.

Images can be `READ` into slots in the LEXT image stack. When an image is read into LEXT, a copy of the disk image is made, and it is this copy which is then worked on. For this reason, many of the LEXT commands work on the data *in situ*. In order to save a modified image it must be written out again with the `WRITE` command.

Within the image structure, along with the data-array itself, is a descriptive *label* and a *type*.

Label is a description of the contents, purely for user information. The *type* is used by LEXT in certain instances which will be described in the appropriate sections below.

D.3 Creating lists and images internally

LEXT can generate a list or image slot internally using the `CREATE` command. The slot is simply filled with a user supplied constant value. The `CREATE` command also has options which allow the creation of particular forms of list, which are used in conjunction with distortion mapping and fitting routines:

- `/KNOTS` for use with `SFIT`
- `/GRID` which creates a simple list of grid coordinates, of *type* MLIST, for use with distortion mapping
- `/FIBOX` which creates a list of boxes (of user specified size) around each object position in the current list, for use with `FIT`. This option could be used, for example, to find more precise centroids for the objects in an image.
- `/MASK` is used to generate a FIBOX list such that the boxes are defined to encompass the images of the slits in a direct image. A MASK list must be present.
- `/BOXES` uses a list which has been created with `CURSOR` to generate a BOXES list in instances where no MASK list is available.

D.4 Mode of operation

LEXT works in two modes corresponding to the stack which it is currently using. The user toggles between modes by use of the `IMAGE` and `LIST` commands.

Many of the generalised functions can be performed on list or image data. The interpretation of the commands depends on the current mode of operation.

D.5 Manipulating the data stack

Internally LEXT holds images and lists in its own in a stack system. There is a separate stack for lists and images. Each stack position is referred to as a slot. The dimensions of the slots and stacks are defined in a startup file (ie. the maximum size of both images and lists and the number of image and list slots). If this is not present in the default directory then the required values are prompted for.

The following commands allow stack examination and manipulation:

- `DIRECTORY` provides information on all the slots of the current mode.
- `EMPTY` is used to clear a slot. By default this command works on the current slot, although a slot number or `/ALL` may be given as a parameter. This command works irrespective of the state (protection) of the slot, and the data is lost. (In fact images erroneously deleted may be recovered as they should still reside in the LDSS_STACK directory).

- `COPY` copies a whole slot to another slot location. Only the *label* is changed to one which reflects the fact that it is a duplicate. The destination slot must not be protected. In list mode an additional qualifier `/COLUMNS` allows extra columns to be appended to the output.
- `BACK` steps the slot pointer back one position (with wrap-around).
- `NEXT` steps the slot pointer forwards one position (with wrap-around).
- `USE` allows specification of current slot number. Alternatively just typing the number of the required slot on the command line is acceptable shorthand. `USE/TYPE` allows the specification of the slot *type* desired. Obviously this option will only work if there is just one slot of that type in the stack.

D.6 Slot status

When the stack pointer is moved to a new slot its status, that is to say its number, *type*, *label*, and, in the case of an image, the filename, is displayed. The *label* is a full description of the contents of the slot, for the benefit of the user.

The command `RELABEL` is used to change the *label* on a list or image. Sensible *labels* are generated automatically when a list or image is created by a LEXT command. `RETYPE` peforms a similar task to change the *type*, although, since these may have semantic meanings to some routines, this command should be used with care.

D.7 Slot protection

Each slot also has a state which offers three levels of protection: `occupied`, `protected` and `save`. The corresponding commands to set this protection are:

- `PROTECT` makes the slot 'write' protected, so that the contents can't be modified, but may still be deleted.
- `FREE` removes the protection from a slot, to leave it 'occupied'. Any operation which is going to alter the contents of a slot requires the slot to be unprotected.
- `SAVE` flags a slot to be saved on exit from the program. In fact, this is not an automatic procedure: the user simply returned to the main prompt and is informed which slots are flagged to be saved.

In each case the `/ALL` qualifier can be used in list mode to apply to all the *slot*s in the *stack* rather than just the current.

D.8 Startup file

When LEXT is started it looks for a file called LEXT.STARTUP. This file should contain the dimensions of the stacks and slots and the optionally the command `INIT`, which actually makes the memory available for the list data block. `INIT` is only required if the startup procedure contains further LEXT commands, say, to automatically read in the list data files. If LEXT.STARTUP is not present then defaults are used where applicable and the remaining values are prompted for.

The dimensions of the image slots and are `SET` via the following internal variables:

- `Nx` defines the number of image pixels in the X-direction.
- `Ny` defines the number of image pixels in the Y-direction.

Further LEXT or DCL commands can be issued from the startup file allowing the user to customise the session, and read in commonly required data. In the case of lists use, the command `INIT` must first be used to tell LEXT to create the necessary internal data storage.

E Internal parameters and header information

LEXT stores a variety of internal parameters. Some of these hold information about the instrumental/detector setup, whilst others control interface options, such as the current pen colour. Many of the LEXT commands make use of this information so it is important that it is set correctly. Some of the internal parameters may correspond to information contained in the FITS headers of the images. The user can ensure consistency by using the `SHOW` and `SET` commands which are detailed below.

Certain of these parameters are set by a specific command, such as the graphics device name, whilst others go through the `SET` command. The current mode can be set by either; thus:

```
LEXT - LIST 1 > IMAGE
```

is the same as writing:

```
LEXT - LIST 1 > SET MODE IMAGE
```

E.1 Examining and saving parameter settings

The `SHOW` command provides details of the current values of some internal parameters, and is dependent on the current *mode*. Several qualifiers enable access to more information:

- `SHOW/INST` displays the settings of the instrumental parameters listed below.
- `SHOW/TELESCOPE` details the telescope parameters.
- `SHOW/MASK` gives details of various mask parameters.
- `SHOW/PLOTTER` gives the plotter settings.
- `SHOW/HEADER` produces a formatted list of the FITS header items which are available for the current image. It may often be useful to use these to set the corresponding internal parameters.

- SHOW/ALL shows all the LEXT internal parameters.

Some internal variables can be saved for future use by the SAVESET command. By default these use a file called LEXT.SET. This file is written as a standard LEXT procedure file, and, hence, can be easily invoked to re-set the values of the internal variables. Being an ASCII file, it can also be easily edited outside LEXT. For standard setups it would be sensible to give a more specific name to this file.

The SET command can be used to set the value of internal parameters. Care should be taken to use the correct units when setting internal parameters.

E.2 Interface options

The various interface options are each described in detail in their appropriate sections. They are:

- MODE: *list* or *image*.
- PEN: The colour on image displays, but has no meaning for hardcopies.
- XST: X-coordinate of start region of interest.
- YST: Y-coordinate of start of region of interest.
- XEND: X-coordinate of end of region of interest.
- YEND: Y-coordinate of end of region of interest.
- ECHO: Decides if commands run within a procedure are displayed on the screen to the user.
- MARKER: The specification of symbols for hardcopy plots. These are defined in the PGPLOT manual, and are specified by a number in the range 0 to 127. The numbers after 31 are just the corresponding ASCII characters.

All of these can be changed with the SET command, although one further interface option, the graphics device, can only be set with the specific DEVICE command.

E.3 Instrumental parameters

Certain fixed parameters which specify details of the instrumental setup are held internally by LEXT so that they can be accessed automatically by any routine.

These are:

- CAMFIELD: the field of the camera in (mm)
- COLFIELD: the field of the collimator in (arcmin)
- DETECTOR: the detector ID (for information only)

- DISPERSION: the dispersion at the detector (Å/mm)
- FRED: the focal reduction factor between the focal (mask) plane and the detector
- FTRANS and BTRANS: the files (.DST or .SDF) used for forward and backward distortion correction — set to `NONE` if not specified
- LAMBLAZE: the blaze (strictly the undeviated) wavelength (Å)
- LAMMAX: wavelength corresponding to the red extreme of the spectrum (Å).
- LAMMIN: wavelength corresponding to the blue extreme of the spectrum (Å)
- LAMZERO: the x position of the zero-order images, expressed as a wavelength of the first order spectrum (Å)
- MISVAL: the magic value used to designate an invalid pixel
- OBJECT: the name of the current field. This is used to generate the names given to the files containing the extracted spectra.
- OBJECTEXTENT: the typical extent of an object on the sky (arcsec).
- ROTATION: the rotation between the mask and detector coordinate systems (degrees measured *clockwise* on the detector)
- TILT: the value of the inclination of the spectra within the boxes (degrees measured *clockwise*). This variable is used when plotting BOXES and in the weighting scheme used by `SQUASH`, but is currently ignored in the extraction routines, which have other ways of dealing with small tilts. NB: TILT does not mean a tilt of the whole spectra relative to the detector, but only a tilt of the locus of the object.
- XCENTRE and YCENTRE: the (x,y) coordinate on the detector which corresponds to the origin of the mask coordinate system (pixel)
- XPIX and YPIX: the size of the detector pixels (μm)
- XSLIT and YSLIT: the default length of the slit in x and y (μm)
- X_FORMAT and Y_FORMAT: the size of the detector (pixels)

These can also be assigned values with the `SET` command, although some can also be redefined as a result of certain LEXT operations such as LFIT.

E.4 Mask parameters

These consist of some of the defaults used in mask design, and also the field scale at the mask focal plane.

- SCALE: the image scale at the focal plane of the telescope, ie. at the mask (arcsec/mm) (The scale at the detector is given by SCALE $\times$ FRED)
- MAXSLITLEN: the maximum allowed length of mask slit on the sky (arcsec)

- MINYMARGIN: the minimum allowed distance between the object and the ends of the slit (arcsec)
- MINYSEP: the minimum allowed separation between two slits (arcsec)
- FIDUCDIAM: default diameter of fiducial holes (arcsec)

E.5 Plotter parameters

The following are classified as plotter specific items, used in generating art-work for LDSS-1 masks at the AAT:

- PENWIDTH: the line thickness for hard-copy plots
- PSCALE: scaling factor for hardcopy plots
- ROH_SEP: the separation between holes in a row-of-holes mask in the Y-direction (arcsec)
- ROH_SIZ: the length of a row-of-holes in the Y-direction (arcsec)
- SLITWIDTH: slit width (arcsec)

E.6 Telescope parameters

The following are classified as telescope specific information:

- GP_X0: X-coordinate for the guide-probe origin (AAT specific).
- GP_Y0: Y-coordinate for the guide-probe origin (ATT specific).
- DRZ: differential atmospheric refraction at the zenith such that

  $$\mathrm{apparentscale} = \mathrm{actualscale} \times (1 + \mathrm{DRZ})$$

  .
- LATOBS: the latitude of the observatory.
- SCALE0: the linear scaling factor from the sky to the mask (radians/mm) – similar to Scale
- SCALE1: the non-linear term for more precise scaling – should be zero at WHT.
- SCALE2: the power term for the scaling – should be zero at WHT

The command `SET FIELD` prompts the user to enter a description of the field-centre coordinates, RA, DEC, EQUINOX, EPOCH and POSITION_ANGLE.

F Data import and export

As described in section D, LEXT has two 'internal' data structures, the *list* and the *image*, although both may be further distinguished by their *type*. Data can be read into, and written from, these internal *slot*s in a variety of ways.

The I/O is principally performed with the commands `READ` and `WRITE`. The same commands are used for both lists and images. When a new file is read, it is stored in the first available slot and its state is automatically set to 'protected'. Further modification of the data will require it to be `FREE`d.

In IMAGE mode data access is performed via the Figaro DSA/DTA routines. Thus it is possible to read and write both FIGARO DST/HDS files or STARLINK NDF(SDF) files. The default is determined by the DCL logical name FIGARO_FORMATS which should be setup with DEFINE/JOB. For example, this should be set to "NDF,DST", if NDF's were the default, but specific DST's might need to be read.

It is important that images are read in in such a way as to leave the red end of the spectrum at the right, and with north up. All possible transformations can be accomodated by use of the qualifiers `/1` up to `/8`. At the time of writing the WHT Tektronix chip required `/3`, which represents a rotation of 180°.

In list mode the default external representation is as a Figaro DTA/HDS file. These files can be examined outside LEXT, with FIGARO EXAM or STARLINK TRACE. These files are unique to LEXT and are not appropriate for input into any other packages.

Any list may also be written or read as an ASCII file by specifying the `/FORMATTED` qualifier. The number of columns in the file must be specified in advance using `SET NCOLUMNS`. A special option to allow the list to be entered directly at the keyboard, use `READ/FORMATTED HAND`.

Extracted spectra may be written into a FIGARO 'SPEC' file by specifying `/SPEC`. These can then be used as input into FIGARO routines which operate on 1D spectra.

The command `FPRINT` creates a formatted list of object information from the POS and MASK lists. Specifically the positions and dimensions of the slits on the mask, and the positions and magnitudes of the objects on the sky. The MASK list, which may be a subset of the POS list, is used as an index and each object is looked up in turn.

The `/CAT` qualifier, required to read and write the special object list files is described in more detail below. `/MANUFACTURE` is used to output the WHT style of MASK design instructions into an ASCII disk file.

A new list or image may be created and initialised with the command `CREATE`. If no qualifiers are present the new structure will contain only an array of constants, and will have *type* TEMP.

F.1 Object catalogues

Catalogue files are the preferred medium for reading and writing high-precision mask coordinates by LEXT. They are read into LEXT with the `READ/CAT` command and written with `WRITE/CAT`. They are text files written in a free format using common astronomical conventions and are thus easily generated from coordinate lists. Their default file type is `.CAT`, and they must have a maximum record length of 132 characters. A catalogue written with `WRITE/CAT` can later be read back into LEXT with `READ/CAT`. Internally the information from a catalogue is stored as a MASK list.

The lines in the file are either interpreted as containing keyword values, object coordinates or a comment. Keywords are valid for the whole file. Coordinate and keyword lines can be mixed in any manner throughout the file. However, for the sake of readability, it is best to segregate the keyword lines to either the top or bottom of the file. Keyword and coordinate lines are distinguished by whether non-numeric characters are present. Coordinate lines must only contain numerals, wild card character `*`, and optional comments at the end. If anything other than the characters `0123456789+-.ED*!` are present, the line is interpreted as being a keyword line. Characters to the right of an exclamation mark `!` are interpreted as a comment and are ignored. Lines that `READ/CAT` can not interpret are also ignored.

F.1.1 Coordinate entries

The format for a coordinate line is

<ID> <RA> <Dec> [Wt] [SL] [Offset] [X] [Y]

The fields are:

<ID> Identification number of object.

<RA> Right Ascension of object. RA is in hours of time, and should be a sexagesimal string, that is standard hours minutes seconds (HH MM SS.SSS) format, although formats such as HH MM.MMMMM, or even HH.HHHH are also accepted.

<Dec> Declination of object. This is in degrees and should also be in sexagesimal format ($\pm$ DD MM SS.SS), although formats such as $\pm$ DD MM.MMMMM, or $\pm$ DD.DDDDDD are also acceptable. The sign of the declination ($\pm$) is optional for northern objects but mandatory for southern objects.

[Wt] Weight for growing slits. Larger weights mean slits grow faster. Wt = 0.0 is reserved for fiducial stars used for aligning the mask. A centred hole is placed at the mask position of such objects, while slits are used for other (WT > 0) objects. Negative weights should not be used, except for WT = MISVAL = -32767, which marks a "deleted" object.

[Sl] The slit length (or fiducial hole diameter). The default units are arcsecs, although this can be changed with the MMUNit keyword.

[Offset] The y coordinate difference between the slit centre and object position: $[Offset] = Y_{\rm cen} - Y_{\rm obj}$. The slits are drawn parallel to the y axis, and therefore they have the same x coordinate as the object. The default units are arcseconds, although this can be changed with the MMUNit keyword.

[X] The x coordinate of the object on the mask in mm.

[Y] The y coordinate of the object on the mask in mm.

The fields in angle brackets (<>) are required, while those in square brackets ([ ]) are optional. Fields are delimited by one or more spaces. Defaults are assumed for blank fields, and were denoted by a word starting with `*`. `X` and `Y` are written with a `WRITE/CAT` but are ignored by `READ/CAT` which recalculates them from the positions and field centre parameters.

F.1.2 Keyword entries

The keyword lines are of the format

<keyword> <value>

and the currently recognized keywords are

LABEL * Acts as a label for the field.

CENtre * The Right Ascension and declination of the field centre in sexgesimal format (as above). The coordinates must be in the same equinox as the coordinate list.

EQuinox * The equinox of the coordinate system used, in years. This MUST NOT be prefixed by B or J (eg neither B1950 nor J2000 is understood; use 1950 and 2000 instead).

EPoch * The epoch of observation, in years eg 1990.85.

PA The APPARENT PLACE position angle of the mask in degrees measured from north towards the east. This is equal to the positional angle of a slit at the field centre. However, since all slits are parallel to the Y axis and sky coordinates are non-cartesian, there will be some rotation of position angles away from the field centre. Default = 0.0 (ie North-South slits).

SLObj The slit length for objects with a blank slit length field. Default is set by the LEXT global "MINSLITLEN" in arcsecs.

SLFid The diameter of fiducial star holes which have a blank slit length field. Default is set by the LEXT global "FIDUCDIAM" in arcsecs.

WDEF The slit growing weight for objects with a blank weight field. Default is 1.0

OFFDefault The offset of the slit centre from the object position along the Y axis, for objects with a blank offset field. Default is 0.0

MMUNit The scale in mm/units at the focal plane for slit lengths, and offsets used in this file. This includes the values for SLO, SLF, and OFFD. MMUN defaults to the mm/arcsec scale of the telescope (ie 1/6.7 for the f/8 focus of the AAT).

Only the capitalized letters are required for the keywords (although they do not have to be capitalized in the file). Extra letters beyond those capitalized above are not considered, so that "SLOPE", and "EQUATE" will be interpreted as the "SLObj", and "EQuinox" keywords respectively. Keyword lines marked with a * are required. If they are not in the file values are prompted for when the file is read by READ/CAT.

G Mask manufacturing tools

There are facilities within LEXT to help prepare the parameters for mask manufacture. These are described here, but for a discussion of their use in practice, see the *LDSS-2 Observer Manual.*

- `PREBOX`: this routine is used to transform a MASK list, which contains the specification of the mask, ie. the slits and fiducial holes, in units of mm at the mask, into a BOXES list which contains the details of where the spectra are expected to lie on the detector. This routine makes use of the internal variables which define the linear mapping from mask coordinates to detector coordinates. Also, if available, it automatically applies the field distortion, which is stored in either image or list form. In order to calculate the extent of the boxes it uses the internal variables LAMMIN, LAMMAX and LAMBLAZE.

- `PREDIRECT`: this routine works similarly to `PREBOX` except that it predicts the results of a direct (undispersed) image, storing the results in a DRCT list.

- `GROW`: updates the BOXES list and, if available, the MASK list, by expanding the slit lengths in the y direction, up to the point where they begin to overlap. The rate of growth of each slit depends on the weighting given to the object.

  This helps make maximum use of the detector area (which is, in fact, reported as a figure of merit). Several internal parameters, such as MAXSLITLEN, MINYSEP etc., define the limits of this procedure.

  Zero-orders are also monitored and are not allowed to overlap with other objects, but are accepted if they impinge only on a sky spectrum. The position of an object within a spectrum is defined by the position of its centre and the internal variable OBJECTEXTENT.

  If the `/CHECK` qualifier is specified then the MASK and BOXES lists are simply checked for possible overlaps, and the results reported. The lists are not modified.

- Several `PLOT` options are useful for mask design. For example, `/BOXES`, `/MASK`, `/FIELD` and `/FIDUCIAL` and `/DIRECT`. These are dealt with in detail in section K.3, which describes the `PLOT` command.

- `CURSOR/EDIT`: when applied to list slots of *type* BOXES or DRCT this can be used to interactively modify the heights (ie. slit lengths) and object positions of a given entry, or to delete an entry completely. If there is a MASK list available then this will be updated simultaneously.

  The default is for this routine to delete the box in which the cursor is when depressed. However, for very crowded fields this may get complicated and the `/CORNER` option means that the bottom left hand corner is used instead.

H Target acquisition tools

Precise target acquisition is particularly crucial process for a multi-slit spectrographs. This is because of the need to align the mask, within three degrees of freedom, so that each object is positioned at the centre of its intended slit.

There will be several standard procedures to aid in this process. Here will simply outline the specialised commands which may be used:

- `CREATE/MASK`: if there is a MASK list in the stack it is used to generate a new FIBOX list which consists of boxes defined so as to surround each slit in the mask. This is useful for finding the centroids of slits in a direct image of the mask. This may be used in conjunction with `FIT/LINE`.
- `FIDUCIAL`: takes the output FIBOX list from `CREATE/FIDUCIAL` and locates the centres of the fiducial holes.
- `FIT/FIDUCIAL`: then locates the stellar centroids within the windows found by `FIDUCIAL`.

I Mapping focal plane to detector coordinates

There are two stages to the mapping between the mask focal plane coordiante system and the detector coordinates. The first is the linear mapping of pixels at the detector to mm at the mask, and the second is to account for the small optical distortion introduced into the detector coordinates by the LDSS-2 optics.

Although generally small, field distortion is can be used for use with `PREBOX` and with mask manufacture from direct images. It is not used in the extraction routines which have algorithms for following distortions empirically.

The important routines are:

- `LFIT` fits an optimised 5 parameter linear transform to a pair of list slots (ie. stretch, translation and rotation). The main function of this routine is to define the first order mapping from mask coordinates (in mm) to detector coordinates (in pixels). The coefficients are displayed.

  If the `/STORE` qualifier is present then it is assumed that the fit defines the mapping of the mask coordinates onto the detector and resets the values of the relevant internal parameters accordingly. This allows the subsequent use of the `TRANSFORM` command.
- `SFIT` fits a bicubic spline to a pair of list slots. It thus maps the distortion between the two sets of points as a function of position. It uses a KNOTS list to define the fiducial points for which the spline parameters are calculated and stored.

  This routine can be used to define the distortion of a matrix mask image (which has been analysed by, say, `MAP`), compared to the expected image (see below). The fit is currently stored in an external transformation file. It can be subsequently used by the routine `DISTORT`.
- `CREATE/GRID` produces a list, according to user defined criteria of grid points such as would define a matrix mask.
- `TRANSFORM` transforms the list coordinates between the mask (mm) and detector (pixels) systems and vice-versa. It produces a general, linear transformation including rotation, translation etc.

  The transformation is defined by the internal variables ROTATION, XPIX, YPIX, FRED, XCENTRE and YCENTRE.

- `EVALUATE` converts a transformation, as generated by SFIT, file into a 2D representation. Specifically the x and y shifts are stored in separate images which are given the *type* XSHFT and YSHFT.

  If these are available then they will be used by DISTORT in preference to the raw spline coefficients, since it saves on CPU time.

- `DISTORT` applies a spline transformation, such as generated in SFIT, to a list or image. By default a fractional pixel interpolation scheme is employed, although this can be over-ridden by other qualifiers.

J Data processing

J.1 Simple Image processing

A range of useful image processing commands is available within LEXT. Namely:

- `ADDI`, `SUBI`, `MULI`, `DIVI` for the combination of two images via the pixel by pixel application of the specified binary operator. The result is stored in the next free slot.
- `ADDC`, `MULC` for the addition of, or multiplication by, a constant. The result overwrites the original.
- `SMOOTH` applies 2D tophat (default), gaussian (`/GAUSSIAN`) or median (`/MEDIAN`) smoothing to an image. The size and specification of the filter is prompted for. This routine operates on the current region unless over-ridden with the `/ALL` option.

These might be used for basic calibration such as debiasing and flat-fielding of the data.

J.2 Simple List processing.

As with image processing there is a range of commands which allow simple operations to be performed on the contents of lists. With lists commands act on either the whole list or just a specified column, as appropriate.

In fact several of the commands are identical to those for images and the context in which they operate depends on the current mode, namely *list* or *image*. For example, if `ADDC` is used when in list mode, it will add a constant to a specified column within the current list. This includes the `SMOOTH` command which, in list mode, convolves the y column with either a tophat or gaussian filter.

Other commands available are:

- `CADD` adds the contents of one column, element by element, to another column.
- `SWAP` swaps two columns of a list slot.
- `APPEND` appends the data in one list slot to the end of another. This should be used with caution as LEXT does not check whether the list *types* are compatible.

- `CCOPY` copies a list column to another column in the same list, or, by using the `/DIFFERENT` qualifier, to another list slot.

- `EDIT` allows the user to edit the contents of a list directly through the STEVE editor. The new list thus created is put into a free slot and the user is asked to supply an appropriate *type* and *label*.

- `POLY` fits a simple (order 0 to 9) polynomial to a list slot using the current x and y columns. Unless the `/NONEW` qualifier is used, the coefficients are written to a list slot.

- `MATCH` attempts to match the positions of elements in two different lists. The second list is rearranged to be in the same order as the first, according to a nearest neighbour criterion.

J.3 Examination and manipulation of data

- The contents of a slot can be written out by use of the `TYPE` command. In *image* mode, this types out a 5 by 19 subset at the requested coordinate position. The default is to centre the region on the coordinates given by X_CENTRE and Y_CENTRE, but the options `/CURSOR` and `/HAND` are also available.

  In list mode, 5 headed columns are printed with the range of lines being optional arguments. In this case there is also an optional qualifier `SPECIFY` which accepts three other arguments which is interpreted as the start and end rows, and the first column from which the output is to begin.

  The `/PRINT` option formats a temporary printronix file of this information, and submits it to the print queue.

- `REPLACE` allows the user to data values of either type, to user specified numbers. Various qualifiers can be used such as `/ENTRY`, `/ROW` etc.

- `STATS` obtains statistics for list column or image data. (ie. mean, min, max, standard-deviation etc.)

- `INVALIDATE` sets parts of a list or image to be flagged invalid. There are many options, such as use of cursor (`/CURSOR`) and cutting out zero-order spectra (`/ZERO`).

- `CLEAN` removes the missing values from a list, or replaces them with user supplied values for an image. In the list case the column which is to be searched for invalids is prompted for.

J.4 More sophisticated image processing

The following are several sophisticated image mode commands for processes such as distortion mapping, bad data etc.:

- `FIT` looks at rectangular regions within an image to find the positions of peaks. It works by finding a simple centroid, or, by use of `/GAUSSIAN`, by fitting a 2D gaussian, with some attempt at background subtraction. The `/LINE` qualifier invokes a centroiding routine appropriate for a linear image such as an arc-line or the direct image of a slit. The output is stored in a CLIST. The regions themselves may be defined in a FIBOX list.

If the `/MASK` qualifier is specified then the FIBOX list is created from the positions defined in a MASK list, along with user defined extensions to the slit size, to be taken as the regions. This tool might be used to find the actual positions of the mask slits on a direct image, by looking in a region around where they are expected.

- `MAP` searches a region of an image for peaks which are the stored in a list slot. A peak is defined as a local maximum, which is above a given threshold, and with all of its immediate neighbours also above the threshold.

  In some cases it might be useful to smooth the image first to minimise noise spikes. For example, `MAP` could be applied to a matrix image and used in distortion mapping.

- `RIDGE` maps the positions of ridge-like peaks in the current image. The user defines the direction of the ridges in the spectra (ie. vertical or horizontal centroiding), a threshold and a box width for centroiding.

- `SUBSET` takes a subset of the current image, by default the current region, and interpolates it to fill the next image slot.

- `SQUASH` creates a profile of a specified BOX by squashing the data in one direction. By default `SQUASH` uses a specified box, and adds up the pixels in the y direction, producing an XPROF list. Further options are `/X`, which produces a YPROF list, and `/WEIGHT` which weights the summation according to the position of the object within the box.

- `CUT` is similar to `SQUASH` but works on the current region.

K Graphical output

Graphical representations of LEXT data can be output to any GKS device. The device is selected with the command

`LEXT - IMAGE 3 > DEVICE` *devicename*

The `/FORMAT` qualifier allows the user to set options for the pen colour, font type and number of plots per page. If devicename is `NONE` then any currently opened device is closed. If the device is required to be cleared use the command `ERASE`.

A device may be closed by using the `CLOSE` command or by typing `DEVICE NONE`. This is required for hardcopy devices before the output can be sent to a printer. It is not necessary to close a device before opening a new one.

The first output on any device draws up axes and a title, according to the current region. Subsequent changes to the region will not effect graphical output until the device is erased, either explicitly with the `ERASE` command or by a new `DISPLAY`. The device will not be erased by a `PLOT`.

K.1 Image display devices

Several options in LEXT make use of an interactive cursor. Due to the number of options available during some of these sessions, it may be better to use the device `IKON_VT`, which responds directly to keyboard buttons, in preference to IKON. (The latter requires the cursor button is depressed, then a keyboard character is typed to decide on the subsequent action to be followed.)

If the image is to be displayed on a X-windows VAXstation, then DEVICE XWINDOWS also allows direct use of the keyboard. Subsequent X-windows are called XWINDOWS2 etc.

K.2 Displaying images

The DISPLAY command is used for images. This has several parameters and options. The user is required to give black and white levels for dynamic scaling. By default the image is scaled spatially so that both x and y fill the screen. This can be over-ridden by use of the /1TO1 option.

The routine calculates sensible default values for the black and white levels. Since this takes some time, the option /FAST can be useful where the black and white levels are known in advance.

The look-up table used in the display can be altered with LUT, which offers a choice of several predetermined LUTs as well as user input. Information about these is supplied with:

```
LEXT - IMAGE 2 > LUT HELP
```

Note that on a hard-copy device, black and white are interchanged.

K.3 Plotting List information

Lists can also be displayed using the command PLOT. PLOT has a large number of options, some corresponding to possible list *types*. Usually in any given list the first two columns are taken as the cartesian coordinates. This can be altered with the SET XCOLUMN and SET YCOLUMN commands.

The available plot types are:

- /1TO1 for true aspect ratio.
- /BOXES A BOXES list has four coordinate pairs associated with each element, defining the vertices of the rectangle, the object position on the slit etc. Thus a PLOT/BOXES will draw up those regions on the device. Additionally /CYCLE will draw subsequent ones in different colour pens.
- /JOIN draws arrows between corresponding pairs of (x,y) positions from two list slots. The user can further specify an expansion factor, by which the length of the arrow is increased, whilst the origin and direction remain the same. This option is useful to visualise the effects of transformations on an image.
- /CIRCLE draws a circle of user defined centre and radius on an existing plot.
- /ELLIPSE similarly draws an ellipse of user defined centre and dimensions on an existing plot.

- `/KNOTS` uses a KNOTS list to draw horizontal and vertical lines representing the spline fitting knots.
- `/LINE` draws in line segments to connect successive points in a list.
- `/MASK` plots a representation of a mask using information in the MASK list. Any coordinate of zero-weight will be be plotted as for a fiducial hole.
- `/NUMBERS` prints the numbers contained in a specified column of the current list, at the cartesian positions defined for each list entry.
- `/SPECTRUM` draws a spectrum list.
- `/FIBOX` for a FIBOX list.
- `/FIELD` draws a rectangle, taking user defined limits.
- `/FIDUCIAL` draws four crosses at the cardinal points a user specified distance from the origin.
- `/ROH` draws a representation of a row-of-holes mask. This qualifier is only for use with `/MASK`.
- `/DIRECT` for plotting of a DRCT list, in the form of an outline of the slits (and fiducial holes) and also the zero-order position.
- `/LIMIT` shows the limits of the field of view, as determined by CAMFIELD and COLFIELD.
- `/TEXT` plots up text at a user defined position

PLOT does not clear the device and so is drawn on top of any existing image or previous PLOT. For interactive displays the line colour can be changed with the command `SET PEN`. For hard copies plots can be made on subsequent pages by ADVANCEing the plotting window. If `ADVANCE` is used on an interactive display the device is simply cleared. (NB: the hardcopy file thus created must be sent to the appropriate physical device by issuing a DCL command.)

K.4 Defining a region of interest

LEXT allows the user to define a current region of interest by use of the `REGION` command. Subsequently all graphics and many other operations will only apply to this region. Note that once a plot is displayed of a given region, then the envelope will apply so long as the display is not erased.

REGIONs can be selected in a variety of ways, the default uses the graphics cursor. Another useful way of specifying the REGION is with the `/AUTO` qualifier: in list mode, this selects the end points according to the extremal values in the current list, whilst in image mode the full size of the image is taken. Alternatively `/FULL` provides the full image size, whichever mode is selected. `REGION/BOX` allows the specification of a particular spectrum, `REGION/SMALL` reduces the size a little, and there are several similar options listed in HELP.

K.5 Interactive examination of data

The user can interact with a displayed image or plot by use of either:

- `CURSOR` is used for both images and lists. The values of data points can be read and stored in a CLIST list slot. The actual position recorded by the cursor can optionally be modified using one of two centroiding algorithms `/FIT` finds a local centre of mass and `/GFIT` fits a 2D gaussian. This could be used in identifying targets, which would then have to be `TRANSFORM`ed into a MASK list.

  If a PLOT is being examined there is the option to edit the corresponding list by means of the `/EDIT` qualifier. This is particularly useful for BOXES and MASK lists, which can be modified to change the size and position of the boxes in addition to deleting entries altogether. Both lists are required so that the information in each remains correlated. Care should also be taken with this routine as it works on proximity to bottom, left-hand corner of the box rather than simply seeing which box the cursor is currently in.

  The particular options, corresponding to the keyboard numeric buttons, are displayed on the terminal.

  The option `CURSOR/FC` allows the field centre to be respecified.

- `BROWSE` can also be used to examine either DISPLAYed images or PLOTed lists.

  In image mode the each cursor read results in the position and value of the pixel to be output. Also, if a BOXES list is available then the box number which the pixel occupies is also output, whilst, if COEFS are present, the wavelength corresponding to the position is reported.

  In list mode the cursor read causes the list to be examined and the number of the closest list element to be reported.

  In both cases the cursor position is read on each button depression, and a position selected outside the display area brings about the exit.

L Spectrum extraction and calibration

Once the data in the image frame has been preprocessed the multiple spectra can be flat-fielded, extracted and calibrated. It is only required that there exist a BOXES list containing the definitions of the spectra locations. The BOXES list can be updated in accordance with the actual data using the `UPDBOXES` command.

The 1D spectra files are created using the `EXTRACT` command and the wavelength calibration of the arc images to take place via the `ARC` command. These commands have many options and are described in detail below. Alternatively the following routines may be useful to perform variations on the standard analysis:

- `SKYSUBTRACT` performs the sky-subtraction for each spectrum. It can be run in either automatic or, by use of the logical argument `PLOT`, interactive mode. The algorithm differs somewhat from that used by EXTRACT.

- `FLUX` uses a fluxing standard contained in an FSPEC list to correct for the spectral response of the detector/instrument combination. It can be multiplied (`/MUL`) or divided (`/DIV`). The spectrum and standard are assumed to have the same dispersion and spectral range.
- `SCRUNCH` transforms the data to a linear wavelength scale.
- `BOXIMAGE` cuts out a given spectrum and puts it into a smaller external 2D image. This might be required if another package is to be used for the subsequent calibration.

  The header items from the parent image are propogated, and information regarding the details about the box is also recorded.
- `HORNE` is an option to perform optimal extraction using the Horne (P.A.S.P., 1986) algorithm. This algorithm is particularly appropriate for spectra which have only small tilts of the object spectrum, such as those produced by LDSS-2.

  It is intended to be performed on images which have already been sky subtracted.

L.1 Flatfielding

In order to take out small scale variations in the sensitivity for the dispersed image, it is necessary to flat-field the data using a white light image. A routine `MAKEFF` exists for the purpose of generating the necessary flat-field, which can then be divided into the data image.

This routine works by dividing each row within a box by the marginal distribution obtained by summing along the columns in that box. This takes out the variation of sensitivity with wavelength but does not account for features which are constant in wavelength for all positions along the slit. If it is believed that genuine features of this type exist, it will be necessary to smooth the marginal distribution before dividing it into the data. This technique will artificially flatten data in boxes affected by vignetting. This could affect the flux calibration if the object is not in the centre of the box. The original image should have uniform illumination of each slit and a signal level high enough to avoid injecting noise into the flattened data.

L.2 Arc subpackage

This is a separate subpackage which can be entered by the command `ARC`. It provides facilities for mapping an arc image to create an arc table, and hence derive scrunch coefficients.

A BOXES list must be provided to give details of the positions of the slit locations. If an ARCL list is present, containing details of the arc-lines, it is used; otherwise one is created and modified.

L.2.1 ARC command interface

When ARC is entered, the prompt changes to:

```
OPTION - ARC fitting option - HE for help >
```

There is a much smaller set of commands available within ARC. These are summarised here:

- `EX` - exit from the routine and return to the LEXT prompt.
- `LA` - list arcline wavelengths in current ARCL list in Å.
- `LF` - For a specified spectrum, lists the lines which have been individually identified with particular arc-lines. This information should be contained in the current LIPOS list, in the form of pixel coordinate of the line centre versus given wavelength of line.
- `RA` - Removes a specified arc-line from the current list (ARCL), and also removes any fits to this arc-line which have been made, from the LIPOS list. The arc-line is identified by its wavelength, in Å, as contained in the appropriate entry in the ARCL list.

  This will not effect any scrunch coefficients which may have been derived using this line. In order to revise these, the fitting procedure must be explicitly repeated using FI or FA.
- `AL` - Adds the user given wavelength of an arc-line to the current ARCL list.
- `CU` - Begin interactive session of identifying lines in an arc spectrum. The arc image should be displayed on the current graphics device. The options are selected by depressing keyboard keys.
  - `D` - displays the selected cursor position.
  - `W` - Allows the user to directly insert a wavelength into the arc-line (ARCL) list. This option cannot be used to directly identify a particular arc-line for insertion into the LIPOS list.
  - F - This is the main option. With it the cursor is used to indicate the approximate position of the line, on the displayed image. A precise position for the line is derived by fitting a gaussian cross-section ridge within a user-defined window around the cursor hit. This fit is indicated graphically, and can be then accepted or rejected. If accepted, the user is prompted for the wavelength to associate with the line.
- `HE` - Displays brief help information on the available ARC commands.
- `FI` - Fits a polynomial of given order to the (pixel,wavelength) pairs for a specified spectrum, from the information stored in the LIPOS list. The fit details are reported to the user, who is then asked whether firstly to store the full information for this fit in its own RESL list slot, and secondly whether to store the scrunch coefficients in the COEFS list slot for the field.
- `FA` - Uses the line positions identified for a given spectrum as a template, and attempts to automatically identify the same lines for each spectrum in the image, and hence produce scrunch coefficients. The line fitting follows the same procedure as the interactive option, CU, by fitting a ridge within a given window around the predicted line position.

  The scrunch coefficients are derived in the same way as for the single spectrum option FI, and stored in the current COEFS list slot. The user is required to specify a maximum value for fitting residuals in order to be acceptable.

  Since the information generated by this routine has not been scrutinised interactively, it is not used to update the current LIPOS list, nor are any RESL lists produced. Instead it is recorded in a FITL list.

  The progress of this routine is reported to the user and the image display is also updated showing the calculated line positions. It is advisable to note possible failures, so that these spectra can be subsequently re-worked individually.

- `AR` - Automatically refine the scrunch fits to each spectrum by searching for fainter lines which are listed in the ARCL list, but haven't been identified in the LIPOS list. This procedure is meant to provide a second order improvement to the fit once an initial attempt has reached the level where the positions of the faint lines can be searched for with confidence.

  The procedure followed is similar to that for FA.

- `CP` - allows setting of several parameters and criteria governing the fitting of arc spectral lines.

Details of standard arc-lines can be found from various sources, for example, in files such as FIGARO_PROG_S:*.ARC

The wavelengths of these can be added manually to the current list using the command `AL`.

L.3 Using the Extract command

This task is used for the extraction of the multiple spectra from a 2D image. The spectra are output into 1D list files, not into slots. In order to define the positions of the spectra on the image there must exist a previously created BOXES list file. The user should declare the box numbers they want by:

```
LEXT - IMAGE mode > EXTRACT 2-5 6-10 15
```

or, if all spectra should be processed:

```
LEXT - IMAGE mode > EXTRACT ALL
```

EXTRACT has a large number of options allowing most of the sophisticated reduction processing to be preformed with the one command, provided the necessary lists are present.

The default is to extract a normal sky subtracted object spectrum for each box. The algorithm used weights the contribution of the object rows according to a gaussian model of the profile. This helps to optimise the signal to noise ratio. However the following qualifiers provide alternatives which may be useful for arc, night-sky or quick-look spectra:

- `/OBJECT` simply takes the object signal from specified rows with no weighting.
- `/SKY` provides a spectrum of just the sky contribution.
- `/WHOLE` uses all the rows within the box to obtain a combined object/sky spectrum

If a normal weighted extraction is to be performed then sky will be subtracted unless the `/NOSUB` qualifier is specified. The subtraction process can be either automatic (the default) or interactive. In the interactive case the user fits the slit profile via the image display cursor. In the automatic case the program will provide a graphical display of its progress by specifying `/PLOT`.

It is also possible to scrunch the spectra to a linear wavelength scale with `/SCRUNCH` (requires a COEFS list), and to flux them with `/FLUX` or `/DFLUX` dependent on whether the fluxing standard is multiplicative or dividing (requires a FSPEC list).

The `/TILT` option can be used to account for tilt of spectral lines if it is large, but this is a slow process and will not usually show any significant difference over the default method.

A Dictionary of LEXT commands

Command	Action	Section
$ or DCL	Executes DCL commands — in batch jobs use DCL only	C.2
<	Execute commands from a LEXT procedure file.	C.1
ADDC	Add a constant to a LIST or IMAGE slot entry.	J
ADDI	Add one IMAGE slot to another.	J
ADVANCE	Advance the plotting window one sub-page.	K
APPEND	Append one LIST slot to the end of another.	J.2
ARC	Enter arc-fitting/wavelength-calibration sub-package.	L.2
BACK	Step backwards to the previous LIST or IMAGE slot.	D.5
BOXIMAGE	Put BOXES sub-images into small external images.	L
BROWSE	Interactive graphical inspection of display or plot.	K.5
CADD	Add one column of a LIST slot to another.	J
CCOPY	Copy the values in a LIST slot column to another column.	J
CLEAN	Remove missing values from a LIST or IMAGE slot.	J.3
CLOSE	Shuts down a graphics device.	K.1
CONTINUE	Continue a command procedure after interruption.	C.1
COPY	Copy one LIST or IMAGE slot to another.	D.5
CREATE	Create a LIST or IMAGE slot or a KNOTS or grid LIST.	D.1
CURSOR	Use the cursor to inspect and fit plotted data.	K.5
DEVICE	Select a graphics device.	K.1
DIRECTORY	List the status and contents of LIST or IMAGE slots.	D.5
DISPLAY	Display the current IMAGE on a plotting device.	K.2
DISTORT	Apply a bicubic spline distortion to a LIST or IMAGE slot.	I
DIVI	Divide one IMAGE slot by another.	J
EDIT	Allow current LIST slot to be edited.	J.2
END	Exit the LEXT package.	C.4
EMPTY	Empty a LIST or IMAGE slot.	D.5
ERASE	Erase the screen of the current plotting device.	K
EVALUATE	Fill IMAGE slots with the X and Y shifts from a transform.	I
EXIT	Exit the LEXT package.	C
EXTRACT	Spectrum extraction function. Many options.	L.3
FIDUCIAL	Centroids fiducial holes.	H
FLUX	Flux the spectrum in the current LIST slot.	L
FPRINT	Create formatted list from POS and MASK lists.	F
FREE	Deprotect current LIST or IMAGE slot.	D.7
GROW	Expand BOXES/MASK regions to optimally fill detector.	G
HELP	Enter HELP facility.	C
HORNE	Performs optimal extraction via the Horne algorithm.	L
IMAGE	Select IMAGE mode.	D.4
INIT	Initialise LEXT during execution of startup procedure.	C.1
INVALIDATE	Set parts of current LIST or IMAGE slot to invalid flag.	J.3

Command	Action	Section
KILL	Exit the LEXT package without checking for SAVEd slots.	C
LFIT	Fit a linear transformation to a pair of LIST slots.	I
LIST	Select LIST mode.	D.4
MAKEFF	Utility to create flat-field images.	L.1
MAP	Search IMAGE for peaks and store positions in LIST slot.	J.4
MATCH	Match up the order of two LIST entries by (x,y) position.	J.2
MULC	Multiply current LIST or IMAGE slot by a constant.	J
MULI	Multiply one IMAGE slot by another.	J.1
NEXT	Step forwards to the next LIST or IMAGE slot.	D.5
OK	Check whether to continue or abort a procedure.	C.1
PLOT	Plot a LIST slot. Many options.	K.3
POLY	Fit a polynomial to the current LIST slot.	J.2
PREBOX	Predict BOXES positions on detector from MASK details.	G
PREDIRECT	Predict slit positions in a direct mask image.	G
PROC	Prompt for commands to be stored in a procedure file.	C.1
PROTECT	Protect current LIST or IMAGE slot.	D.7
QUIT	Exit the LEXT package.	C.4
READ	Read an external file into a LIST or IMAGE slot.	F
REGION	Define the current region.	K.4
RELABEL	Change the *label* on a LIST or IMAGE slot.	D.6
REPLACE	Change values in the current LIST or IMAGE slot by hand.	J.3
RETYPE	Change the *type* of a LIST or IMAGE slot.	D.6
RIDGE	Map positions of peaks in X or Y in current IMAGE region.	J.4
SAVE	Flag the current slot to be written out before exit.	D.7
SAVESET	Save the current internal parameter settings.	E
SCRUNCH	(Re-)Scrunches a spectrum to a linear wavelength scale.	L
SET	Set the value of an internal variable.	E
SFIT	Fit a bicubic spline to a pair of LIST slots.	I
SHOW	Display the values of internal variables.	E.1
SKYSUBTRACT	Perform 2D sky-subtraction on current IMAGE.	L
SMOOTH	Apply smoothing to current IMAGE region or LIST column.	J.1
SQUASH	Compress selected BOX in current IMAGE slot in X or Y.	J.1
STATS	Obtain statistics on current LIST or IMAGE slot.	J.3
STOP	Exit the LEXT package.	C.4
STORE	Write current internal variable values to a *.SET file.	E
SUBI	Subtract one IMAGE slot from another.	J
SUBSET	Squash or stretch to/from subset of IMAGE slot.	J.4
SWAP	Swap two columns in the current LIST slot.	D.5
TRANSFORM	Transform LIST slot coordinates between mask and detector.	I
TYPE	Type out a subset of the current LIST or IMAGE slot.	J.3
USE	Select the current LIST or IMAGE slot.	D.5
WRITE	Write current LIST or IMAGE slot to an external file.	F

B Standard types of List

As mentioned previously LEXT has a variety of uses for list data. Different functions may operate with only certain lists so in order to differentiate between them lists are designated one of the following *types*:

- BOXES defines rectangular regions of the image which are used to designate the positions and extent of each of the spectra within the 2D image. (All in pixels).

  (X-start, Y-start, X-end, Y-end, ID, Y-pos object, Y-extent obj, X-pos zero-order)
- KNOTS defines the fiducial points for the spline.

  (X-value, Y-value)
- MASK defines the mask details.

  (ID, Obj X (mm), Obj Y (mm), Slitlen, Slitoffset, Obj app RA (rad), Obj app dec (rad), Weight)

  Note that zero weight conventionally designates a Wood's hole.
- POS holds object positions and magnitudes. This is only for user information, rather than processing. It has no official column headers, but, if it is to be output by `FPRINT` then the following are assumed:

  (CosX, CosY, ID, B, R, B-R)
- ARCL holds standard arc-line wavelengths.

  (Lambda (Å))
- CLIST object positions in pixel units. May also be any list of points.

  (X-pos, Y-pos, Height, X-sig, Y-sig, Background)
- MLIST object positions in mm units at the focal plane.

  (As CLIST)
- FIBOX defines the extent and positions of rectangular regions for use with FIT. (All in pixels).

  (Xcen (pix), Ycen (pix), X-extent, Y-extent)
- LIPOS stores line positions identified for each arc spectrum.

  (X (pix), Lambda (Å), Box num)
- COEFS contains linearity correction for SCRUNCH, for each arc spectrum.

  (Npt fitted, Coef X^0, Coef X^1, Coef X^2, Coef X^3, Coef X^4, Coef X^5, Coef L^0)
- RESL contains the full details of the fit to the arc lines in a given spectrum.
- YPROF profile of pixel values in Y direction.

  (Y-val, Summed int)
- XPROF profile of pixel values in X direction.

  (X-pix, Flux, Lambda(Å))

- OPROF profile of object spectrum, not scrunched.
  (X-pix, Flux, Lambda(Å))
- WPROF profile of weighted spectrum, not scrunched.
  (X-pix, Flux, Lambda(Å))
- SPROF profile of sky spectrum, not scrunched.
  (X-pix, Flux, Lambda(Å))
- SPEC contains a 1D spectrum as a function of wavelength.
  (Lambda(Å), Flux)
- OSPEC scrunched object spectrum.
  (Lambda(Å), Flux)
- WSPEC scrunched weighted spectrum.
  (Lambda(Å), Flux)
- SSPEC scrunched sky spectrum.
  (Lambda(Å), Flux)
- FSPEC contains fluxing standard.
  (Lambda(Å), Response)
- DRCT contains a boxes *type* file, created by PREDIRECT for a direct image.
- RESL keeps details of the scrunch fit to the arc lines for an individual box.
- FITL list contains details from auto-refine during automatic arc fitting.
- DLIST distorted list

The designated *type* of a list can be modified at any time by means of the `RETYPE` command. This is useful to change the semantic interpretation of the list data. LEXT will even allow an invented *type*, which may, of course, make sense if the user wants to store any unusual information, but could not be interpreted automatically by LEXT.

C Procedure FIND_TWEAK

The following listing of the procedure FIND_TWEAK, used for target acqusition, serves as an example of how to write LEXT procedures.

```
#***********************#
# Authors - Keith Taylor #
#          Nial Tanvir  #
#                       #
#***********************#
set echo
#******************************************************************#
#* FIND_TWEAK - operates on an acquisition image (ie. a direct image#
#*           of the target through the mask)  and its corresponding #
#*           catalogue file which it uses to determine the shift    #
#*           between the stars and their respective holes.          #
#*           It then predicts the offsets to feed into the          #
#*           WHT's TCS TWEAK proceedure.                            #
#******************************************************************#
#******************************************************************#
#*                                                                  #
#*  Calling Sequence: FIND_TWEAK p1 [p2 p3]                         #
#*       where:   p1 = number of fiducial holes  [compulsory]       #
#*                p2 = Name of acquisition image [optional]         #
#*                p3 = Name of catalogue file    [optional]         #
#*                                                                  #
#******************************************************************#
ok
#
#  Have you selected a display device ?
#
:query
:goto kt1
dev
:label kt1
image
#
#  Have you already read in an acquisition image ?
#
:query
:goto kt2
#
#  Read in the image.
#
image
read/3 $2
:goto kt3
:label kt2
image
```

```
dir
#
#  Are you pointing at the relevant image ?
#
:query
:goto kt4
use
:label kt4
:label kt3
list
dir
#
#  Have you already a catalogue file ?
#         ... it has to be in slot 1 with all other slots empty.
#
:query
:goto kt5
#
#  Read in the catalogue file and predict rectangular regions (in pixels)
#  surrounding slits and fiducial holes.
#
#  NB: all list slots will be emptied. If any are required you should
#      answer 'n' here, write them out to disk, and then type 'continue'.
#
ok
list
empty/all y
read/cat $3 $3
:label kt5
list
clean 8
use 1
free
empty
copy 2 1
use 2
free
empty
use 1
create/mask 21 21
#***************************************************************************
#          Finding the geometric centres of the fiducial holes.
#***************************************************************************
fiducial
clean 1
match 4 2 matched_fibox
use 2
rety fbx
use 4
#***************************************************************************
```

```
#    Now finding the centroids of the fiducial stars within the holes.
#***********************************************************************
fit/fid 2
#***********************************************************************
#  Each fiducial hole image will now be displayed with the calculated centre
#                  of hole and star for inspection.
#
# Note that, you will have an opportunity later to interactively edit out
# any bad holes/stars. For now, only leave at the exit points if you
# think that you will be able to perform a fix outside this procedure.
#
#***********************************************************************
:loop $1
reg/fibox $$$
disp/1/fast
use 4
set pen 3
set marker 4
plot
use 6
set pen 4
set marker 5
plot
ok
:back
#***********************************************************************
#
#  The full image will now be displayed with the vectors between the
#  calculated positions of the stars and the centres of the holes. For
#  clarity the lengths of the vectors are scaled up by a factor of 50(!).
#
#***********************************************************************
ok
region/full
er
set pen 2
plot/join/1 6 4 50
set pen 4
plot/num 0
#***********************************************************************
#
#  Now is your opportunity to reject any stars/holes which you think should
#  not be included in the fit.
#
#  Use the cursor to edit out bad vectors (keep at least 3 !)
#  The cursor should be placed at the base of the vector.
#***********************************************************************
free
cursor/edit
lfit/noscale/field 6 4
```

```
#***************************************************************************
#  OK - you got it, Bud - now be so good as to tell your friendly T.O.
#                          to perform the TWEAK.
#***************************************************************************
set noecho
exit
```

D Summary of main LEXT internal parameters

These LEXT parameters are essential for mask design.

- X_FORMAT and Y_FORMAT – extent of CCD array
- XPIX and YPIX – pixel size (μm)
- SCALE – Image scale at mask (arcsec/mm)
- FRED – focal reduction factor between telescope and camera
- SLITWIDTH – slit width (arcsec; only affects the plotting in LEXT)
- FIDUCDIAM – diameter of fiducial holes (arcsec)
- MINSLITLEN and MAXSLITLEN – minimum and maximum slit widths (arcsec)
- MINYSEP – minimum distance between adjacent slits (arcsec)
- MINYMARGIN – minimum distance between an object and the slit ends (arcsec)
- OBJECTEXTENT – default extent of the targets (arcsec)
- DISPERSION – the dispersion at the detector (Å/mm)
- LAMMIN and LAMMAX – the minimum and maximum wavelengths considered (Å)
- LAMZERO – the wavelength of zero order (Å ; normally zero)
- LAMBLAZE – the undeviated wavelength (Å ; usually close to blaze)

```
# Parameter file for LDSS-2 with medium dispersion grism and Tektronix 1024 CCD
 set XPIX                 24
 set YPIX                 24
 set X_FORMAT             1024
 set Y_FORMAT             1024
 set DISPERSION           220
 set FRED                 5.4717
 set SCALE                4.50836
 set LAMBLAZE             5725
 set LAMMIN               3000
 set LAMMAX               8000
 set LAMZERO              0
 set MINSLITLEN           10.0
 set MINYSEP              1.0
 set MINYMARGIN           5.0
 set MAXSLITLEN           60.0
 set OBJECTEXTENT         6.0
 set FIDUCDIAM            10.0
 set SLITWIDTH            1.5
 set COLFIELD             11.5
 set CAMFIELD             33.9
 set DRZ                  2.5E-04
 set LATOBS               0.50197
```

Figure 11: An example of a file containing statements to set up internal parameters in LEXT
.

E Catalogue format

Catalogue files are the preferred medium for reading and writing high-precision mask coordinates by LEXT. They are read into LEXT with the READ/CAT command and written with WRITE/CAT. They are text files written in a free format using common astronomical conventions and are thus easily generated from coordinate lists. Their default file type is .CAT, and they must have a maximum record length of 132 characters. A catalogue written with WRITE/CAT can later be read back into LEXT with READ/CAT.

The lines in the file are either interpreted as containing keyword values, object coordinates or a comment. Keywords are valid for the whole file. Coordinate and keyword lines can be mixed higgedly piggedly in any manner throughout the file. However, for readability sake it is best to segregate the keyword lines to either the top or bottom of the file. Keyword and coordinate lines are distinguished by whether non-numeric characters are present. Coordinate lines must only contain numerals, wild card character "*", and optional comments at the end. If anything other than the characters "0123456789+-.ED*! " are present, the line is interpreted as being a keyword line. Characters to the right of an exclamation mark (!) are interpreted as a comment and are ignored. Lines that READ/CAT can not interpret are also ignored.

E.1 Coordinate entries

The format for a coordinate line is

<id> <RA> <Dec> [Wt] [SL] [Offset] [X] [Y]

The fields are:

<id> Identification number of object.

<RA> Right Ascension of object. RA is in hours of time, and should be a sexagesimal string, that is standard hours minutes seconds (HH MM SS.SSS) format, although formats such as HH MM.MMMMM, or even HH.HHHH are also accepted.

<Dec> Declination of object. This is in degrees and should also be in sexagesimal format (+– DD MM SS.SS), although formats such as +–DD MM.MMMMM, or +–DD.DDDDDD are also acceptable. The sign of the declination (+–) is optional for northern objects but mandatory for southern objects.

[Wt] Weight for growing slits. Larger weights mean slits grow faster. Wt = 0.0 is reserved for fiducial stars used for aligning the mask. A centred hole is placed at the mask position of such objects, while slits are used for other (WT > 0) objects. Negative weights should not be used, except for WT = MISVAL = -32767, which marks a *deleted* object.

[Sl] The slit length (or fiducial hole diameter). The default units are arcsecs, although this can be changed with the MMUNit keyword.

[Offset] The Y coordinate difference between the slit centre and object position: Offset = Ycen - Yobj. The slits are drawn parallel to the Y axis, and therefore they have the same X coordinate as the object. The default units are arcsecs, although this can be changed with the MMUNit keyword.

[X] The X coordinate of the object on the mask in mm.

[Y] The Y coordinate of the object on the mask in mm.

The fields in angle brackets (<>) are required, while those in square brackets ([]) are optional. Fields are separated by one or more spaces. Defaults are assumed for blank fields, and were denoted by a word starting with "*". X and Y are written with a WRITE/CAT but are ignored by READ/CAT which recalculates them from the positions and field centre parameters.

E.2 Keyword entries

The keyword lines are of the format

<keyword> <value>

and the currently recognized keywords are

CENtre * The Right Ascension and declination of the field centre in sexagesimal format (as above). The coordinates must be in the same equinox as the coordinate list.

EQuinox * The equinox of the coordinate system used, in years. This MUST NOT be prefixed by B or J (eg neither B1950 nor J2000 is understood; use 1950 and 2000 instead).

EPoch * The epoch of observation, in years e.g. 1992.85.

PA The APPARENT PLACE position angle of the mask in degrees measured from north towards the east. This is equal to the positional angle of a slit at the field centre. However, since all slits are parallel to the Y axis and sky coordinates are non-cartesian, there will be some rotation of position angles away from the field centre. Default = 0.0 (ie North-South slits).

SLObj The slit length for objects with a blank slit length field. Default is set by the LEXT global *MINSLITLEN* in arcsec.

SLFid The diameter of fiducial star holes which have a blank slit length field. Default is set by the LEXT global *FIDUCDIAM* in arcsecs.

WDEF The slit growing weight for objects with a blank weight field. Default is 1.0

OFFDefault The offset of the slit centre from the object position along the Y axis, for objects with a blank offset field. Default is 0.0.

MMUNit The scale in mm/units at the focal plane for slit lengths, and offsets used in this file. This includes the values for SLO, SLF, and OFFD. Default is the mm/arcsec scale of the telescope as given by the *reciprocal* of the LEXT global *SCALE*, i.e. MMUNIT = 1/*SCALE*. If *SCALE* is not specified the mm/arcsec scale for the AAT Cassegrain focus is used.

Only the capitalized letters are required for the keywords (although they do not have to be capitalized in the file). Extra letters beyond those capitalized above are not considered, so that "SLOW_and_easy", "Equus_the_horse", and "epping_boys_high" will be interpreted as the "SLObj", "EQuinox", and "EPoch" keywords respectively. Keyword lines marked with a * are required. If they are not in the file values are prompted for when the file is read by READ/CAT.

E.3 Positional accuracy.

The coordinates used to design a mask should be of the highest precision. Once a mask is made there is no way to adjust the position of the slits. Even errors of 0.5 arcsec can make a significant difference in S/N, considering that most masks have a slit width of 1.5 arcsec and are made for the study of faint objects. Therefore it is recommended that the RELATIVE positional accuracy of the coordinates is kept to a few tenths of an arcsec. The accuracy of the LEXT software is limited by its predominantly REAL*4 implementation, giving positions accurate to about 0.01 arcsec.

It is not that important to beat down the zero-point errors to the FK4 or FK5 system. The accuracy of the field centre position is also not that important, at least during the design of the mask. It can be tweaked during the design, and any offsets resulting from the manufacture can be measured and at the telescope, and the field centre adjusted. However, it is very important that the fiducial stars' positions are measured at the same time as the program objects. These are used to position the telescope. If they are not precisely on the same coordinate system as the program objects it is quite likely that objects will not fall on the slits.

E.4 Example

Below is an example catalogue for LDSS-1, first in a format acceptable by READ/CAT, and then reformatted by WRITE/CAT. An example of the output from WRITE/MAN is also shown.

Input

```
EPOCH 1990.8       ! Observing October 1990.
EQUINOX 1950.0     ! 1950 coordinates
CEN 1 31 20.175 - 5 47 10.43
PA 140.0
188    1 31 29.588 - 5 46 40.71   0  ! Fiducial star
394    1 31  7.060 - 5 44  0.33   0  ! Fiducial star
288    1 31 25.162 - 5 50  9.01   0  ! Fiducial star
451    1 31 28.955 - 5 50  4.64      ! The rest are galaxies
461    1 31 28.391 - 5 49  7.67
242    1 31 27.919 - 5 48 49.33
240    1 31 27.775 - 5 48 31.14
157    1 31 25.472 - 5 48 34.24
98     1 31 24.768 - 5 48 18.79
164    1 31 21.048 - 5 48 48.15
94     1 31 21.7   - 5 48  0.6
1      1 31 20.175 - 5 47 10.43
22     1 31 20.030 - 5 47 34.73   * 8.0 ! This slit starts 8" long
107    1 31 20.592 - 5 47 47.64         ! The rest take the default
42     1 31 19.974 - 5 46 34.23
49     1 31 17.191 - 5 46 47.75
217    1 31 20.421 - 5 45 34.75
144    1 31 12.700 - 5 46 28.41
207    1 31 18.560 - 5 44 56.73
225    1 31 12.461 - 5 45 34.99
```

```
336    1 31 16.783 - 5 44  9.68
337    1 31 14.803 - 5 44 10.38
389    1 31  8.603 - 5 45  0.36
339    1 31 14.400 - 5 43 32.15
544    1 31 10.886 - 5 43 38.37
```

Output from WRITE/CAT

```
 EQUINOX  1950
 EPOCH  1990.8
 CENTRE    1 31 20.176  - 5 47 10.43
 PA  140
 MMUNIT  0.1492537
!id        R.A.          Dec.      Wt.    Length    Offset      X(mm)     Y(mm)
 188    1 31 29.588  - 5 46 40.71  0      10.000     0.000     18.905    10.113
 394    1 31  7.060  - 5 44  0.33  0      10.000     0.000     -4.082   -40.537
 288    1 31 25.162  - 5 50  9.01  0      10.000     0.000     -8.670    27.556
 451    1 31 28.955  - 5 50  4.64  1      15.000     0.000     -1.782    32.502
 461    1 31 28.391  - 5 49  7.67  1      15.000     0.000      2.734    25.184
 242    1 31 27.919  - 5 48 49.33  1      15.000     0.000      3.692    22.411
 240    1 31 27.775  - 5 48 31.14  1      15.000     0.000      5.196    20.126
 157    1 31 25.473  - 5 48 34.24  1      15.000     0.000      0.972    17.176
 98     1 31 24.768  - 5 48 18.79  1      15.000     0.000      1.257    14.400
 164    1 31 21.048  - 5 48 48.15  1      15.000     0.000     -7.908    12.416
 94     1 31 21.700  - 5 48  0.60  1      15.000     0.000     -2.225     7.919
 1      1 31 20.176  - 5 47 10.43  1      15.000     0.000      0.000     0.000
 22     1 31 20.030  - 5 47 34.73  1       8.000     0.000     -2.584     2.568
 107    1 31 20.592  - 5 47 47.64  1      15.000     0.000     -2.867     4.848
 42     1 31 19.974  - 5 46 34.23  1      15.000     0.000      3.138    -4.424
 49     1 31 17.191  - 5 46 47.75  1      15.000     0.000     -2.907    -6.873
 217    1 31 20.421  - 5 45 34.75  1      15.000     0.000      9.619   -10.577
 144    1 31 12.700  - 5 46 28.41  1      15.000     0.000     -8.705   -15.527
 207    1 31 18.560  - 5 44 56.73  1      15.000     0.000     10.102   -17.591
 225    1 31 12.461  - 5 45 34.99  1      15.000     0.000     -3.975   -21.973
 336    1 31 16.783  - 5 44  9.68  1      15.000     0.000     11.597   -25.516
 337    1 31 14.803  - 5 44 10.38  1      15.000     0.000      8.154   -28.278
 389    1 31  8.603  - 5 45  0.36  1      15.000     0.000     -7.223   -31.465
 339    1 31 14.400  - 5 43 32.15  1      15.000     0.000     11.143   -33.223
 544    1 31 10.887  - 5 43 38.37  1      15.000     0.000      4.554   -37.555
```

Output from WRITE/MAN

```
:FIELD 3c435a_l1

 Label   - ASTR:3C435A
 Equinox - 1950
 Epoch   - 1992.6
 Centre  -  21 26 38.992    7 20 10.00
 PA      - -7

:SLITS
 13
  56.89, -79.89,  17.62
  34.94, -52.93,   9.37
 -24.73, -42.00,  10.52
  20.67, -29.19,  13.08
 -24.42,  -5.98,  11.72
  44.24,  17.96,   8.31
 -13.34,  28.05,   9.93
  71.38,  50.85,  10.02
  30.84,  60.28,   7.11
  76.50,  71.15,  14.39
 -61.74,   6.66,  12.17
  35.19, -17.19,   9.18
  22.76,  39.42,  10.78

:STARS
  4
 102.25, -63.58,   5.00
  -9.05, -66.17,   5.00
  71.16, 110.17,   5.00
 -87.94,  84.27,   5.00

:END
```

Figure 12: An example of a file containing mask manufacturing instructions

F Wavelength maps

For each grism, data for the spectrum of a CuAr arc lamp is given in two ways: (1) a plot of a sample spectrum with wavelengths marked (Figs 13-16) and (2) a table showing the results of a sample wavelength-position fit. (Tables 13-16). The actual relationship between wavelength and position will depend on the position of the slit.

Figure 13: Extracted spectrum of CuAr with the low dispersion grism (*LOW*)

Table 13: Sample wavelength calibration for CuAr with the low dispersion grism (*LOW*)

Channel	Wavelength	Calculated	Discrepancy	Line#
162.3267	9784.5029	9784.7031	0.2002	1
173.7100	9657.7861	9657.5723	-0.2139	2
212.5117	9224.4990	9224.3428	-0.1563	3
221.5908	9122.9668	9123.0479	0.0811	4
262.4153	8667.9443	8668.1611	0.2168	5
275.6128	8521.4219	8521.3604	-0.0615	6
298.7408	8264.5234	8264.4424	-0.0811	7
327.2691	7948.1758	7948.1890	0.0132	8
347.5340	7723.9800	7724.0107	0.0308	9
355.5787	7635.1060	7635.1318	0.0259	10
378.3795	7383.9810	7383.5962	-0.3848	11
388.4259	7272.9360	7272.9487	0.0127	12
399.8812	7147.0420	7146.9277	-0.1143	13
407.1342	7067.2178	7067.2202	0.0024	14
416.4084	6965.4302	6965.3970	-0.0332	15
424.8877	6871.2891	6872.4009	1.1118	16
435.7045	6752.8340	6753.9146	1.0806	17
442.8033	6677.2822	6676.2485	-1.0337	18
466.6873	6416.3071	6415.5376	-0.7695	19
513.1519	5912.0850	5911.5103	-0.5747	20
551.8049	5495.8740	5496.4468	0.5728	21
597.0931	5017.1631	5017.0620	-0.1011	22
602.0119	4965.0801	4965.5645	0.4844	23
631.6654	4657.9009	4658.0029	0.1021	24
669.3045	4277.5278	4276.2588	-1.2690	25
676.8939	4199.6299	4200.6904	1.0605	26
690.0090	4072.1101	4071.3748	-0.7354	27
702.6833	3947.5300	3948.0637	0.5337	28

```
RMS error:       0.56, Line width used:  0.80

Order of fit:   5

 0.8307935577354688D-11 -0.1340119590698429D-07 0.9081933402004803D-05
-0.2736789302840305D-02 -0.1079666108289552D+02 0.1157892611228203D+05
```

Figure 14: Extracted spectrum of CuAr with the blue medium dispersion grism (*MED/BLUE*)

Table 14: Sample wavelength calibration for CuAr with the blue medium dispersion grism (*MED/BLUE*)

Channel	Wavelength	Calculated	Discrepancy	Line#
55.8706	8264.5234	8264.7666	0.2432	1
114.5345	7948.1758	7948.0605	-0.1152	2
156.2538	7723.9800	7723.8359	-0.1440	3
172.8345	7635.1060	7634.9463	-0.1597	4
219.8312	7383.9810	7383.6890	-0.2920	5
240.6217	7272.9360	7272.8672	-0.0688	6
264.2592	7147.0420	7147.1216	0.0796	7
279.2982	7067.2178	7067.2607	0.0430	8
298.5115	6965.4302	6965.3984	-0.0317	9
316.2255	6871.2891	6871.6548	0.3657	10
338.5972	6752.8340	6753.5020	0.6680	11
353.1441	6677.2822	6676.8237	-0.4585	12
366.8350	6604.8530	6604.7695	-0.0835	13
402.7394	6416.3071	6416.3447	0.0376	14
408.7843	6384.7168	6384.7012	-0.0156	15
435.7682	6243.1201	6243.7461	0.6260	16
449.6925	6172.0298	6171.2085	-0.8213	17
499.5909	5912.0850	5912.4678	0.3828	18
533.0875	5739.5200	5739.9277	0.4077	19
559.1616	5606.7329	5606.3267	-0.4063	20
580.6898	5495.8740	5496.5220	0.6479	21
642.0282	5187.7461	5186.4160	-1.3301	22
667.0335	5062.0371	5061.2866	-0.7505	23
686.2102	4965.0801	4965.8794	0.7993	24
718.6735	4806.0210	4805.5430	-0.4780	25
726.9457	4764.8652	4764.9346	0.0693	26
772.1011	4545.0518	4545.1787	0.1270	27
779.0596	4510.7329	4511.6162	0.8833	28
844.7731	4199.6299	4199.0405	-0.5894	29
865.0320	4103.9121	4104.3940	0.4819	30
899.0550	3947.5300	3947.4390	-0.0911	31
930.5639	3803.1721	3804.4602	1.2881	32
939.5880	3765.2700	3763.9561	-1.3140	33

```
 RMS error:        0.58, Line width used:  1.00

 Order of fit:   4

 0.2919603424406206D-09 -0.2026285267407393D-06 0.2842190413556393D-03
-0.5443302136844694D+01  0.8568032054526452D+04
```

Figure 15: Extracted spectrum of CuAr with the red medium dispersion grism (*MED/RED*)

Table 15: Sample wavelength calibration for CuAr with the red medium dispersion grism (*MED/RED*)

Channel	Wavelength	Calculated	Discrepancy	Line#
57.3152	8264.5234	8264.5293	0.0059	1
115.9556	7948.1758	7948.1221	-0.0537	2
157.6526	7723.9800	7724.0425	0.0625	3
174.2240	7635.1060	7635.1948	0.0889	4
221.2025	7383.9810	7383.8247	-0.1563	5
241.9763	7272.9360	7272.9336	-0.0024	6
265.6038	7147.0420	7147.0601	0.0181	7
280.6354	7067.2178	7067.1396	-0.0781	8
299.8402	6965.4302	6965.2285	-0.2017	9
317.5393	6871.2891	6871.5107	0.2217	10
339.8658	6752.8340	6753.5698	0.7358	11
354.4210	6677.2822	6676.8462	-0.4360	12
368.1093	6604.8530	6604.8052	-0.0479	13
404.0711	6416.3071	6416.0439	-0.2632	14
410.0630	6384.7168	6384.6621	-0.0547	15
437.0343	6243.1201	6243.6538	0.5337	16
450.9136	6172.0298	6171.2607	-0.7690	17
500.7675	5912.0850	5912.3545	0.2695	18
534.0324	5739.5200	5740.8037	1.2837	19
560.5043	5606.7329	5605.1128	-1.6201	20
581.8288	5495.8740	5496.3823	0.5083	21
643.0414	5187.7461	5187.1123	-0.6338	22
668.0462	5062.0371	5061.9233	-0.1138	23
687.1658	4965.0801	4966.6396	1.5596	24
719.6962	4806.0210	4805.5112	-0.5098	25
728.0645	4764.8652	4764.3008	-0.5645	26
773.0864	4545.0518	4544.8589	-0.1929	27
780.0766	4510.7329	4511.1958	0.4629	28
845.6921	4199.6299	4199.5474	-0.0825	29
865.5753	4103.9121	4103.9438	0.0317	30

```
 RMS error:       0.58, Line width used:  1.50

 Order of fit:  10

-0.9424988456191865D-24  0.4067576866842583D-20 -0.7525524268956207D-17
 0.7808671003325572D-14 -0.4993849800134690D-11  0.2038715667084528D-08
-0.5326183519054469D-06  0.8706836804261911D-04 -0.8242856089165049D-02
-0.4995482148387141D+01  0.8566179584915310D+04
```

Figure 16: Extracted spectrum of CuAr with the high dispersion grism (*MED/BLUE*)

Table 16: Sample wavelength calibration for CuAr with the high dispersion grism (*HIGH*)

Channel	Wavelength	Calculated	Discrepancy	Line#
68.5122	5495.8740	5495.3438	-0.5303	1
86.0192	5451.6519	5452.1714	0.5195	2
151.0161	5292.5171	5292.6064	0.0894	3
194.0565	5187.7461	5187.6226	-0.1235	4
234.0315	5090.4951	5090.6470	0.1519	5
286.0787	4965.0801	4965.2144	0.1343	6
335.0711	4847.8101	4848.0679	0.2578	7
352.7338	4806.0210	4806.0679	0.0469	8
370.1714	4764.8652	4764.7290	-0.1362	9
415.7065	4657.9009	4657.3936	-0.5073	10
436.2100	4609.5669	4609.3628	-0.2041	11
464.0057	4545.0518	4544.5601	-0.4917	12
478.6262	4510.7329	4510.6206	-0.1123	13
526.0810	4400.7598	4401.1846	0.4248	14
549.2548	4348.0640	4348.1587	0.0947	15
555.5106	4333.5610	4333.8926	0.3315	16
633.0545	4158.5908	4158.8174	0.2266	17
645.0946	4131.7241	4131.9365	0.2124	18
657.6050	4103.9121	4104.0947	0.1826	19
707.0172	3994.7920	3995.0391	0.2471	20
729.0117	3947.5300	3946.9756	-0.5544	21
774.0031	3850.5811	3849.6133	-0.9678	22
813.0164	3765.5500	3766.2588	0.7087	23

```
RMS error:       0.39, Line width used:  2.00

Order of fit:   3

0.9602472321444220D-07  0.1045408027795212D-03 -0.2483892165373404D+01
0.5664999221813987D+04
```

G Filter throughput

The measured throughput of the three broadband filters, PB, PV and PR is shown in Fig. 17.

Figure 17: Measured throughput of the broadband Harris/NOAO photometric filters used with LDSS-2