EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral

Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

LA SILLA OBSERVATORY

SOFI

User's Manual

Doc. No. LSO-MAN-ESO-40100-0004

Issue 1.6

05/11/2002

Prepared . . . C. Lidman, J-G. Cuby 16/08/2000 . . .
Name Date Signature

Revised . . . L. Vanzi 00/00/2002 . . .
Name Date Signature

Revised . . . M. Billères 05/11/2002 . . .
Name Date Signature

Reviewed . . . O. Hainaut, E. Pompei 17/11/2002 . . .
Name Date Signature

Released . . . O. Hainaut 17/11/2002 . . .
Name Date Signature

*****

Change Record

Issue/Rev.	Date	Section/Parag. affected	Reason/Initiation/Documents/Remarks
0.9	02/05/98	All	Creation
1.0	14/08/98	All	
1.1	12/11/98	All	New templates
1.2	25/02/99	Some	New Grism
1.3	16/08/00	Some	New IRACE and New Templates
1.4	05/11/02		Some addition and corrections
1.6	13/03/04		update of the module

Contents

List of Figures

Chapter 1

Introduction

SOFI or **S**on **OF** **I**SAAC is the infrared spectrograph and imaging camera on the NTT. In many ways, it resembles EFOSCII on the 3.6m. Both are focal reducing instruments capable of imaging, spectroscopy and polarimetry.

SOFI offers the following observing modes.

- imaging with plate scales of 0.145, 0.276 and 0.288 arc-seconds/pixel using broad and narrow band filters in the wavelength range 0.9 to 2.5 microns.
- low resolution (R=600), 0.95-2.52 micron spectroscopy with fixed width slits of 0.6, 1 and 2 arc seconds.
- medium resolution (R=1500) H and Ks-band spectroscopy, with fixed width slits of 0.6, 1 and 2 arc seconds..
- 0.9-2.5 micron imaging polarimetry

This manual is divided into several chapters. For proposal writers, it is sufficient to read chapter 2, the chapter describing the instrument. For those who will be observing at the telescope, it is sufficient to read up to the end of chapter 4. Chapter 3 discusses how to use observation templates to set up observations and chapter 4 describes how to use the instrument at the telescope. For those who will reduce data taken with SOFI, it is sufficient to read chapters 2, 3 and 5. Chapter 5 discusses how to reduce data taken with SOFI. At the end, there are appendixes which contain various information useful for observers (template examples, fits headers...).

1.1 A First and Final Word

The authors of the manual hope that you find this manual useful in writing SOFI proposals or for preparing for your SOFI run. The manual is continually evolving. Some sections still need to be written and some figures still need to be included. If you have any suggestions on how to improve the manual please contact the la Silla infrared instrument force (ls-infrared@eso.org).

In addition to the information provided by this manual, there is the SOFI Template Signature Files (hereafter TSF) Parameters Reference Guide, which contains detailed information on the SOFI templates. Those of you who are successful in being awarded SOFI time must read this document, the template manuals and the related P2PP Users' Manual before coming to observe with SOFI.

There is also a WEB page dedicated to SOFI. It is accessible from the SciOp home page.

`http://www.ls.eso.org/lasilla/sciops/`

There you will find recent news, efficiency measurements and other useful data that do not easily fit into this manual. This WEB page is updated frequently.

1.2 Applicable documents

1 VLT-MAN-ESO-14100-1510 OS Users' Manual

2 VLT-MAN-ESO-14100-1531 DCS Users' Manual

3 VLT-MAN-ESO-14100-1094 ICS Users' Manual

4 VLT-MAN-ESO-00000-000/1.1 P2PP Users' Manual

5 VLT-MAN-ESO-00000-000 SOFI TSF Parameters Reference Guide

1.3 Reference Documents

1.4 Abbreviations and Acronyms

Acronym	Description
BOB	Broker of Observing Blocks
DCR	Double Correlated Read
DCS	Detector Control System
DEC	Declination
DIT	Detector Integration Time
EMMI	ESO's Multi-Mode Instrument
ESO	European Southern Observatory
FWHM	Full Width at Half Maximum
ICS	Instrument Control System
IR	Infra-Red
ISAAC	IR Spectrograph And Array Camera
NDIT	Number of DITs
NDR	Non-Destructive Read
NINT	Number of NDITs
NTT	New Technology Telescope
OB	Observing Blocks
OS	Observing Software
P2PP	Phase 2 Proposal Preparation
PSF	Point Spread Function
RA	Right Ascension
RON	Read Out Noise
SOFI	Son Of ISAAC
TCS	Telescope Control System
TSF	Template Signature File
VLT	Very Large Telescope
ZP	Zero Point

Table 1.1: Abbreviations and Acronyms used in this manual.

Chapter 2

SOFI - Son of ISAAC

2.1 Optical Layout

SOFI is mounted on the Nasmyth A focus of the NTT. The light from the tertiary mirror of the telescope enters the front window which has no optical power. Immediately after the front window is a cryogenically cooled mask wheel which coincides with the telescope focus. The mask wheel contains several masks: one for each imaging scale, three for long slit spectroscopy, a pinhole mask and a special mask used with polarimetry.

The optical layout is shown in Figure 2.1.

The mask wheel is followed by a collimating lens, two filter wheels, a grism wheel, an objective wheel, and then the detector itself. The re-imaged pupil of the telescope, the primary mirror, is located on a slightly undersized stop just before the grism wheel.

The first filter wheel contains the standard broad band near IR filters, several narrow band filters, two order sorting filters, an open position and a fully closed position. The second filter wheel contains more narrow band filters a focus pyramid, an open position and a fully closed position.

The grism wheel contains three grisms for long slit spectroscopy, a Wollaston prism for imaging polarimetry, an open position and a fully closed position.

The objective wheel contains two objectives for imaging at $0\farcs288$ and $0\farcs144$ per pixel, a spectroscopic objective, an open position and two fully closed positions.

2.2 Imaging

SOFI offers imaging at several different pixel scales. The pixel scales and the fields of view are summarized in Table 2.1. The large and small field objectives are used with the corresponding mask in the mask wheel that covers the same field of view. This reduces the amount of stray light entering the instrument. The spectroscopic objective is used with the large field mask.

Objective	Pixel Scale	Field of View
Large Field Objective	0.288	4.94' x 4.94'
Spectroscopic Objective	0.276	4.71' x 4.71'
Small Field Objective	0.145	2.47' x 2.47'
Large Field Objective + Focal Elongator	0.146	2.49' x 2.49'

Table 2.1: The fields of view and the pixel scales available with SOFI.

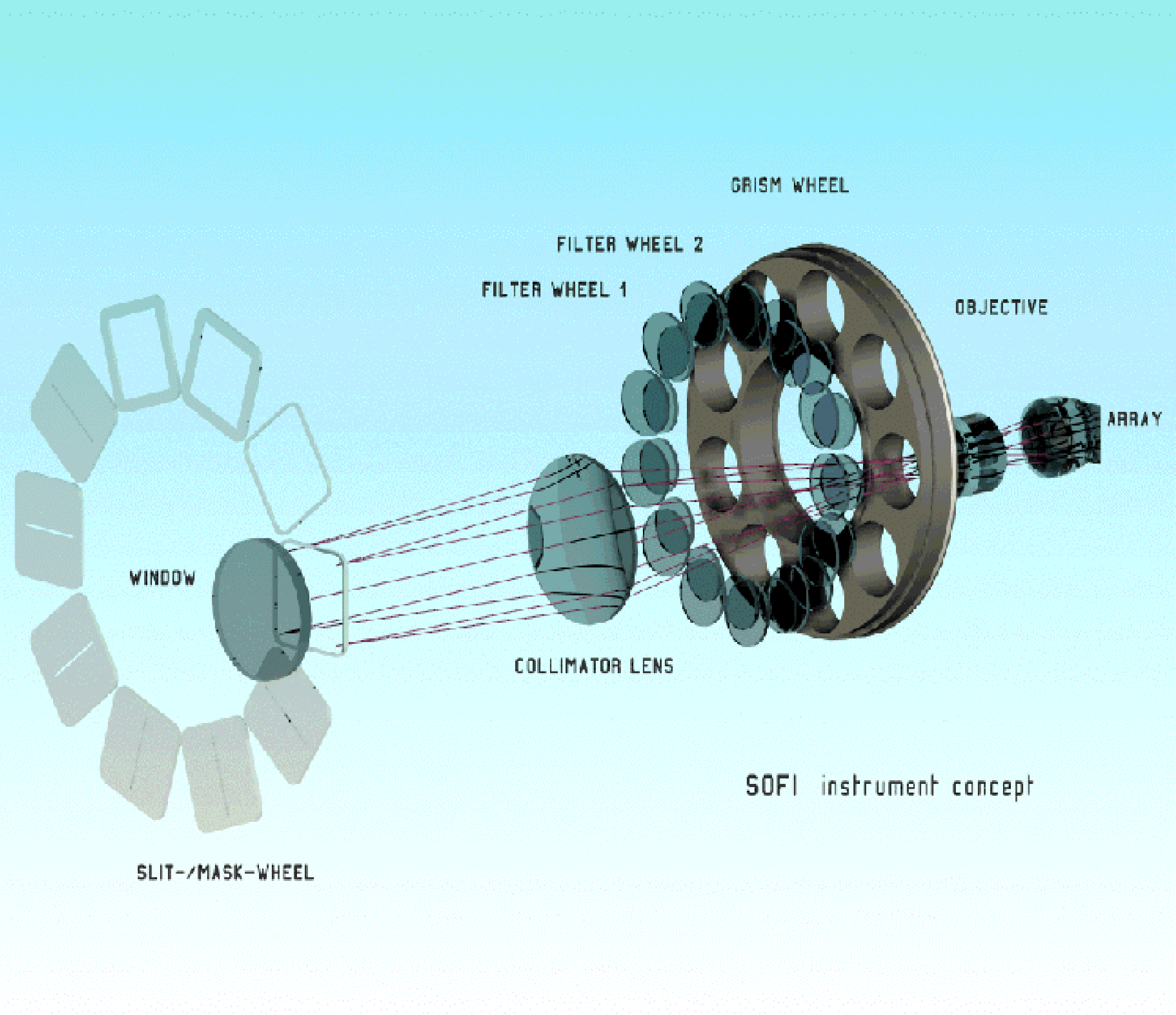


Figure 2.1: Optical Layout of SOFI

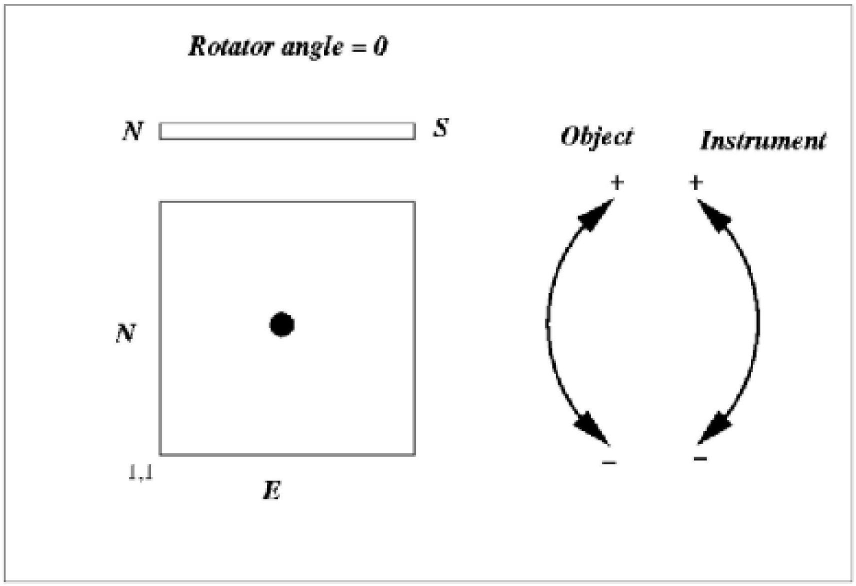


Figure 2.2: Orientation of SOFI: In imagery the North is on the left and the East on the bottom of the image. The slit for the spectroscopy is oriented North-South.

For a normal use of SOFI (rotator angle = 0) the orientation is showned in the Figure 2.2. You could modify the orientation simply using a rotator angle in the template. This option could be useful in spectroscopy if you want to align two objects in the slit (the positive angle is from the north to the east).

The spectroscopic objective can be used to take images with a scale that is a bit finer than that of the large field objective; however, this objective is chromatic. This means that the pixel scale is a function of wavelength. At J, H and K_s the pixel scales of are respectively $0\farcs275$, $0\farcs276$ and $0\farcs277$ per pixel. It also has a central light concentration, so that images taken with this objective must be flat-fielded with the large field objective.

All the aforementioned objectives suffer various amounts of image degradation over their respective fields of view. For the large field objective, there is significant image distortion in the bottom left and top left corners. For the small field objective, there is a complicated pattern of distortion which may mean that it is difficult to use PSF fitting routines for crowded field photometry.

There is a focal elongator in the grism wheel which can be used in combination with the large field objective to image with a pixel scale that is similar to the pixel scale of the small field objective. However, this mode is 10% to 15% less efficient, but the image quality is superior than that of the small field objective.

Imaging can be done through the standard IR broadband filters: J, H, K short; a Z filter which peaks at 0.9 microns; and many narrow band filters. The filters, together with their central wavelengths and widths at half maximum, are listed in Table 2.2. Listed also are the cut-on wavelengths for the two order sorting filters. These filters are used with the two low resolution grisms.

The filter curves for all filters are drawn in Appendix B together with the atmospheric transmission above La Silla.

The K short or K_s filter is different from both the standard K filter and the K' filter defined by Wainscoat and Cowie (1992, AJ, 103, 332). The long wavelength edge of the K_s filter is similar to that of the K' filter, but the short wavelength edge is similar to that of the K filter. Thus, the

Filter Name	Filter Wheel	Central Wavelength (μm)	Width (μm)	Peak Transmission (%)
Z	1	0.9	0.140	
J	1	1.247	0.290	
H	1	1.653	0.297	83
Ks	1	2.162	0.275	88
NB 1.061	1	1.061	0.010	
NB 1.083 HeI J	2	1.083	0.016	61
NB 1.187	1	1.187	0.010	
NB 1.215	2	1.215	0.018	
NB 1.257 [FeII] J	2	1.257	0.019	
NB 1.282 Pβ	2	1.282	0.019	
NB 1.644 [FeII] H	2	1.644	0.025	
NB 1.710	2	1.710	0.026	
NB 2.059 HeI K	2	2.059	0.028	81
NB 2.090	1	2.090	0.020	
NB 2.124 $H_2(S1)$	2	2.124	0.028	78
NB 2.170 Brγ	2	2.167	0.028	71
NB 2.195	1	2.195	0.030	
NB 2.248	2	2.248	0.030	
NB 2.280	2	2.280	0.030	69
NB 2.336 (CO)	2	2.336	0.031	
GBF	1	0.925 cut-on	—	
GRF	1	1.424 cut-on	—	
Open	1 and 2	—	—	—
Closed	1 and 2	—	—	—

Table 2.2: The broad and narrow band filters available with SOFI.

K_s filter avoids both the atmospheric absorption feature at 1.9 μm and radiation from the thermal background beyond 2.3 μm. The difference between K_S and K is given by K-K_S = -0.005(J-K). The conversions between the SOFI magnitudes and those of Persson et al. (1998) are as follows:

$$J(p) - J(s) = -0.007\ (J-K)$$

$$H(p) - H(s) = -0.022\ (J-K)$$

$$K_S(p) - K_S(s) = 0.023\ (J-K)$$

2.3 Long Slit Spectroscopy

SOFI offers low and medium resolution, long slit spectroscopy. The large field objective is used in this mode. There are three grisms available with SOFI: two low resolution grisms and a medium resolution grism.

Of the two low resolution grisms, one covers the region from 0.95 to 1.64 microns and the second covers the region from 1.53 to 2.52 microns. Both grisms are made of KRS5 (refractive index ≈ 2.44) and the entrance surface of both is inclined to the optical axis. The blaze angle of the grooves is equal to the apex angle of the prism. The wavelength ranges, the resolving powers and the resolutions of the grisms are given in Table 2.3.

The new medium resolution grism gives about twice the resolving power of the two low resolution

Grism Number	Order Sorting Filter	Wavelength Range (microns)	Resolution	Dispersion (Å)/pixel
Blue	GBF	0.95-1.64	930	6.96
Red	GRF	1.53-2.52	980	10.22

Table 2.3: The wavelength range and the resolution of the low resolution grisms. The resolution is that measured for the 0.6 arc-second slit. The resolution scales with the slit width.

grisms. It is used with the Ks and H filters as order sorting filters in the 3rd and 4th orders to cover respectively the Ks and H atmospheric transmission windows. The wavelength ranges, the resolving powers and the resolutions of the grisms are given in Table 2.4. The wavelength ranges are defined by the H and Ks filters.

The grism can also be used in the higher orders with the J and Z filters, However, there is significant overlap between these orders, so the useful wavelength range is limited. Furthermore, the the line profile degrades in the blue, so that the resolution is not significantly better than that obtained with the low resolution blue grism.

Grism Order Name	Order Sorting Filter	Wavelength Range (microns)	Resolution	Dispersion (Å)/pixel
3	Ks	2.00-2.30	2200	4.62
4	H	1.50-1.80	1500	3.43
5	J	1.20-1.28	1400	2.71
6	J	1.17-1.24	1400	2.22
7	Z	0.89-0.93	1400	1.87
8	Z	0.86-0.95	1400	1.58

Table 2.4: The wavelength range and the resolution of the medium resolution grism. The resolution is that measured for the 0.6 arc-second slit.

Three slits of different fixed widths, 0.6, 1.0 and 2.0 arc seconds, are available. The slit length is 290 arc seconds.

2.4 Polarimetry

SOFI offers imaging polarimetry. A Wollaston prism in the grism wheel splits the incoming parallel beam into two beams that are perpendicularly polarized. The beams are separated by 48 arc seconds. Thus an image taken with the Wollaston prism will contain two images of every object. To avoid sources overlapping, a special mask, consisting of alternating opaque and transmitting strips, can be inserted at the focal plane. Thus, in a single exposure, at least half the field will be missing. So three exposures, with telescope offsets in between, are required to cover one field.

The Wollaston prism is not achromatic, so the exact separation between the two beams is a function of wavelength. At J, the separation is 48.3 arc seconds, while at K_s, the separation is 47.4 arc seconds. The beam separation is also a function of position.

To measure the Stokes parameters and hence the degree and position angle of polarization a second set of images with the Wollaston prism rotated 45 degrees with respect to the first pair are required. The rotation is done by rotating the entire instrument. The Stokes parameters are then determined as follows.

$$I = i(90) + i(0) = i(45) + i(135)$$

$$Q = i(0) - i(90)$$

$$U = i(45) - i(135)$$

where $i(\alpha)$ is the intensity of the source which transmits light that is polarized at angle α. We have assumed that the rotator is at a position angle of 0 degrees for the first measurement. This need not be the case.

The degree of linear polarization and the polarization angle are given by;

$$P = \frac{\sqrt{U^2 + Q^2}}{I}$$

$$\theta = 0.5\tan^{-1}\frac{U}{Q}$$

To derive the correct value of θ, attention needs to be paid to the signs of U and Q.

This algorithm neglects instrumental polarization. Preliminary measurements indicate that the instrument polarization is 2%. As it is caused by the tertiary mirror, the vector defining the instrument induced polarization will rotate relative to the sky. A method to eliminate the instrumental polarization is outlined by Sperello di Serego Alighieri (1989, Proceedings of 1st ESO/ST-ECF Data Analysis Workshop).

A technical report has been released, which describes in details this mode and its operation. It is available on the SOFI web page (Wolf, Vanzi & Ageorges 2002, in http://www.ls.eso.org/lasilla/NEWNTT/sofi).

2.5 The DCS - Detector Control System

The DCS is made up of the detector, the front-end electronics, and the controller (IRACE).

The IRACE controller controls the detector front-end electronics and manages pre-processing of the data before sending it to the SOFI workstation. It includes an embedded Sparc and two sets of transputers. Further details on the IRACE system can be found at:

`http://www.eso.org/projects/iridt/irace/`.

The amount of data pre-processing depends on the readout mode. The readout modes available with SOFI are discussed below.

The detector used by SOFI is a Rockwell Hg:Cd:Te 1024x1024 Hawaii array with 18.5 micron pixels. The array is read out in four quadrants. The average quantum efficiency is 65 %. The dark current is very low, 20 e-/hour, and the readout noise with the IRACE controller in DCR (Double Correlated Read) mode is 12e-. In NDR (Non Destructive Read), values as low as 3e- have been reached with integrations of one minute. About 0.1% of the pixels are bad. An updated mask of bad pixels is available in the SOFI web page.

The well depth of the array is around 100,000 electrons. The array is linear up to 60,000 electrons. The gain of the array ∼ 5.5 e-/ADU. Although the array is linear to 10,000 ADU, we recommend that observers keep the exposure short enough so that the *background* does not exceed 6,000 ADU.

This is due to the bias of the array, which has a complicated dependence on the flux when the flux is above 6,000 ADU.

The DCS has to cope with backgrounds that range from a fraction of a ADU/sec/pix, as seen in the spectroscopic modes to six hundred ADU/sec/pix, as seen during summer with the K_s filter and the large field objective. The high count rate from the background, particularly at K_s, limits a single integration to about 10 seconds, which drops to 6s for full moon observations. Thus, in order to accumulate sufficient photons without saturating the detector, the control system acquires many individual integrations and then averages them on the fly into a final frame.

In this context, we define `DIT`, the *Detector Integration Time,* as the amount of time during which the signal is integrated onto the detector diodes, and `NDIT` as the number of detector integrations that are obtained and averaged together. These averaged frames make up the raw data, and in normal co-add mode, they are the smallest block of data presented to the user. So that the total exposure time of a single image is `NDIT`x `DIT`. Note that the single `DIT` or the averaged `NDIT` can be displayed in the RTD (Real Time Display).

Additionally, in the spectroscopic modes, one can define several consecutive exposures as defined by `NINT`.

2.5.1 Readout Modes

Unlike optical CCDs, the charge in individual pixels is not shifted from pixel to pixel during the readout process. Each pixel is independently read and each column is individually reset. This enables one to develop several readout methods. For SOFI, two readout methods are available: DCR (Double Correlated Read) and NDR (Non-Destructive Read). DCR incurs less overheads and is suitable for imaging and low resolution spectroscopy. NDR has a lower read out noise and is suitable for low and medium resolution spectroscopy.

- **Double Correlated Read:** Here the voltage is sampled twice, once at the beginning of the integration and a second time at the end of the integration. This method is called Double Correlated Read or DCR for short. It is commonly used in high background situations where integrations are forced to be short. In principle this method is susceptible to 1/f noise; however, the Poisson noise from the background will be, by far, the most important noise source. The minimum integration time for SOFI in this mode is 1.2 seconds.
- **Non-Destructive Read:** In Non-Destructive Read or NDR the array is sampled several times after the reset. The number of samples is more or less proportional to `DIT`, we will call the number of samples `NSAMP`. The flux in each pixel is computed by fitting a linear function to the voltage as a function of time. The fitted slope is then multiplied with the integration time. There are several ways the signal can be read in the NDR mode. The one used in SOFI concentrates the read-out at the beginning and at the end of the integration, in this way the noise is minimized. This mode is called Fowler. Unfortunately with the number of readings the glowing produced by the shift-registers at the border of the array increases. For `NSAMP` = 60 the photon noise of the glowing starts to compete with the read-out noise and above 60 becomes the dominant source of noise. For this reason the `NSAMP` must not exceed 60. To further minimize the noise, keeping `NSAMP` small, the analogic signal can be sampled several times for each reading, this is done with the parameter `NSAMPIX`. The read-out noise is reduced approximately by the square root of the number of samples `NSAMP`. This method is also less susceptible to 50Hz pickup. The drawback of the NDR is that it takes slightly longer to process the data although the disadvantage becomes smaller as the exposure time increases. The shortest integration time in this mode is given by 1.64 × `NSAMP`. NDR is only available for the spectroscopic modes. For most applications we recommend `NSAMP` =30 and `NSAMPIX` = 4.

There is a noiseless component of the signal introduced by the reset which is somewhat unstable a short time after the reset. Thus, there is a small delay of 100ms between the reset and the first read. This component decays with time, for this reason dark frames taken with long `DIT` have negative counts.

The Hawaii array, like the NICMOS III array is read out simultaneously in four quadrants. This leads to a characteristic jump in the count level at rows 1 and 513. This jump depends on the `DIT` and on the incident flux on the array.

2.5.2 Windowed Reading

The SOFI detector can be windowed. Each window is defined by the starting pixel coordinates and the size of the windowed region. The entire array is still read out by the IRACE controller; however, only the windowed section is transferred to the workstation. This will lead to a slight decrease in overheads.

2.6 Calibration Unit

There is a calibration unit that is located inside the adaptor. This contains a halogen lamp for spectroscopic flat fielding, Xenon and Neon lamps for wavelength calibration. Line identifications are given in the Appendix A.

The halogen lamp is not suitable for flat fielding image data. Use the dome flat field lamp for this. However, the halogen lamp can be used to flat field spectroscopic data. These flats are often called Nasmyth flats. For Nasmyth flats, a night sky spectroscopic flat should be used to take out the spatial response introduced by the lamp.

2.7 Instrument Performance and the Exposure Time Calculator

In the following table we list the zero-point of the broad band filters with the large field objective as measured during July '98, the average background as measured from December '97 to July '98 and detection limit for both point and extended sources. The limits are similar for the small field and spectroscopic objectives. For the detection limits in the spectroscopic modes and for detection limits with the narrow band filters, refer to the SOFI web page, together with recent measurements of the ZPs.

Filter	ZP	Average Background	Detection Limit	
		Mag. sq. arc second	Point Source	Extended Source
J	23.2	15.5-16.1	22.7	22.1
H	23.1	13.4-14.7	21.8	21.4
K_s	22.5	12.8-13.3	20.8	20.4

Table 2.5: Measured SOFI performance for the broad band filters: 1 hour exposure.

The point source detection limits are based on the following assumptions:

- Signal to noise ratio of 5, computed over 21 pixels,
- Pixel scale: 0.29 arc seconds/pixel.
- 1 hour exposure made up of 60 one minute integrations.

- Seeing 0.75 arc seconds.
- Airmass 1.2
- Backgrounds of 16, 14.2 and 13.0 in J, H and K_s respectively.

The extended source detection limits are based on real images taken during the December '97 test nights. The limits were determined for an aperture with a diameter of 3 arc seconds and for a S/N of 4.

The values of Table 2.5 can be re-scaled to different S/N ratios, fluxes (F) and integration times (t) keeping in mind that for background limited performances $S/N \propto F\sqrt{t}$.

Being the read-out noise 12 e^- in the double correlated mode and the conversion factor about 5.5 ADU/e^- background limited performances are reached when $ADU \gg 30$.

2.8 Instrumental Overheads

The fraction of time spent not collecting photons is defined as the instrumental overhead. There are several sources of instrumental overhead, the 0.1 second delay between the reset and the first read, the 1 second it takes to read out the array, the time it takes to offset the telescope between image positions and any remaining time before the next `DIT` starts. Recall that the sequencer is not interrupted unless the `DIT` is changed. It is difficult to give a precise estimate of the instrumental overhead, but here is a common example. A one hour exposure made up of 60 one minute, unguided exposures (`DIT` = 10 and `NDIT` = 6) with telescope offsets in between will take 80 minutes. Guided exposures will take 35 to 50% overheads.

Chapter 3

Observing in the IR

3.1 The IR Sky

Observing in the IR is more complex than observing in the optical. The difference arises from a higher and more variable background and by strong absorption throughout the 1 to 2.5 micron wavelength region.

Shortward of 2.3 microns, the background in dominated by non-thermal emission, principally by aurora, OH and O_2 emission lines. The vibrationally excited OH lines are highly variable on a time scale of a few minutes. Pronounced diurnal variations also occur. The lines are strongest just after sunset and weakest a few hours after midnight. A complete description and atlas of the sky emission lines can be found in the paper Rousselot et al. 2000, A&A 354, 1134.

Long-ward of 2.3 microns, the background is dominated by thermal emission from both the telescope and the sky, and is principally a function of the temperature. The background in K_s can vary by a factor of two between the winter and summer months. It also depends on the cleanliness of the primary mirror. Imaging in broadband K_s and the wide field objective can result in backgrounds of several hundred ADU/sec.

The IR window between 1 and 2.5 microns contains many absorption features that are primarily due to water vapor and carbon dioxide in the atmosphere. These features are time varying and they depend non-linearly with airmass. The atmosphere between the J and H bands and between the H and K bands is completely opaque. The atmospheric transmittance between 1 and 2.5 microns as seen by SOFI is plotted in Appendix B. As the amount of water vapor varies so will the amount of absorption. The edges of the atmospheric windows are highly variable.

These difficulties have led to the development of specific observing techniques. These techniques are encapsulated in the templates that are used to control SOFI and the telescope. In this section we link common observational scenarios with specific templates and we give you some concrete examples. In later sections we discuss some finer points. The templates are described in detail in The SOFI TSF Parameters Reference Guide.

3.2 Imaging

It is not unusual for the objects of interest to be hundreds or even thousands of times fainter than the sky. Under these conditions it has become standard practice to observe the source (together with the inevitable sky) and subtract from it an estimate of the sky. Since the sky emission is generally variable, the only way to obtain good sky cancellation is to do this frequently. The frequency depends on the wavelength of observation and on meteorological conditions. Ideally one would like to estimate the sky more quickly than the time scale of the sky variations. While this could be done with the traditional single-channel photometers, the overhead in observing with cameras and the necessity of integrating sufficient photons to achieve background limited performance are such that the frequency is of the order of once per minute. This sky subtraction technique has the additional advantage that it automatically removes offsets due to fixed electronic patterns (bias) and dark current.

There are two standard techniques to estimate the sky. The first is appropriate for angularly large objects or crowded fields and the second is appropriate for angularly small objects or uncrowded fields.

3.2.1 Large Objects or Crowded Fields.

For objects larger than 20% of the field or for very crowded fields, it is necessary to image the sky and object separately. Unfortunately, it is common that the sky frames will contain other objects, and by Murphy's law, one of these objects will be in the same region as the science object. To avoid this embarrassment, it is standard to obtain several sky images, usually in the context of several object-sky pairs. This technique assumes that the sky fields are sufficiently uncrowded that on any given position of the array most of the images will have sky, and only a minority will have objects. Clearly, a minimum of three sky images are necessary for this technique.

This technique is encapsulated in the template called **SOFI_img_obs_AutoJitterOffset**. The parameters of this template are listed in Table 3.1. While preparing such observations, please keep in mind that the total duration of an imaging OB should never exceed 1 hour. The example corresponds to the maximum duration acceptable.

Parameter signature	Value
Exposure Name	NGC6118
DIT	10
NDIT	6
Number of exposures	12
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Filter wheel 1	Ks
Filter wheel 2	open
Instrument Mode	LARGE_FIELD_IMAGING
Combined Offset? (T/F)	F
Jitter Box Width (arcsec)	20
Sky Offset Throw (arcsec)	600
Rotate Pupil? (T/F)	T

Table 3.1: The parameters in the template SOFI_img_obs_AutoJitterOffset with commonly used values.

In this template, one observes alternatively the object and sky. There are 12 exposures in total, six on the object and six on the sky. The sky positions are randomly chosen to lie on a circle that is centred on the object. The diameter of this circle is set by the parameter "`Sky Offset Throw`." Each of the six sky positions is different. Each of the six object positions are also different. The object positions are randomly chosen to be within a square box that is centred on the object. The dimension of the box is set by the parameter "`Jitter Box Width`." Autoguiding is set by the parameter "`Combined offset`." If selected, guiding is done when the telescope is pointing to the object field. As the

NTT tracks very well and as one usually spends no more than a few minutes on a single position, autoguiding is not required.

At the end of the template the telescope returns to the original position.

The parameter "`Rotate Pupil`" is an option which allows you to rotate the instrument in between the sky an object positions so that the one obtains better sky cancellation. For imaging in filters with high backgrounds, that is the Ks and narrow band filters with central wavelengths greater than 2.2 microns, we recommend that you set this option to T (true).

For a more detailed discussion about guiding options, the algorithm used to compute the offsets, and the reasoning behind the option to rotate the pupil, please to refer to section 3.6.

If you wish to enter the offsets manually, use the template **SOFI_img_obs_JitterOffset**. If one wishes to use a more complex pattern that does not involve observing the object and the sky alternatively, use the either **SOFI_img_obs_Jitter** or **SOFI_img_obs_GenericImaging**. These templates are discussed fully in The SOFI TSF Parameters Reference Guide.

3.2.2 Small Objects or Uncrowded Fields.

If the object of interest is small enough, it is not necessary to take separate sky observations. In this case one can dither within the field and use the object frames to create sky frames. As a rule, the offsets should be greater than 10 arc-seconds, and if very deep exposures are required, the offset vector should not be replicated. For example, an offsetting scheme that is based on a rectangular grid of points will in a deep exposure show faint negative images arranged symmetricly around each real image.

A pseudo-random offsetting scheme (see section 3.6) is used in the template **SOFI_img_obs_AutoJitter**. The offsets are restricted to be within a square box centred on the object.The dimension of the box is defined by the parameter "`Jitter Box Width`." This and other parameters of the template are listed in table 3.2.

Parameter signature	Value
Exposure Name	Hubble_Deep_Field
DIT	10
NDIT	6
Number of exposures	60
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Filter wheel 1	Ks
Filter wheel 2	open
Instrument Mode	LARGE_FIELD_IMAGING
Combined Offset? (T/F)	F
Jitter Box Width (arcsec)	40
Return to Origin? (T/F)	T

Table 3.2: Parameters in the SOFI_img_obs_AutoJitter template with commonly used values.

If the value of the "`Return to Origin`" parameter is true (T), the telescope, at the end of the template, moves back to where it was at the start of the template. In general, autoguiding is not required.

For a more detailed discussion about guiding options and the algorithm used to compute the offsets, please to refer to section 3.6.

If you wish to enter the offsets individually, use the template **SOFI_img_obs_Jitter**. This template is discussed fully in The SOFI TSF Parameters Reference Guide.

3.2.3 Maps of Large Fields

To cover a large area of the sky with a map the template **SOFI_img_obs_AutoJitterArray** is available. This template allows to define an array of positions (NEXPO) through a list of offsets in RA and DEC and to randomly jitter (number of jitter positions defined by NJITT) around each of the offset positions. The parameters of the template are listed in Table 3.3

Parameter signature	Value
Exposure Name	SOFI_Map
DIT	10
NDIT	6
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
NJITT	6
NEXPO	9
Jitter Box Width (arcsec)	40
Filter wheel 1	Ks
Filter wheel 2	open
Instrument Mode	LARGE_FIELD_IMAGING
Combined Offset? (T/F)	F
Return to Origin? (T/F)	T
RA Offset List (arcsec)	0 450 450 0 -450 -450 0 450 450
DEC Offset List (arcsec)	0 0 0 -450 0 0 -450 0 0

Table 3.3: Parameters in the SOFI_img_obs_AutoJitterArray template with commonly used values.

3.2.4 Standard Stars

The IR window between 1 and 2.5 microns contains several large absorption features that are primarily due to water vapour and carbon dioxide in the atmosphere. The edges of the atmospheric windows are highly variable. Unfortunately, the edges of some IR filters, particularly J and K_s, are defined by these absorption features. Thus, when the column density of water vapour is variable, good photometry can be difficult to achieve. On good nights (generally when the humidity is low) it has been possible to achieve better than 1% photometry; however, on most nights this should be considered as the best limit.

To get good photometry you should choose standard stars that are as close as possible to your program objects and you should observe them before and after you observe your program objects. The classical, optical method of determining extinction co-efficients by observing standards over a wide range of airmasses works less well in the infra-red as the extinction co-efficients are not a linear function of airmass.

During the night you should observe at least three different standards and you should observe at least one standard every two hours. On nights where the humidity (which is a rough measure of the water column vapour) is varying considerably, let's say by 40% in one hour, you will need to observe standards more frequently.

When observing standards, two or more images of the standard star are obtained with a telescope shift(s) in between. In this way one image can be used as the reference sky of the other(s). If several images are obtained, the uniformity of the flat-field illumination can be checked.

Several standard star lists are currently available, but it should be noted that each list was created using detectors and filters that differ from the detectors and filters used with SOFI. Note also that most standards were observed with single channel photometers with very wide apertures. Thus close companion stars were probably included. The standards listed in Carter and Meadows (1995, MNRAS, 276, 734) have proved to be very useful, although they may prove to be too bright for SOFI. The more recent NICMOS standards are more suitable as one does not need to defocus the telescope. They will be the standards of choice for most observers. Predefined OBs are available at the telescope for these stars. A list of references to these and other standard star lists as well as useful papers regarding the transformations between one photometric system and another are available at the telescope.

It is important that you take care where the standard star lies on the array. Use the RTD (Real Time Display) to find areas that are clear of bad pixels. Furthermore, check if other objects are in the field. The offset between exposures should not be such that other objects in the field interfere with flux of the standard when one frame is subtracted from another. Alternatively, the standard can be observed in several different parts of the array. A pattern of five exposures with the standard observed once in the centre of the array and once in each of the quadrants is one example. This example is demonstrated in the SOFI template **SOFI_img_cal_StandardStar**.

Parameter signature	Value
Exposure Name	S9104
DIT	5
NDIT	10
Number of exposures	5
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Filter wheel 1	J
Filter wheel 2	open
Instrument Mode	LARGE_FIELD_IMAGING
Combined Offset? (T/F)	F
Return to Origin? (T/F)	T
X offset list (arcsec)	0 75 -150 0 150
Y offset list (arcsec)	0 75 0 -150 0

Table 3.4: Parameters in the standard star template with commonly used values.

In this template the offsets are along array columns and rows and the units are arc-seconds. The offsets are relative. This template is very similar to the template **SOFI_img_obs_Jitter**. Indeed one can use the **SOFI_img_obs_Jitter** template to do the same observation; however, we strongly encourage observers to use the **SOFI_img_cal_StandardStar** template as it is both easier to use and it tags the resulting images as standard star frames for archiving purposes.

In general autoguiding is not required and it is useful to set the "`Return to Origin`" parameter to true.

3.3 Polarimetry

In Polarimetry, a Wollaston prism and a mask wheel consisting of alternating opaque and transmitting strips are inserted into the beam. The width of the transmitting sections are about 40 arc seconds, whereas the width of the opaque sections are slightly larger. Thus, to cover the whole field one needs to take three separate images shifted by 30 arc seconds from eachother. This techniques is embodied in the template **SOFI_ima_obs_Polarimetry**. The parameters for this template are listed in Table 3.5.

Parameter signature	Value
Exposure Name	Planetary_Disk
DIT	1.8
NDIT	10
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Number of exposures	3
Filter wheel 1	J
Filter wheel 2	open
Combined Offset? (T/F)	F
Return to Origin? (T/F)	T
X offset list (arcsec)	0 0 0
Y offset list (arcsec)	-32 32 32
Rotator Offset	0

Table 3.5: Parameters of the polarimetric template with commonly used values.

This example takes three exposures in the *J* band. By default, the polarimetric mode uses the large field objective. Offsets are relative to array rows and columns, are independent of the rotator angle and are in arc-seconds. In this example, three exposures with offsets along the Y-direction are taken. In this way, an entire field can be covered. Observers may wish to include additional exposures with offsets in the X-direction to help with sky subtraction.

To measure the Stokes parameters and hence the degree and direction of linear polarisation, one needs at least one additional set of observations with a position angle different from the first. The usual practice is to take two sets of observations with a rotational offset of 45 degrees. This can be done with the "Rotator Offset" parameter.

There are two ways to do this. In the first method, one includes two observation templates for each polarimetric observation, one with the "Rotator Offset" angle set to zero and the second with the "Rotator Offset" angle set to 45. Alternatively, one can set the rotator angle through the acquisition template (See The SOFI TSF Parameters Reference Guide) and keep the "Rotator Offset" angle zero in both case. Since the rotator axis does not correspond to the centre of the array, the later method is preferable when one is trying to determine the linear polarisation of a single object. For those who wish to map the polarisation over a large field, either method can be used.

Objective	Rotation Centre (x,y)
Large Field	517,504
Small Field	501,505
Spectroscopic Objective	537,502
High Resolution Imaging	447,487

Table 3.6: The mechanical rotation centre for four of the six imaging modes.

3.4 Spectroscopy

3.4.1 Small Objects and Uncrowded Fields

In spectroscopy, like imaging, accurate sky cancellation is important. If the object is small enough, the object can be observed at different slit positions. Sky cancellation is then achieved by subtracting one frame from another. This technique is embodied in the template **SOFI_spec_obs_AutoNodOnSlit**. The parameters for this template are listed in Table 3.7.

Parameter signature	Value
Exposure Name	Hubble_Deep_Field
DIT	60
NDIT	3
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Spectro Mode	LONG_SLIT_RED
Which Slit	long_slit_1
Combined Offset? (T/F)	T
Jitter Box Width (arcsec)	10
Return to Origin? (T/F)	T
Nod Throw Along Slit (arcsec)	60
NINT	3
Number of Cycles	4

Table 3.7: Parameters in the template SOFI_spec_obs_AutoNodOnSlit with commonly used values.

In this template the telescope nods the object between two positions along the slit that are "`Nod Throw Along Slit`" arc seconds apart. For convenience we will call one of these positions, position A and the other position B. At position A the object is observed for 9 minutes and the observer will receive 3 frames (specified by `NINT`), each the average of 3 (specified by `NDIT`) 60 second exposures. The telescope then moves to position B, where it again integrates for nine minutes producing three frames, each the average of three 60 second exposures. This completes one cycle. The number of cycles is defined by the parameter "`Number of AB or BA cycles`." In this particular case the number of cycles is 4, so the total exposure time is 60 x 3 x 3 x 2 x 4 = 72 minutes. If the number of cycles is greater than 1, the telescopes moves in the following pattern: A, B, B, A, A, B, B, A, etc. Between consecutive A or B positions, there is no telescope offset, but one can include random offsets between the A and B positions. This is defined by the parameter "`Jitter Box Width`." In the example given here the 1st and 2nd A positions will differ. Additionally the 1st and 3rd B positions will also differ.

In principle, the nodding frequency should be similar to that used during direct imaging. However, the desire to reach background limited performance forces longer exposures in the spectroscopic modes. As a general rule, one should limit the time spent at any one position to less than 15 minutes.

Although guiding is optional, we recommend that you guide. To do so, set the parameter "`Combined offset`" to true.

For faint objects requiring long `DIT` both modes of observation can be used with the Non Desctructive Read-Out. This is done with the templates **SOFI_spec_obs_AutoNodNonDestr** and **SOFI_spec_obs_GenSpecNonDestr**. In addition to the parameters of Table 3.7 these two templates include those showed in Table 3.8. The array is read a number of times equal to `NSAMP`, for each read-out the signal is sampled `NSAMPIX` times. The minimum `DIT` that can be used for a given `NSAMP` can be calculated, in seconds, as 1.64 × `NSAMP`.

Parameter signature	Value
NSAMP	30
NSAMPPIX	4

Table 3.8: Parameters in the templates with Non Destructive Read-Out and commonly used values.

3.4.2 Extended Objects and Crowded Fields

For more complex nodding patterns or for observations of either extended objects or crowded fields, please use the template **SOFI_spec_obs_GenericSpectro**. This template is discussed in The SOFI TSF Parameters Reference Guide.

WARNING: Frames taken with the NDR mode must be flat-fielded using dome flats taken with the same mode. For this reason a specific templates exists:**SOFI_spec_cal_DomeFlatNonDestr**.

3.4.3 Atmospheric Standards

The issue of flux calibrating IR spectra is still very much an issue of some debate. This section is written not as the definitive method to flux calibrate IR spectra, but rather it is written to illustrate the problems involved and to illustrate various methods.

As the IR window is dominated by time varying atmospheric absorption features that depend non-linearly with airmass, it is necessary to divide object spectra with the spectrum of what we shall call an atmospheric standard (IR spectroscopic standards do not exist). The standard should be at an airmass that is as close as possible to that of the science target, it should be observed immediately after or immediately before the target and it should be observed with the same slit. Atmospheric standards are observed in exactly the same way as the science targets. Use the template **SOFI_spec_obs_AutoNodOnSlit** for this.

It is very important that object and standard star spectra are accurately aligned. A small misalignment will result in poor cancellation of the atmospheric absorption features. Misalignment could be caused by instrument flexure or, when the seeing is smaller that the slit width, by inaccurate centring of objects in the centre of the slit. The spectra can be re-aligned by using the atmospheric absorption features.

Ideally, after the division by the atmospheric standard, one should then multiply by the absolute spectral energy distribution of that standard. However, this information is usually not available, so one has to model the spectral energy distribution of the standard. For hot stars, a blackbody fit to the star may be appropriate, but for stars later than spectral type B, a more accurate description of the energy distribution may be required.

The final step is to flux calibrate the object spectrum. This is done by integrating the object spectrum over one or more broadband filter band-passes and scaling the result with the respective broadband magnitudes.

This is very different to what is done to flux calibrate spectra in the optical. In the optical, atmospheric absorption is a relatively smooth function of wavelength, so it is sufficient to divide extracted spectra by a smoothed standard star spectrum and then multiply by the smoothed absolute energy distribution of the standard. In the IR, accurate spectroscopic standards do not exist.

The choice of which standard to use depends on the which part of the spectrum is of interest. All stars have absorption lines, so the idea is to choose a star which does not have strong features near the wavelength of interest. Hot stars provide relatively featureless spectra; however, they have strong hydrogen absorption lines, so they should not be used as flux calibrators if the region around the hydrogen lines is of interest. Later type stars such as G stars have weaker hydrogen lines, but are contaminated by weak absorption lines. These stars have the additional advantage of being very numerous. Stars of later type should not be used as these stars contain numerous weak lines throughout their spectra. However, such stars have very weak hydrogen absorption and may be usefully employed to determine the strength of hydrogen absorption in the hot stars. In general, IR standards are significantly brighter than optical standards, nevertheless, stars should be fainter than seventh magnitude. Good signal to noise is required for standards star spectra as no smoothing is employed in the flux calibration process. A list of O, F and G type stars with magnitudes appropriate for SOFI spectroscopy is available at the telescope and on the SOFI webpage.

For some observers, this may be all that needs to be done for flux calibration. However, for more accurate results, there is still some work to do. We may want to correct for spectral features in the star used to do the flux calibration. This wavelength dependent correction is called a flat spectrum star correction.

To remove spectral features imposed by the spectroscopic standard, it is customary to observe a star lacking such features. That is, observe a late type star if the spectroscopic standard was an earlier type star and visa-versa if the spectroscopic standard was a late type star. The ratio between the two spectra are formed, a fitted continuum is removed and all regions outside the spectral features imposed by the original standard are set to unity. This is then divided into the extracted spectrum.

3.5 Calibration Frames

3.5.1 Darks

The concept of bias frames with IR arrays does not have the same meaning as CCD bias frames. In the IR, a zero second exposure is not possible. It is better to think of all exposures without direct illumination as dark frames.

Dark frames are taken with the template **SOFI_img_cal_Darks**. The parameters for this template are listed in Table 3.9.

In this template, one can enter a list of `DIT`s and `NDIT`s. If the number of exposures is greater that the number of elements in either of these lists, the list is repeated until the the correct number of exposures have been completed.

The structure seen in these frames is quite complicated. In general it is not a linear function of time. The signal is made of several components: shading, a component which depends on the `DIT` and on the incident flux; heat from the readout amplifiers, commonly referred to as amplifier glow; and classical dark current from the random generation of electron/hole pairs. The heat from the readout amplifiers is a function of the number of reads only whereas the dark current is a linear function of

Parameter signature	Value
Exposure Name	Dark_Frames
DIT LIST	10 10 20 20 10 10
NDIT LIST	6 6 3 6 3 6
Number of exposures	12
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1

Table 3.9: Parameters in the SOFI_img_cal_Darks template with commonly used values.

the time.

It is currently under study whether a dark frame can be generated from frames dealing with each of these components or whether a dark frame can only be generated by taking data in exactly the same way and with exactly the same exposure time as the science observations.

Darks appear to be stable over the period of typical observing run. Thus it is sufficient to take darks once only during the run.

Other than depending on the `DIT`, the shading pattern seen in darks frames also depends on the incident flux. Thus subtracting a dark frame from a science frame with the same `DIT` will not remove the shading pattern perfectly. This issue is discussed in more detail later.

3.5.2 Flat Fields

As in the case of visible, one must also correct for differences in pixel sensitivities. The method for creating flat fields is identical in both the spectroscopic and imaging modes. They are created by exposing alternatively an illuminated and an unilluminated dome panel. The flat-field images are constructed from the difference of the two. This technique is especially important when working beyond 2.3 microns, where it removes the thermal component of the signal, which does not depend on the intensity of the flat-field lamp. Spectroscopic flats must be taken with the same slit as the observations.

Imaging flat-fields can also be obtained from the twilight sky or from the observations themselves. However, dome flats represent better the low frequency sensitivity variations of the array.

Twilight spectroscopic flats cannot be used to flat field data, although they can be used to determine the slit function for spectroscopy of extended sources.

Spectroscopic flat fields can be taken with the halogen lamp in the calibration unit (Nasmyth flat). Again one takes an image with the lamp on and off. The flat is the difference between the two. The optical path length between the Nasmyth flat field lamp and the front window of SOFI is considerably smaller that the path length between the incandescent lamp on the floor of the dome and the front window of SOFI. Thus one will see less of the strong atmospheric absorption features in the Nasmyth flats.

There are four templates to create dome flat fields, two for imaging **SOFI_ima_cal_DomeFlats** and **SOFI_ima_cal_SpecialDomeFlats** and two for spectroscopy **SOFI_spec_cal_DomeFlats** and **SOFI_spec_cal_DomeFlatNonDestr**. Please note that the last template must be used ONLY to flat frames taken with the NDR Mode. In Table 3.10 is an example for imaging dome flats.

The template first takes four exposures in total: the first with the lamp off, then two exposures with the lamp on and then a final exposure with the lamp off. The intensity of the dome flat field lamp is

Parameter signature	Value
Exposure Name	Imaging_Dome_Flats
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Number of exposures	1
DIT LIST	3
NDIT LIST	60
Filter wheel 1	J
Filter wheel 2	open
Instrument Mode	LARGE_FIELD_IMAGING

Table 3.10: Parameters in the SOFI_img_cal_DomeFlats template with commonly used values.

controlled by a panel on the tcs machine. The instrument operator or the support astronomer will adjust the voltage until a level of a few thousand counts is reached.

In this template, one can enter a list of `DIT`s, `NDIT`s. If the number of exposures is greater that the number of elements in either of these lists the list is repeated until the the correct number of exposures have been completed. Each exposure generates a sequence of 4 frames, as explained before. If the parameter "Number of Exposure" is > 1 a corresponding sequence of frames will be generated. The template **SOFI_spec_cal_DomeFlatNonDestr** contains in addition the parameters of Table 3.8.

It was noted earlier that shading, one of the components that make up a dark frame, is a function of the incident flux. This means that the method of creating dome flats described above does not remove perfectly the shading pattern. The effect for most observations is small, and manifests itself as a discontinuity of a few percent in the ZP across the center of the array. For most programs, this is not a major problem. Nevertheless, we have developed a technique to remove this effect, and this technique is embodied in the template **SOFI_spec_cal_SpecialDomeFlats**. This template, in addition to the four frames taken with the template **SOFI_spec_cal_DomeFlats**, takes frames with the mask partially obscuring the array. Each exposure generates a sequence of 8 frames. If the parameter "Number of Exposure" is > 1 a corresponding sequence of frames will be generated (so generally, use 1). These frames are used to estimate the shading. Further details are given in the section describing data reduction.

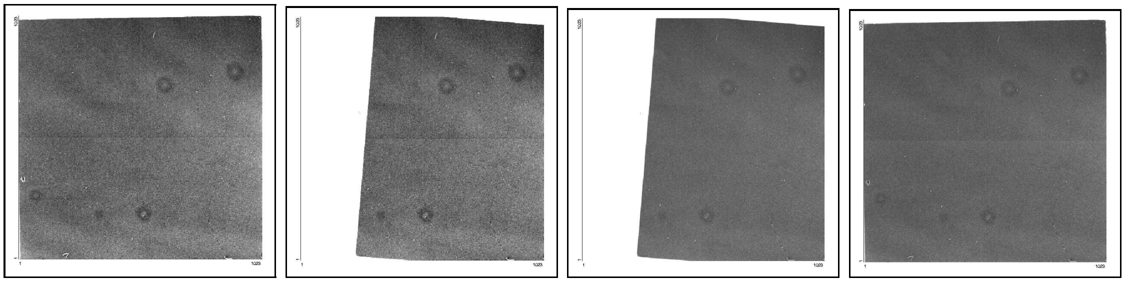


Figure 3.1: Examples of Special Dome Flat images. From left to right: lamp off, lamp off with mask, lamp on with mask, lamp on.

Flat Field frames in the large field mode and J, H and Ks broadband can be downloaded from the SOFI Web page.

Recently, we did a check of the stability of the flats in imagery. A report is available in the web page (http://www.ls.eso.org/lasilla/sciops/sofi/flat_stat.ps). The main result is that, over a period of 2 years, the larger deviation to an average flat is 4% in the worst case, and most of the time the deviation is smaller than 2%. So, it's not necessary to take flats each day during a run as the flats are quite stable. You can take some flats at the beginning of your run, and if you don't do high precision photometry, it'll be enough.

3.5.3 Illumination Corrections

It is often the case that the flat field generated from the dome, the twilight sky or the night sky itself does not represent completely the low frequency sensitivity variations of the array. This can be removed by observing a bright star (a standard preferably) over a grid of 5 to 16 positions across the array. After sky subtraction and flat fielding with the uncorrected flat, the intensities (not the magnitudes) are fitted with a low order polynomial. The surface generated by this fit is then multiplied into the flat to create the corrected flat field. This surface is sometimes called an illumination correction. Without this correction the low frequency variability is between 1 and 3 % depending on the filter, the objective and the type of flat used. Correcting dome flats with a plane improves this to better than 1%.

Illumination Correction Surfaces can be downloaded from the SOFI Web page. Templates for observing a standard star in a array of 16 positions are available in the impex directory of SOFI on wsofi (in the calib directory: **SOFI_Illum_Correction_H**). It should be noted that the illumination correction frame should be used only together with the flat field that was used to create it.

3.5.4 Arcs

Wavelength calibration can be done with the Xenon and Neon lamps in the adaptor. The Xenon lamp has a better distribution of lines and is by itself sufficient to calibrate the wavelength scale of data taken with the low resolution grisms. Both the Neon and Xenon lamps should be used to calibrate the medium resolution grisms.

Arcs are taken with the template **SOFI_spec_cal_Arcs**. The parameters in this template are displayed in Table 3.11. In this template, one can enter a list of `DIT`s, `NDIT`s, grisms, slits and lamps. If the number of exposures is greater that the number of elements in either of these lists, the list is repeated until the the correct number of exposures have been completed. The choices for the lamps are: Xe - Xenon, Ne - Neon, B - Both and N - None. Although, the template enables one to do this, it is best to keep things simple, i.e. just takes arcs with one slit and if another slit is required, run the template again with that slit.

In general you should avoid taking arcs during the night since the high illumination levels of the arcs may cause persistence problems. It is therefore advisable in such cases that you use the arcs in the morning after your run to do the wavelength calibration and then use the atmosphere to check the zero point of the calibration during the night. Both OH emission and sharp atmospheric absorption lines can be used. The P1 branch lines of OH are very good for wavelength calibration. Avoid the blended Q branch lines. Sample spectra for Xenon, Neon, and the main OH emission lines are displayed in appendix A.

Predefined OBs with the correct exposure times are available.

Parameter signature	Value
Exposure Name	Arc_Calibration
DIT LIST	2 2 2 2
NDIT LIST	5 5 5 5
Number of exposures	4
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Spectro Mode	B R
Slit List	1
Lamp List	N Xe N Ne

Table 3.11: Parameters in the SOFI_img_cal_Arcs template with commonly used values.

3.6 Finer Points

3.6.1 Choosing `DIT`, `NDIT` and `NINT`

The appropriate value of `DIT` depends on the intensity of the source and the background. First and foremost, the `DIT` must be kept short enough that moderately bright objects of scientific interest do not saturate. On the other hand, in order to maximise the S/N ratio, one would like to work in background limited instrument performance, i.e. the sky intensity in a single frame should be sufficiently high that the sky shot noise will dominate over the detector read-out noise. In the K_s band, where the sky is bright, this can be reached with `DIT`s of one second. Through the spectroscopic modes, where the background is lower, longer `DIT`s are necessary.

For most observations this will mean a `DIT` between 10 and 60 seconds.

Once `DIT` is chosen, `NDIT` can be determined from the desired offsetting frequency. During good weather conditions one can stay on the object as long as 2 minutes for broad band imaging (5 minutes for narrow band imaging and 15 minutes for spectroscopy) before switching to the sky, and in this case `NDIT` = 2 min / `DIT` is appropriate. If conditions are not so good, e.g. the sky intensity is fluctuating rapidly, or if one simply does not wish to integrate that long, then a lower value of `NDIT` can be used. As a general rule, the switching frequency should be higher for larger fields of view or longer wavelengths.

An additional restriction on the offsetting frequency applies to imaging observations. Unlike equatorial telescopes, the pupil plane of the NTT rotates relative to the image plane and, for reasons which may be due to internal reflections within the objectives, this causes pupil ghosts (images of the telescope support structure near the primary mirror) to appear in sky subtracted images. The effect is greatest when the parallactic angle changes quickest and this occurs when the telescope is near the meridian. The effect is worst for images taken in K_s and the large field objective. To minimise this effect, the beam switching frequency should be such that the parallactic angle does not change by more than 0.5 degrees between exposures. For 'jittered' images the residual effect is at or below the shot noise level when applying standard reduction techniques which involve running sky measurements over ≈ 10 frames. For applications requiring large object-sky offsets, it is advisable to use a strategy which automatically equalises the parallactic angle of the two. This strategy can be employed in two SOFI templates: **SOFI_img_obs_AutoJitterOffset** and **SOFI_img_obs_JitterOffset** ("rotate pupil").

Finally, in the spectroscopic mode only, one can accumulate `NINT` exposures in one position (with small jitter) before moving the telescope to other side of the nod.

Observing Mode	Description
LARGE_FIELD_IMAGING	Imaging with the large field objective
LARGE_FIELD_SO_IMAGING	Imaging with the large field objective
SMALL_FIELD_IMAGING	Imaging with the small field objective
POLARIMETRY	Polarimetric mode
LONG_SLIT_RED	Long slit spectroscopy with the red grism
LONG_SLIT_BLUE	Long slit spectroscopy with the blue grism
LONG_SLIT_Ks	2.0-2.3 micron, long slit spectroscopy with the medium resolution grism
LONG_SLIT_H	1.5-1.8 micron, long slit spectroscopy with the medium resolution grism
DARK	Dark exposures
UNDEFINED	Undefined Mode

Table 3.12: The currently supported SOFI observing modes.

3.6.2 Autoguiding

The NTT tracks very well over most of the sky. For most IR observations, the exposures are short enough that there will be no need to guide. However, if you choose to guide you should be aware that there are two ways to start the autoguider. The first is called box2star. In this mode the guide box is centred on the star before guiding starts. The second is called star2box and in this case the telescope is moved so that the star is centred in the box. In the former case, the telescope does not move before guiding starts; in the latter case, the telescope does move. In the generic templates there will be a choice. In the more specific templates, the choice will be made for you.

In general, if the exposure is longer than 10 minutes one should guide and one should use box2star. This means that most spectroscopic observations must be guided.

3.6.3 SOFI Observing Modes

For SOFI, there are several standard observing modes. For example, there are modes for wide field imaging and long slit spectroscopy. The observing mode defines which optical elements are inserted into the beam. As an example, in the large field imaging mode, the grism wheel is set to open, the mask wheel is set to the large field mask, and the objective wheel is set to the wide field objective. The modes available with SOFI are given in the following table (cf. 3.12).

3.6.4 Template Parameters - Signatures and Keywords

Template parameters can be described either by their signature, which are aimed at being self-explanatory, or by their keyword, which are more meaningful to the OS (Observing Software). When a template is created with P2PP, the signature form of the parameter will be displayed. When the OB is passed to BOB for execution, signatures are translated into keywords. Although users will mostly be faced with signatures, they will later see the corresponding keywords, either when BOB is executing the template, or later in the FITS image headers where some of these keywords are stored.

As an example, setting the filter on filter wheel 1 is done with the signature `Filter wheel 1`, whereas the corresponding keyword is `INS FILT1 ID`.

3.6.5 File Naming and Exposure Number

Exposure names consist of a base name, defined by the parameter "`Exposure Name`," plus an extension of the type _0003.fits. The extension is automatically set. If the base file name is found on disk, the sequential number is automatically incremented. I.e. if there exists a file "fileName_0024.fits" on disk, the first file generated by the template is "fileName_0025.fits". If no file with the base name is found on disk, the sequential number is automatically set to 0001. **DO NOT** use spaces, slashes or other non-alphanumeric characters in file names and target names, otherwise the SOFI OS will report an error.

Signature	Keyword	Default	Description	Input Value
`Exposure Name`	`DET EXP NAME`	–	Exposure Base filename	ngc1068
`Number of Exposures`	`SEQ NEXPO`	–	Number of exposures for the template	10

Table 3.13: File naming signatures and keywords.

The first filename will be ngc1068_0001.fits if no file with the "ngc1068" string was found on disk, and the last file will be ngc1068_0010.fits.

3.6.6 Detector Window

In all templates, **except acquisition templates**, it is possible to window the detector.

Signature	Keyword	Default Value	Explanation
`Number of rows`	`DET WIN NX`	1024	Number of rows
`Number of columns`	`DET WIN NX`	1024	Number of columns
`First column of window`	`DET WIN STARTX`	1	First column of window
`First row of window`	`DET WIN STARTY`	1	First row of window

Table 3.14: Detector Window Signatures and Keywords.

Chapter 4

Phase 2 Preparation and Observing with SOFI

4.1 The VLT environment: P2PP, BOB, OS, TCS, DCS, ICS

Observations at the NTT are done under the VLT environment. In this environment, observers will arrive one to two days before their observations start and, with the support of the introducing astronomer, fully specify their observations.

Observations are described by observing blocks (OBs). OBs are made up of three components: a target, an acquisition template and an observation description. The observation description is itself made up of one or more observation and calibration templates.

Templates are the heart of OBs. They are simplest unit of observation. They are split into three categories: acquisition, observing and calibration. The templates are described fully in The SOFI TSF Parameters Reference Guide.

The P2PP tool enables observers to create lists of targets and observing descriptions and then associate them with an acquisition template to form an OB. Your support astronomer will show you how to do this, for a detailed description of how to use the P2PP tool please refer to the P2PP Users' Manual.

Once the OBs are created, they can be stored either in the local cache which resides on the same machine as where the OBs were created (~/p2pp-cache/ID#) or they can be exported as ASCII files. The exported format of the files are easier to understand than the files copied to the local cache, so they can be edited by one's favourite program and then imported to P2PP at a later date (beware not to change the format of the file).

In visitor mode, P2PP is used to select OBs for execution. Observing blocks are selected by highlighting them with the left mouse button in the P2PP window. Once selected, the instrument operator will transfer the OB to BOB (Broker of Observing Blocks) where they will be executed.

In general, this is all the observer needs to do. Some observer intervention may be required during the execution of an observing block. For example, the user may need to select the correct object to be put in the slit. Everything else is automatic.

BOB is a very versatile tool. It can be used to display the contents of an OB, it can be used to skip templates within an observing block, and it can be used to pause at a template. Thanks to this facility it is possible to fine tune the execution of an OB in real time. We recommend to produce OBs that are as complete as possible.

BOB runs a Tcl script which sends commands to the OS (Observing Software) which then sends commands to the TCS (Telescope Control System), the DCS (Detector Control System) and the ICS (Instrument Control System). The status of the instrument is displayed in the OS GUI (Graphical User interface) and the results are displayed on the RTD (Real Time Display). The results are also sent to the archive machine and the workstation wg5off. This will be discussed in more detail later.

When creating OBs, it is useful to keep them as simple as possible. Do not create complex OBs which switch from one mode to another.

4.2 Arriving at the Telescope.

When you arrive at the telescope, you will be confronted by a vast number of terminals. Most of these are of no concern to you. You will be primarily interested in the terminals at the end of the room. Starting from right to left there is a linux PC which can be used to log into the mountain network and then to the outside world (drlntt). Next to this is the terminal wh5dhs where you run P2PP. Immediately to the left of wg5dhs is wg5off, where you can run IRAF, MIDAS, eclipse, IDL and other useful programs. From here you can access and examine your data. Immediately to the left of the wg5off terminals is the dual screen terminal for EMMI. To the left of this terminal will be the terminal that runs BOB. And finally the next terminal is a dual screen terminal displaying the SOFI OS GUI and the RTD (Real Time Display). You will use the RTD on this terminal very often during your run.

When you arrive at the telescope, the entire system will have been started for you by the daytime operator. During the night you will have a telescope/instrument operator (TIO). It is important to emphasise that the telescope/instrument operator will be the one controlling BOB and SOFI. You as an observer will be selecting OBs for execution via P2PP.

The TIO is responsable for the operation and safety of the telescope and instrument; he has the authority to refuse an action that would jeopardize this safety, this include closing the telescope in case of dangerous weather conditions.

On the terminal, wg5off, do the following.

- In a workspace of your choice you can start either an IRAF or MIDAS. Both reduction packages are supported. Your data is stored as FITS files in the directory /data/raw/yyyy-mm-dd/. We suggest that you do all your reductions in this directory. At the end of the night or the end of your run, you can save the raw data and any reductions to the DAT drive attached to this machine. Observers are responsible for saving their own reduced data.
- In another workspace, click the mouse button in the window free area of the screen to bring up the TCS status panel . This panel shows the status of the telescope.

On the terminal wg5dhs, do the following.

- If required, login to this terminal as `visitor`. Your introducing astronomer can provide the password.
- In a workspace of your choice, click the mouse button in the window free area of the screen to start P2PP using the mouse (data flow > P2PP observations VM). You will need to login with a username and password. If you do not have it, ask your introducing astronomer.

You are now ready to observe.

4.2.1 Image Analysis

The optics of the NTT are actively controlled, and to get the best out of the NTT, frequent correction to the optics are necessary. The telescope aberrations are determined by examining images of a guide star recorded through a Hartmann mask. The process is called image analysis. Its outcome is used to compute corrections to the optical configuration, which are applied as deformations to the primary mirror and as displacements of the secondary along three axis.

As most exposures in the IR are relatively short, the image analysis is done off line. Time spent doing image analysis is not spent on your source, thus image analysis should be used wisely. It usually takes 5 to 10 minutes to perform an image analysis and verify the result. Once, done the telescope will be at the correct focus. It is no longer necessary to check the focus after image analysis.

How frequently one does an image analysis depends on the required image quality. Here are some hints on how frequently it should be done.

i) If image quality needs to be better than 1.0", image analysis should be done if the altitude changes by 20 degrees. For long integrations, where the source is changing altitude, one should perform the image analysis at an altitude that is 20 degrees higher if the source is rising or 20 degrees lower if the source is setting. The analysis should be repeated once the altitude of the object differs from the altitude where the previous image analysis was done by more than 20 degrees. In this way the object is never observed more that 10 degrees from the last image analysis.

ii) If the image quality does not need to be so good, (this is usually the case for spectroscopic observations) then perform the image analysis once at the beginning of the night. It should be done with the telescope at an altitude where the bulk of the observations will be done. Typically, this is at 60 degrees (Zenith Distance 30 degrees).

iii) Good focus is very important. Poor focus can result in distorted images if any aberrations are present. In fact distorted images are a good sign that either the telescope needs to be refocused or another image analysis needs to be done. The focus depends linearly with the temperature of the four serurriers. The co-efficient is 0.079 mm of M2 movement per degree. In good seeing, a displacement in M2 of 0.03 mm induces a noticeable degradation in the image quality. So if the temperature has changed by 0.5 degrees or more since the last focus, one should refocus. On La Silla, the temperature changes quickest during the first hour of the night.

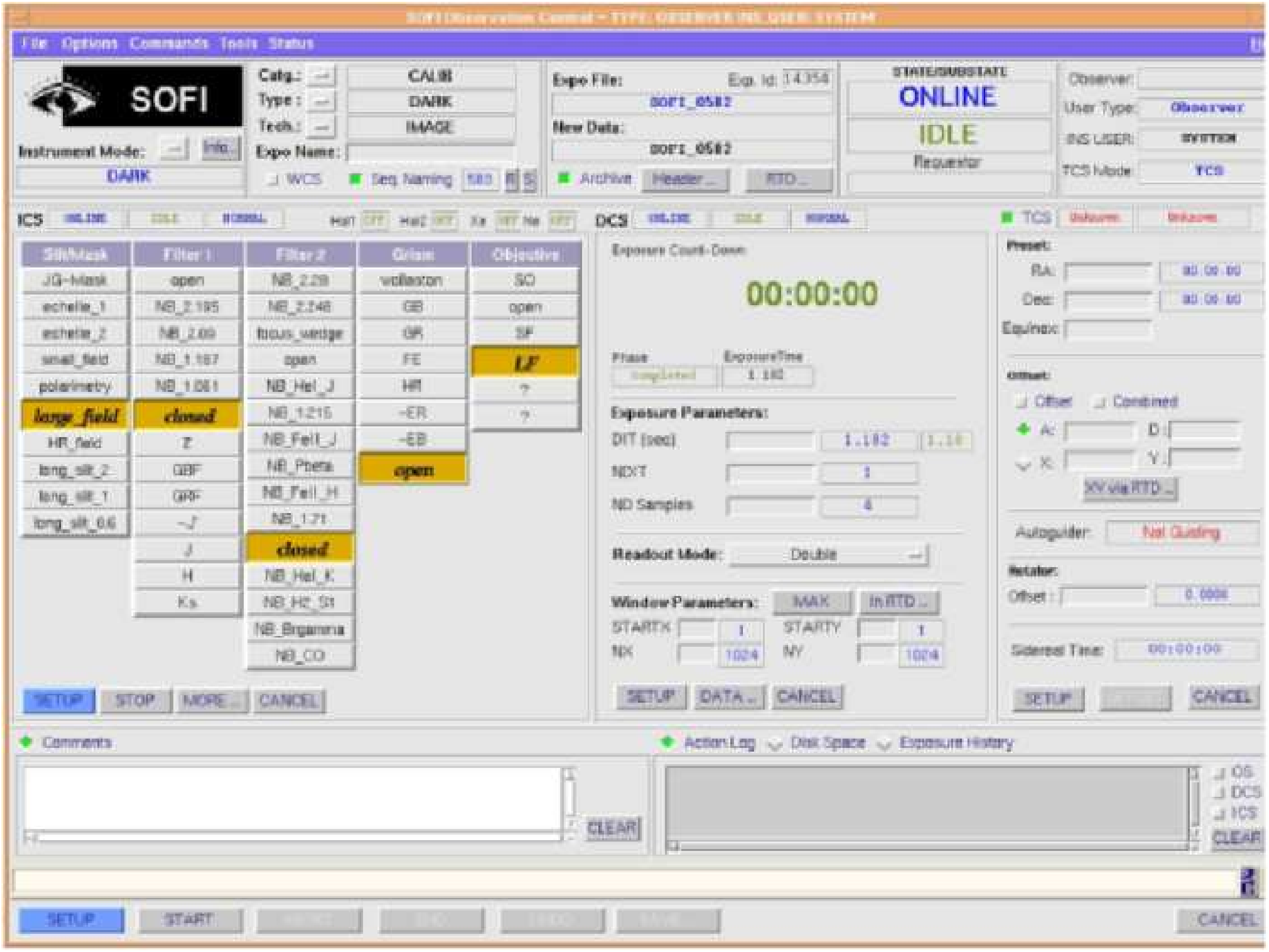
iv) During long integrations, greater that five minutes, it is possible to run the NTT is "closed loop", that is, the optics are adjusted during the observations. For SOFI, integrations are usually shorter. As a general guideline, however, you should trust the TiO's experience.

4.2.2 Focusing

Focusing can be done with the focus pyramid that produces five separate images There is a specific template to do the focusing. The use of this template is described in The SOFI TSF Parameters Reference Guide. Note that the image analysis normally correct the focus, so the template is used mostly as an health check.

4.3 The SOFI OS GUI Panel

The SOFI OS GUI panel is used by the instrument operator to show the status of the instrument. It can also be used to setup the instrument, the detector, execute exposures and even point the telescope. A detailed description of this panel is given in the OS manual (VLT-MAN-ESO-14100-1510). In addition to the OS GUI panel, there are various panels related to ICS, DCS and IRACE and a large number panels that show the status of the instrument and the detector. These panels are not of direct interest to the observer.



Catg.: CALIB
Type: DARK
Tech.: IMAGE
Instrument Mode: DARK
Expo Name:
Expo File: SOFI_0582
Exp. Id: 14354
New Data: SOFI_0582
STATE/SUBSTATE: ONLINE IDLE
Requestor
Observer:
User Type: Observer
INS USER: SYSTEM
TCS Mode: TCS
Exposure Count-Down: 00:00:00
Phase: completed
ExposureTime: 1.182
DIT (sec): 1.182
NDIT: 1
ND Samples: 4
Readout Mode: Double
STARTX: 1
STARTY: 1
NX: 1024
NY: 1024
RA: 00:00:00
Dec: 00:00:00
Autoguider: Not Guiding
Rotator Offset: 0.0000
Sidereal Time: 00:00:00

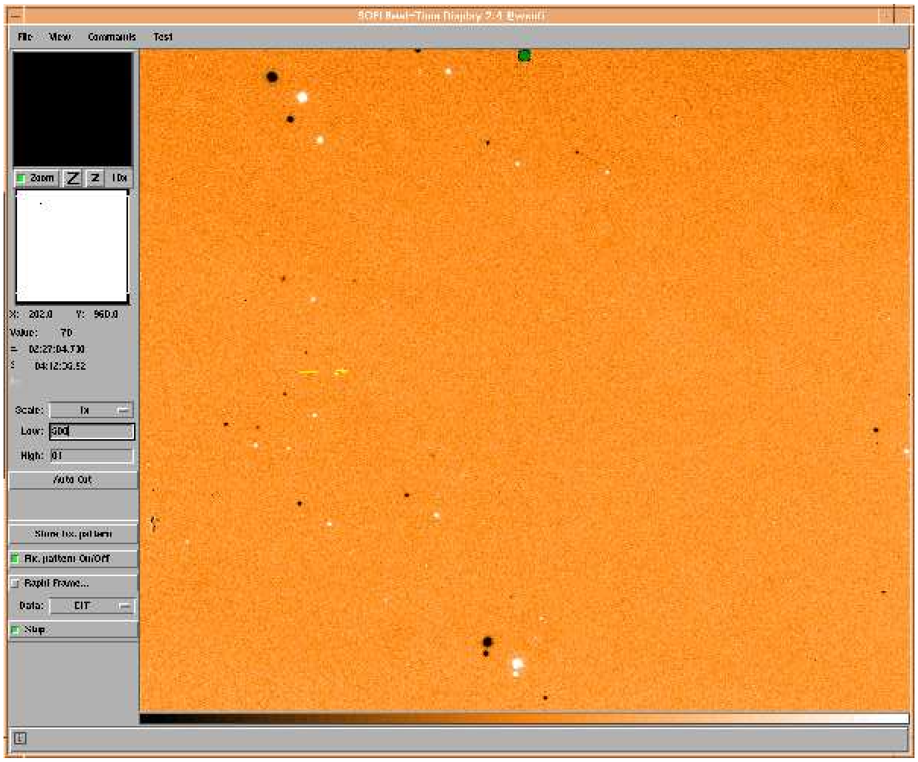
Figure 4.1: OS of SOFI

We do not allow observers to use this panel to start exposures, as it is far more efficient to observe with OBs running on BOB. Furthermore, data archiving, a fundamental requirement at the NTT and the VLT, is only possible if frames are accurately classified. This will always be the case if OBs are used, but this is not always true if exposures are started from the OS GUI. The OS GUI will be used only for trouble shooting.

4.4 RTD

The SOFI RTD (Real Time Display) is a versatile tool which one uses frequently. As the array is continuously read out, images are continuously displayed on the RTD. During acquisition or when the instrument is idle, the data is not written to disk.

A very useful feature of the RTD is the ability to store a frame into memory that is subsequently subtracted from incoming frames. This is essential for recognising faint objects on backgrounds with



X: 202.0 Y: 960.0
Value: 70
02:27:04.700
04:12:36.52
Scale: 1x
Low: 500
High: 01
Data: DIT

Figure 4.2: Real Time Display, with the "Store Fixed Pattern" option enabled.

significant structure. The stored frame is called a fixed pattern and to activate this feature, click on the button labelled `Store Fixed Pattern` on the RTD screen and the current image will be stored. Click then on `ON/OFF....` to subtract the stored images from the following ones. You'll probably have to click on the button labelled `Auto Cuts` or edit the cut levels directly to see the image. Clicking on `Store Fixed Pattern` again will load a new fixed pattern.

The RTD can display each individual frames or it can be used to display the average of `NDIT`frames. The option is selected from the button labelled `DIT`if the RTD is displaying each frame or INT if the RTD is displaying the average of `NDIT`frames.

The menus on the top left hand corner of the RTD can be used to activate sub-windows which the observer may find useful. The `pick object` sub-window can determine the centroid and FWHM of selected objects, in pixels. The `statistics` sub-window can be used to display the statistics of a region that can be defined by the cursor. The `cuts` sub-window can be used to plot a trace that can be defined by the cursor, which is especially useful to check the count levels in spectra.

The RTD display is also used with the acquisition templates to place objects of interest into slits, into the clear portion of the polarimetric mask or to other positions on the array. The interaction between the RTD and the acquisition templates is described more fully in The SOFI TSF Parameters Reference Guide.

4.5 The Data Flow Path

The raw data passes from the detector to the IRACE controller where pre-processing of the data occurs. Exactly what the pre-processing does depends on the readout method The data is then written to disk as FITS files on the instrument workstation (wsofi) and displayed on the RTD.

Copies of the data are then sent to the archive (wg5dhs) and the computer used by the astronomer (wg5off). It is the later computer from which the observer can access the raw data. They are stored in the directory /data/raw/yyyy-mm-dd/ and have filenames which reflect the universal times when they were created.

4.5.1 The Calibration Plan

The calibration plan aims to ensure that all data stored in the archive can be fully calibrated. These calibration data are taken on a routine basis, both by observers wishing to calibrate their own data and by the observatory support staff. Observers are encouraged not to rely on the calibration plan to provide them with these data, but to take their own calibration data.

4.6 At the End of the Night and at the End of Your Run

We will provide you with one set of CDs with all the raw data that were acquired during your run. If you need mpre than one set, you should make the copies yourself (we can provide blank CDs or tapes). I fyou want to save reduced data, you must do it yourself. In that case, you should save a copy of your data at the end of the night. Do not do it at the end of your run. It is common to create over 2Gb of data per night with SOFI. Leaving the data saving until the end of the run may mean that you miss your plane! The data is stored in the directories /data/raw/yyyy-mm-dd/ on the machine wg5off. You can use the DAT drive that is located next to the work station (ask TiO).

At the end of your run you should fill out the End of Mission Report. This can be done via Netscape. Go to the La Silla home page:

`http://www.ls.eso.org/lasilla/index.html`

and click on *End of Mission Report.*

Chapter 5

Data Reduction

This chapter does not aim to be the ultimate guide to reducing SOFI data but it does outline the general steps and it does provides useful tips. It represents the experience the NTT team has gained in reducing data from SOFI. This section of the manual will evolve with time and we are very keen to hear of any suggestions that people may have.

There are two read out methods available with SOFI, NDR and DCR. Data taken in one readout method should **NOT** be used to calibrate data taken in another.

The exposure time keyword represents the total integration time for a single image, i.e. `DIT`x `NDIT`. As the image you receive is the **average** of `NDIT`exposures of `DIT`seconds, the correct number to use for flux calibration is `DIT`and not the value given in the exposure time keyword.

5.1 Imaging

5.1.1 Subtracting the Dark Frame

First and foremost, a SOFI dark frame changes with the `DIT`, so if this frame is subtracted from other frames, the `DIT`must be identical.

Secondly, the underlying bias pattern to any image is a function of the flux incident on the array, so it is not always useful to subtract the dark frame. In cases where the mean count level is low, for example narrow band images, the dark frame is a good approximation to the underlying bias pattern. In cases where the mean flux level is high, for example broad band images, the dark frame is a poor approximation to the underlying bias pattern, so subtracting it serves no real purpose.

5.1.2 Sky Subtraction

This is a critical operation, which depends on how many frames one has at one's disposal. In general, the more frames you have, the better the results.

a- Jitterred Observations

Here is a procedure to remove the sky from a stack of n jittered frames, where n is large.

i) For each image, take the 10 images that were taken closest in time. These images will be used to estimate the sky.

ii) Scale these 10 images to a common median and flag the two highest and two lowest pixels. From the unscaled images, reject the flagged pixels and take the average of the remaining pixels to form the sky frame. Clearly, there are many ways to reject pixels. Furthermore, the scaling can be either additive or multiplicative. We encourage you to experiment at this point.

iii) Scale the sky image to have the same median as the image from which it will be subtracted and subtract it.

b- Observations With Offset Skies

This can be done in two ways.

a) If the observation was done with alternating object and sky frames one can subtract individual sky frames from the corresponding object frames. This will mean that the sky-subtracted object frames will have negative images of objects that are in the sky frames. If the number of object-sky pairs is large enough, the sky-subtracted object frames can be combined to remove the negative images.

b) One can also combine the sky frames first before sky subtraction. The skies are combined in a similar way to that for dithered observations. The median of the sky is scaled so that it matches that of the object frames and then the resulting image is subtracted from each object frame.

5.1.3 Flat Fields and Illumination Corrections

Creating a good flat field for SOFI data is difficult. The simplest way of creating flat fields is to subtract an image of the dome flat field screen with the dome lamp off from an image with the dome lamp on. This flat field has two short-comings. Firstly, the shade pattern of the array is a function of the flux, so the shade pattern in the image with the lamp on is different from that in the image with the lamp off. Thus the difference of the two will contain a residual shade pattern. Secondly, the illumination of the dome panel is slightly different from that of the sky. Both these effects are at the 1-2% level and both can be removed.

The residual shade pattern can be removed if the **SOFI_ima_cal_SpecialDomeFlat** template was used. This template takes the usual sequence of images with the dome lamp on and off and, in addition, it takes the same set of images with the mask wheel vignetting the array. The vignetted part of the array is relatively free of scattered light, so it can be used to estimate and remove the shade pattern. However, this estimate of the shade pattern is valid for the frame that is vignetted and it is not valid for unvignetted frame. The difference can be estimated from a region that is common to both the vignetted and unvignetted frames. The method is outlined below.

i) Collapse the following image sections along detector rows to form one dimensional images: columns 50 to 150 in the vignetted image, columns 500 to 600 in vignetted image and columns 500 to 600 in the unvignetted image. For reference, call these images A, B and C.

ii) The difference between the shade pattern in the vignetted and unvignetted images is C-B. As the intensity of the flat field lamp is relatively unstable one usually sets the mean of (C-B) to zero.

iii) The shade pattern in the unvignetted frame is then A+(C-B) and this one dimensional image should be subtracted from the unvignetted frame.

iv) Steps i) to iii) should be done for the images with the lamp on and the images with the lamp off. Once the shading pattern is removed for both, one subtracts the image with lamp off from the image with the lamp on to form the flat field.

A small MIDAS/IRAF procedure performing these steps is available at the telescope and from the SOFI web page in the Data Reduction section, named special_flat.cl and midas_specialflat.prg.

The residual illumination pattern is removed by dividing the flat field with what is often called an illumination correction. The illumination correction is created by fitting a plane to the fluxes (not magnitudes) of a star that is scanned over a grid of 9-16 positions across the array. Updated Illumination Correction Surfaces can be downloaded from the Web Page of SOFI.

Twilight sky flats and flats created from the observations themselves can also be used to flat field the data. However, these frames suffer from the same problems as the uncorrected dome flats and, in the case of the shade pattern, it is not clear how they can be corrected.

5.1.4 Interquadrant Row Cross Talk

When a bright source is imaged on the array a "ghost" is produced that affects all the lines where the source is and all the corresponding lines in the lower, or upper, part of the detector. Though the effect is not completely understood it is well described and can be easily corrected. The intensity of the ghost is in fact 1.4 10^{-5} × the integrated flux of the line. A complete description of this phenomenom can be found at:

`http://www.ls.eso.org/lasilla/Telescopes/NEWNTT/sofi/crosstalk.pdf`

5.2 Long Slit Spectroscopy

5.2.1 Sky Subtraction

In most cases, one simply needs to subtract one image from another. This should remove most of the night sky emission. The residuals can be removed in the extraction process.

5.2.2 Flat Fields

Spectroscopic flats are taken with the dome flat field screen. Like imaging flats, one subtracts an image with the dome lamp off from an image with the dome lamp on. These flats also suffer from the shortcoming that the shade pattern is not perfectly removed. The slits do not cover the entire chip; there is a region approximately 50 pixels wide which is free of direct illumination. It may be possible to use this region to estimate the residual shade pattern and correct the flat.

5.2.3 Arcs

For the red and blue low resolution grisms, it is sufficient to use the Xenon lamp for wavelength calibration. For the new medium resolution grism, both the Xenon and Neon lamps should be used.

The main Xenon and Neon lines are identified in Appendix A. For the medium resolution and red grisms, a cubic fit to calibrate the dispersion is adequate. For the blue grism, a quartic fit is better.

5.2.4 Removing Slit Curvature

Spectra taken with all SOFI grisms show slit curvature. For the red and blue grisms, the curvature amounts to a few pixels from the middle of the slit to the edge, and is well fitted with a quadratic. For most observers, removing the slit curvature is an unnecessary step. Observers who observe extended objects may want to correct it.

The correction is done by doing a 2-dimensional wavelength solution to arc spectra and both MIDAS and IRAF have tasks to do this. For the red and blue grisms a quadratic in the slit direction and a cubic or quartic in the wavelength direction is adequate. There are no cross terms.

For the medium resolution grism, the slit curvature is larger. As yet, we have not tried to do a 2 dimensional wavelength solution to arc spectra taken with this grism.

5.2.5 Removing Atmospheric Features and Flux Calibration

IR spectra are dominated by atmospheric absorption features. To remove these features it is customary to observe a star with a featureless spectrum at a similar airmass to the that of the target.

Removing atmospheric features is a critical operation. In general, the spectra of the atmospheric standard and the spectra of the science target will not have exactly the same wavelength scale. They may differ by as much half a pixel. This could be caused by internal flexure within the instrument or by the science object and the standard being on different parts of the slit. Thus, before dividing the standard into the science target, one should use the atmospheric absorption features in both to realign the spectra.

After removing atmospheric features, one must multiply the divided spectrum with the true spectrum of the standard. As the latter is usually not known with any great precision, one must model the spectrum of the standard. This can be either a blackbody in the case of hot stars or a something more precise in the case of cooler stars.

The only sensible way to do flux calibration is to observe the science target in one or more broad band filters and scale the spectrum so that it agrees with the broadband measurements. In this way an absolute calibration of 5% is achievable.

5.3 Polarimetry

As in the imagery case, you should start to use a bad pixel mask that you can retrieve at `http://www.ls.eso.org/lasilla/Telescopes/NEWNTT/sofi/setup/bad_pix.html`. Then, you have to apply the flat field correction to take into account the sensitivity distribution of the chip. The flat field exposures should be performed using the same filter as the object exposures and the Wollaston prism in the optical path. Since the whole instrument rotates in order to provide a certain orientation of the Wollaston prism, separate exposures at different orientations are not required. We recommend to take dome flats, as using the sky map, some ghosts of the object on consecutive images may result in a wrong flatfield especially at the position(s) of the object. Exposures with the lamp OFF and with the lamp ON must be combined to obtain the final flat field:

$$\text{FF} = (\text{lamp\_ON\_a - lamp\_OFF\_a}) + (\text{lamp\_ON\_b - lamp\_OFF\_b})$$

The final flat field is polarized,i.e., the median value of the upper field is different from the median value of the lower field. However, this problem can be overcome by an independent normalisation of the flat field in each field.
A further artificial polarization is introduced due to the deviation of the transmission ratio of the Wollaston prism (idel: 50%:50% = intensity upper:lower beam). Three alternatives for the correction of the wrong transmission ratio are proposed (to see them in detail, please read the technical report available in `http://www.ls.eso.org/lasille/Telescopes/NEWNTT/sofi`):

- Use the factor of $C_{Ks} = 0.968$ and $C_J = 0.954$.
- Since the sky is also affected by this effect, a good measure for the intensity ratio of both beams can be derived from the median of the lower/upper image. This method may not be applied if the polarized object covers a large fraction of the lower/upper image (because then the median value may be influenced by the possibly polarized object) and moreover, this method only works properly if the background radiation of the sky is unpolarized and the images are not affected by scattered moonlight.
- Fitting a $cos(2\theta)$ function to the intensity of the object on the image as a function of the orientation (θ) of the Wollaston prism (see Ageorges 2000, `http://www.eso.org/~nageorge/Pola/`

`sofipola.html`).

The next step is the sky subtraction: since the intensity of the background radiation is an additive component to the intensity of the object, the subtraction of the sky will also result in the removal of the contribution of the sky polarization to the net polarization of the object. Therefore, the sky has to be estimated and substracted independently for both the upper and the lower field.

Finally, the remaining instrumentation polarization is expected to be mainly caused by the reflection on the tertiary mirror M3. It should therefore depend on the altitude angle of the telescope. However, the remaining instrument polarization was found to be < 0.3% (Ks band) and < 0.4% (J band) (see Appe. B of the technical report for more details). Since the (statistical) error of the results from which these limits have been derived is in the same order of magnitude, a possible contribution by the mirror M3 could not be extracted.

If you pan to do polarimetric observations with SOFI we recommand to read carefully the three following reports:
`http:///www.ls.eso.org/lasilla/Telescopes/NEWNTT/sofi/pol/report.ps`
`http:///www.ls.eso.org/lasilla/Telescopes/NEWNTT/sofi/pol/tech_rep_polarimetry.ps`
`http://www.eso.org/~nageorge/Pola/sofipola.html`

Appendix A

Calibration Arcs

The adaptor contains both Xenon and Neon lamps. The Xenon lamp produces an even spread of lines for both the red and blue grisms. It is well suited for wavelength calibration. Figure A.1 show the main Xenon lines for the blue grism. There are two electronic ghosts, caused by the very bright lines near one micron, between 1.35 and 1.4 microns. Figure A.2 shows the main Xenon lines for the red grism. The continuum in the red is thermal emission from the lamp.

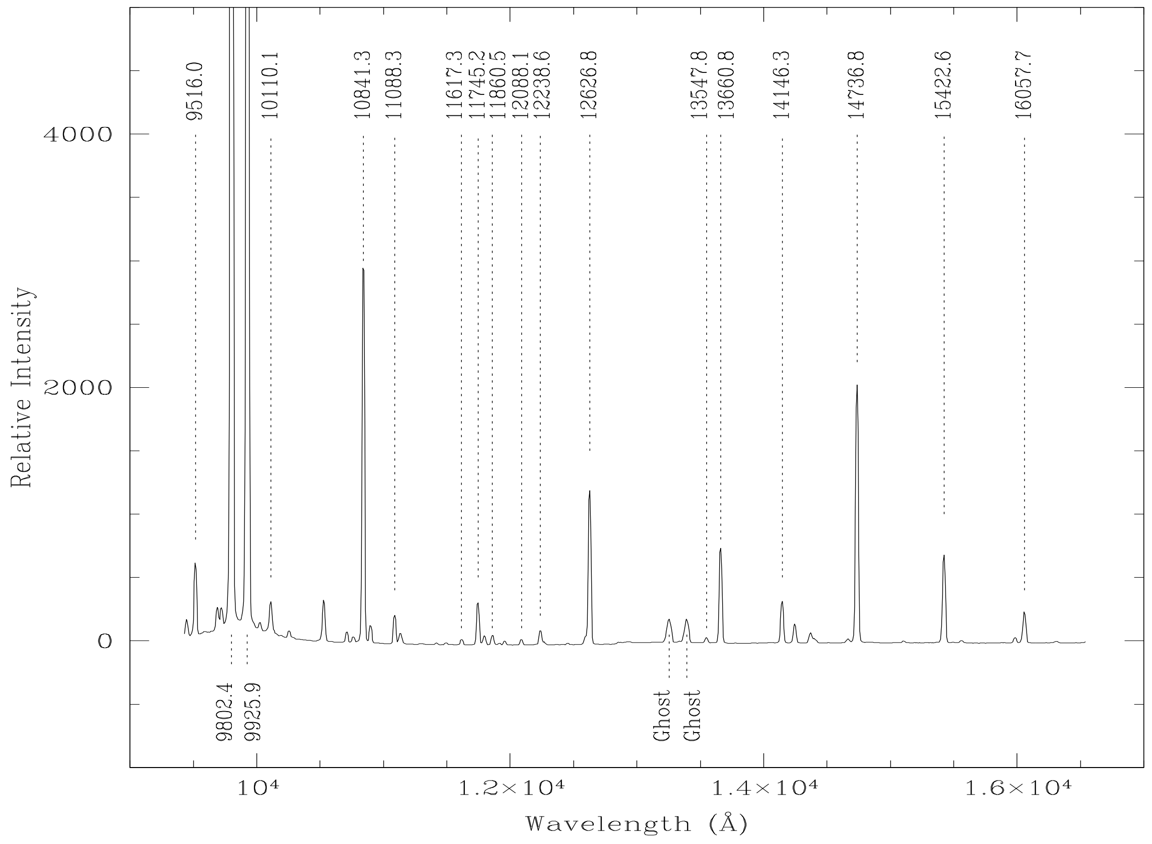


Figure A.1: A Xenon arc spectrum taken with the blue grism. The main lines are marked.

Both the Neon and Xenon lamps should be used to calibrate the medium resolution grism. Figures A.3, A.4, A.5 and A.6 show the main Xenon and Neon lines.

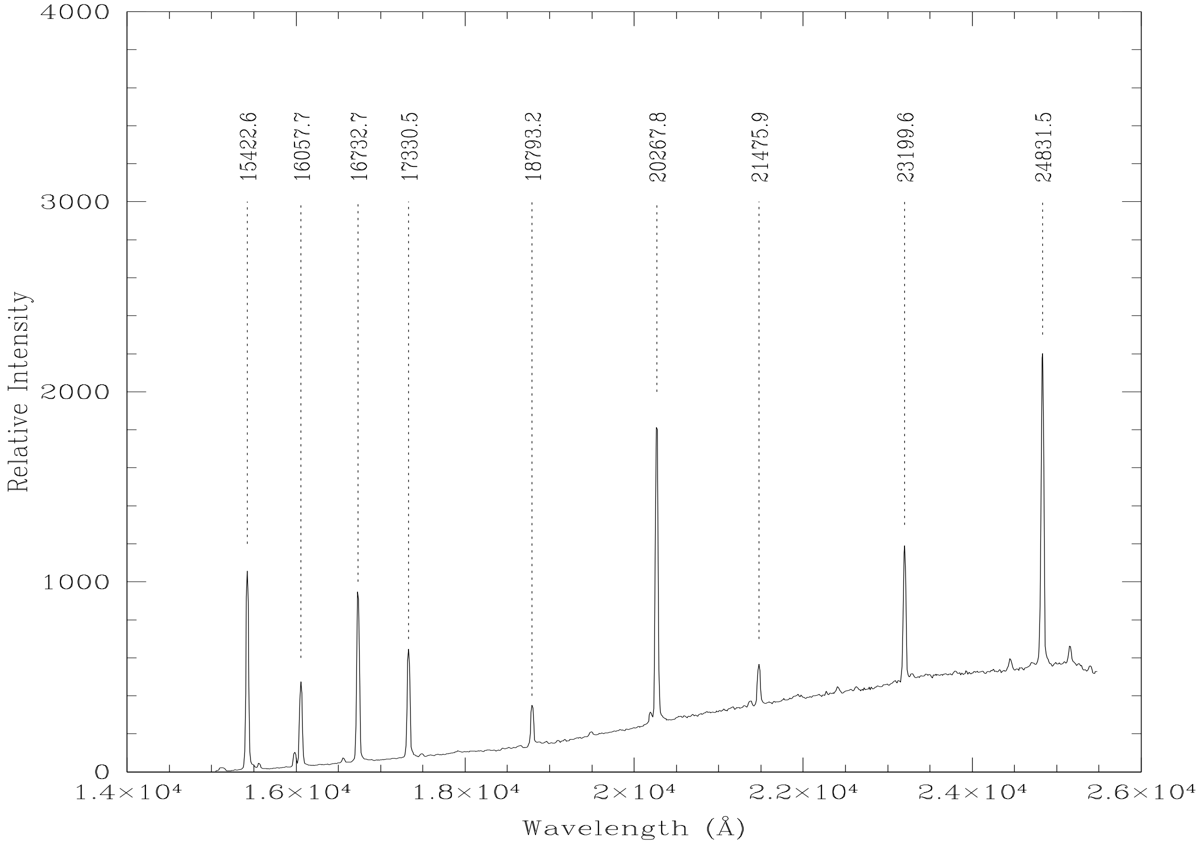


Figure A.2: A Xenon arc spectrum taken with the red grism. The main lines are marked.

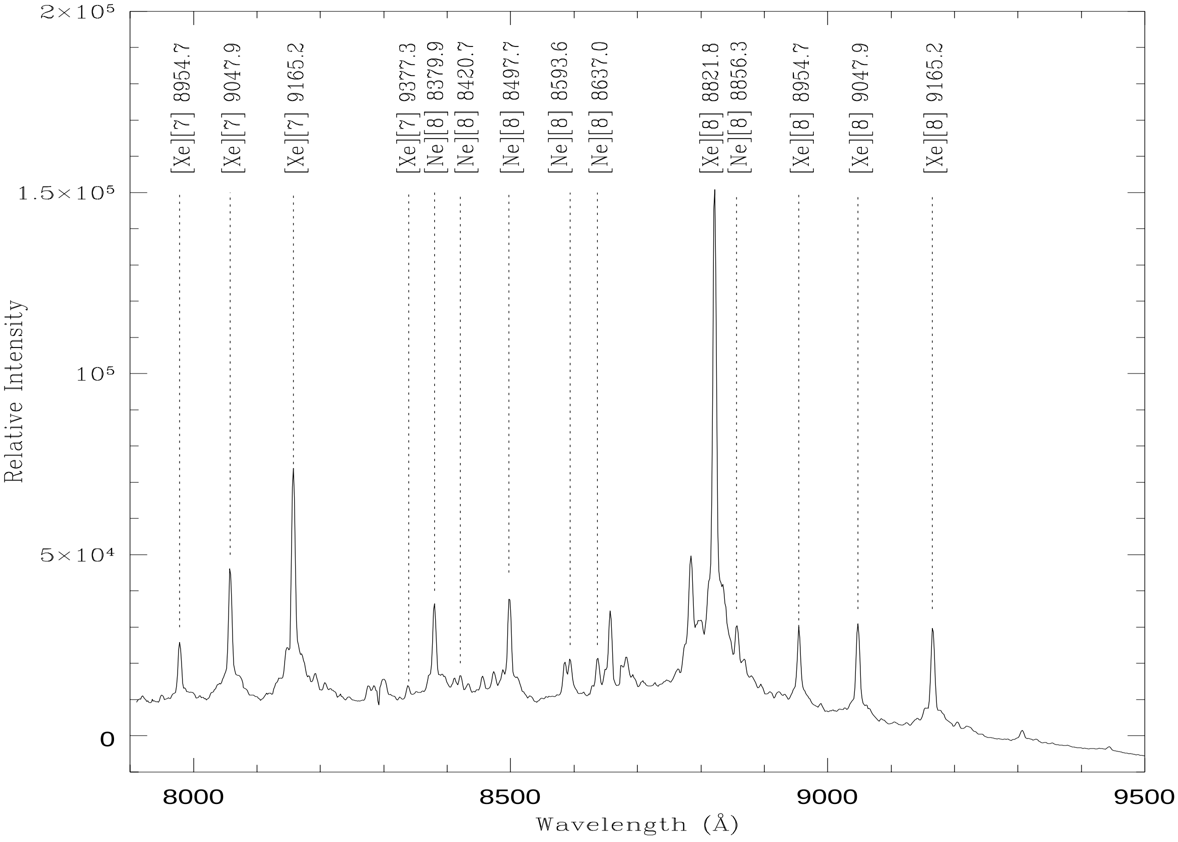


Figure A.3: A Xenon and Neon arc spectrum taken with the medium resolution grism and the Z filter. The main lines are marked.

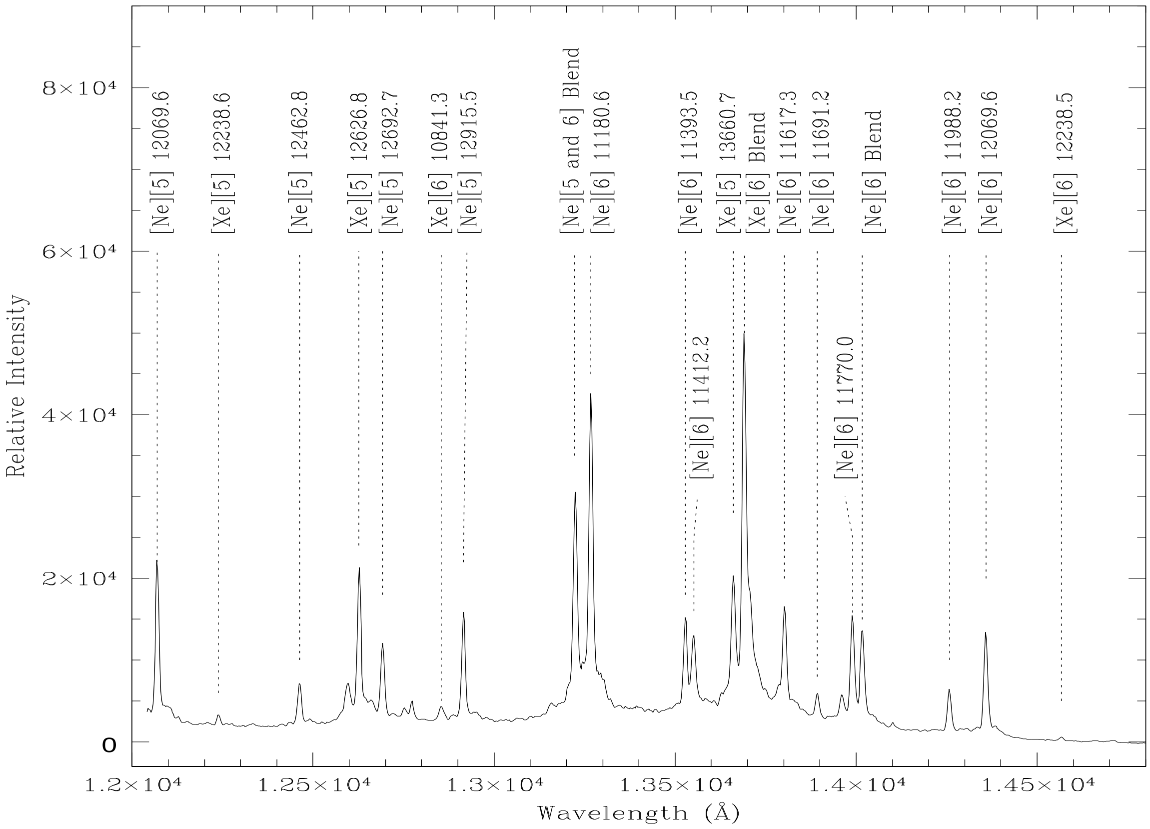


Figure A.4: A Xenon and Neon arc spectrum taken with the medium resolution grism and the J filter. The main lines are marked.

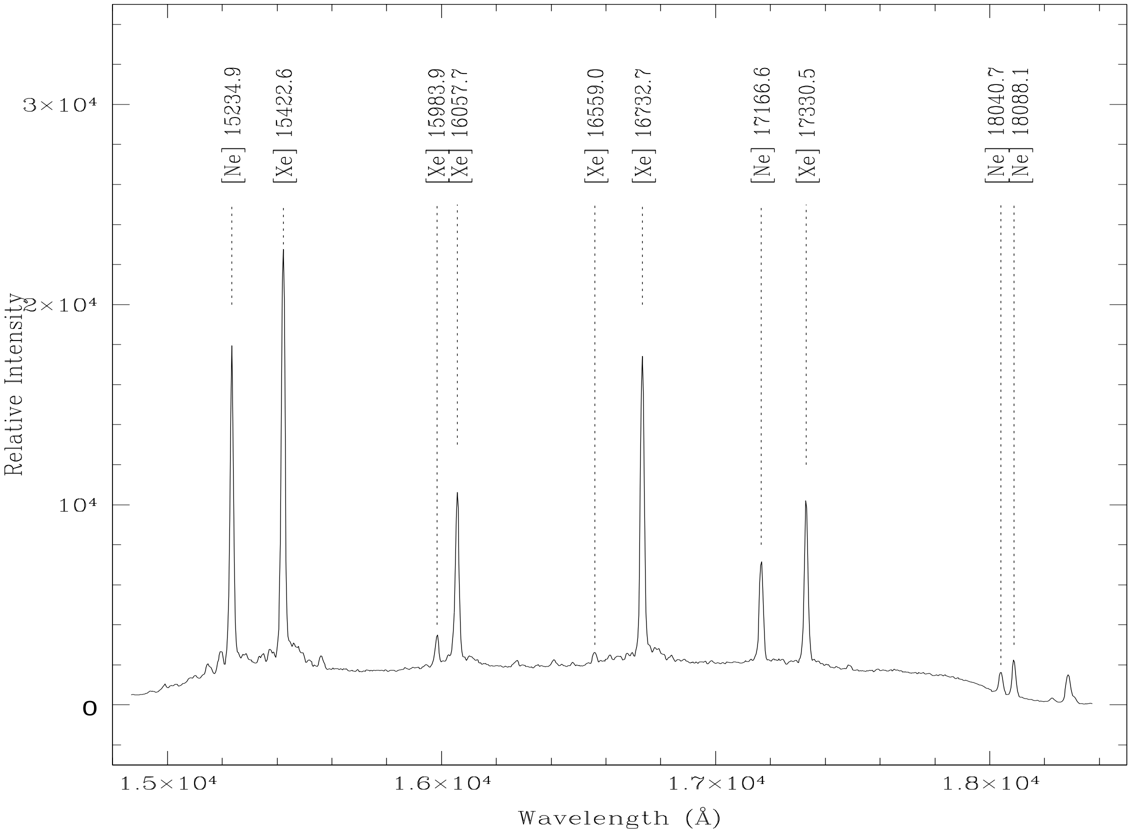


Figure A.5: A Xenon and Neon arc spectrum taken with the medium resolution grism and the H filter. The main lines are marked.

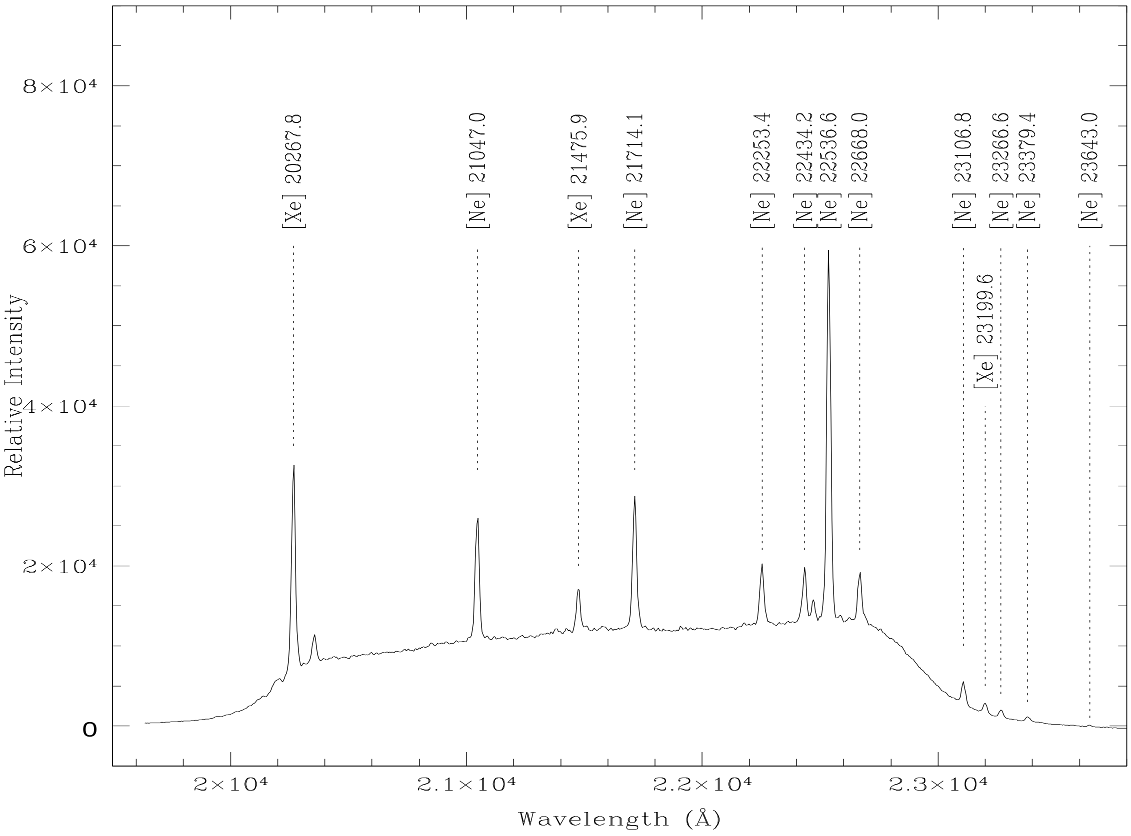


Figure A.6: A Xenon and Neon arc spectrum taken with the medium resolution grism and the Ks filter. The main lines are marked.

Appendix B

Atmospheric Absorption

In Figure B.1 the atmospheric transmission in the 0.8 to 2.5 micron region is plotted as a function of wavelength. Also plotted are the pass-bands for all SOFI filters.

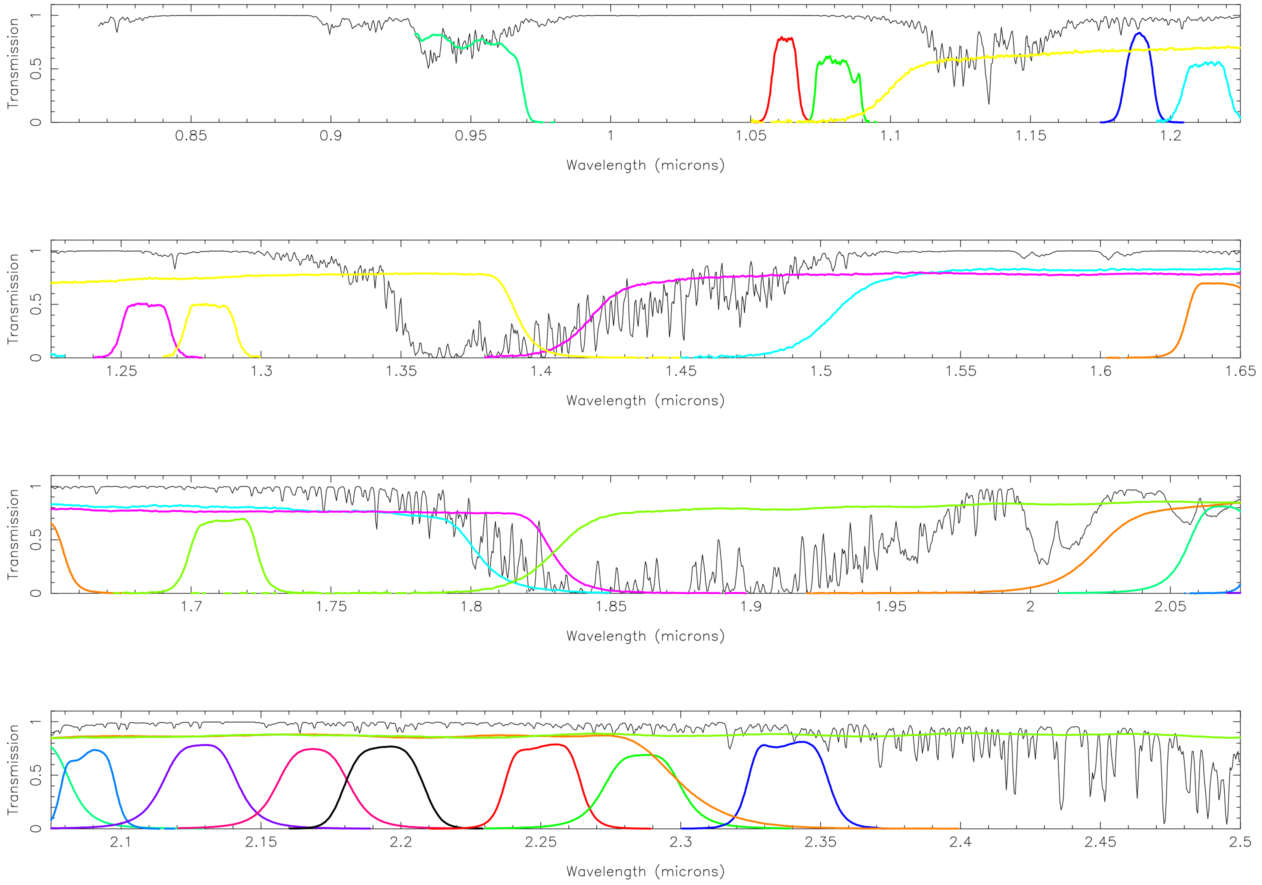


Figure B.1: The atmospheric transmission at a resolution of 8Å. Most of the SOFI filters plus some additional ones from ISAAC are marked. In the top figure and starting from left to right the filters are: Z, NB 1.061, NB 1.083 He I, J, NB 1.187, and NB 1.215. In the second figure, the filters are: NB 1.257 [FeII], NB 1.282 Pβ, an order sorting filter which is used only in ISAAC, H and NB 1.644 [FeII] H. In the third figure, the filters are: NB 1.710, an order sorting filter used in only in ISAAC, K short, a narrow band filter used only in ISAAC, NB 2.090, NB 2.170 Brγ, NB 2.195, NB 2.248, NB 2.280 and NB 2.336 (CO).

Appendix C

SOFI Templates

Tables C.1, C.2, C.3, and C.4 associates templates with observational scenarios.

Type of Acquisition	**Template(s) to use**
Simple telescope preset	SOFI_img_acq_Preset
Preset telescope and move object. object onto a pixel	SOFI_img_acq_MoveToPixel
Preset telescope and centre an object in a slit	SOFI_img_acq_MoveToSlit
Preset telescope and position an object for polarimetry	SOFI_img_acq_Polarimetry

Table C.1: Short guide for acquisition templates

Type of Imaging	**Template(s) to use**
Deep imaging of uncrowded fields	SOFI_img_obs_AutoJitter or SOFI_img_obs_Jitter
Imaging of extended objects or crowded fields	SOFI_img_obs_AutoJitterOffset or SOFI_img_obs_JitterOffset
Map of extended fields	SOFI_img_obs_AutoJitterArray
Imaging Polarimetry	SOFI_img_obs_Polarimetry
Imaging requiring complex telescope offsets and/or guiding options.	SOFI_img_obs_GenericImaging

Table C.2: Short guide for imaging templates

Type of Spectroscopy	**Template(s) to use**
Spectroscopy of point–like or moderately extended objects	SOFI_spec_obs_AutoNodOnSlit
As above but in Non Destructive read-out mode	SOFI_spec_obs_AutoNodNonDestr
Spectroscopy of extended objects (i.e. wider than $\sim$ 2 arc-minutes), or complex sequences of slit positions	SOFI_spec_obs_GenericSpectro
As above but in Non Destructive read-out mode	SOFI_spec_obs_GenSpecNonDestr

Table C.3: Short guide for spectroscopic templates

Type of calibration	**Template(s) to use**
Telescope Focus	SOFI_img_cal_FocusWithWedge
Standard Star (imaging)	SOFI_img_cal_StandardStar
Darks	SOFI_img_cal_Darks
Arcs (spectroscopy)	SOFI_spec_cal_Arcs
Imaging Dome Flat Fields	SOFI_ima_cal_DomeFlats
Special Imaging Dome Flats	SOFI_ima_cal_SpecialDomeFlats
Spectroscopic Dome Flats	SOFI_spec_cal_DomeFlats
Spectroscopic Adaptor Flats	SOFI_spec_cal_Flats

Table C.4: Short guide for calibration templates

Examples of templates :

This section is for quick reference only. You should refer to the SOFI Template Signature Files manual for details.

C.1 Imagery templates

C.1.1 SOFI_img_obs_AutoJitter :

Table C.5: SOFI_img_obs_AutoJitter

Parameter signature	Value
Exposure Name	NGC6118
DIT	10
NDIT	6
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Number of Exposures?	6
Filter wheel 1	Ks
Filter wheel 2	open
Instrument Mode	LARGE_FIELD_IMAGING
Combined Offset? (T/F)	F
Jitter Box Width (arcsec)	20
Return to origin? (T/F)	T

In this example you are going to have 6 images (fits files). Each of them corresponds to the average of 6 exposures (`NDIT`) of 10 seconds (`DIT`). Each image is jittered regarding to the previous one, and the jitter offsets are chosen randomly inside a box of 20 arcsec (`Jitter Box Width`)around the central position. At the end of the exposures, the telescope moves back to the preset positon (`Return to origin = True`).

C.1.2 SOFI_img_obs_AutoJitterArray :

The SOFI_img_obs_AutoJitterArray allows you to define large offsets and to jitter around each offset position.
In this example, you will have 4 main positions defined in the RA and DEC offset lists. The number of exposures is defined by `Number of Exposures`, and so if you have less offsets than number of exposures, BOB will start again with the first offset. It repeats simply the list of offsets you enter until it has the same number of exposures. Each offset is done from the last position.
Around each of the offset position, you will have 3 images with jitter (inside a box of 20 arcsec : `Jitter Box Width`).
To summarize, you will have 3 (`NJITT`) jittered positions around the 4 offest positions (`Number of Exposures?`), that means 3 x 4 images = 12 images. Each image is the average of 6 exposures (`NDIT`) of 10 seconds (`DIT`). So the total exposure time is 10 x 6 x 3 x 4 = 12 minutes (whitout the overheads).

Table C.6: SOFI_img_obs_AutoJitterArray

Parameter signature	Value
Exposure Name	NGC6118
DIT	10
NDIT	6
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Number of Exposures?	4
NJITT	3
Jitter box width (arsec)	20
Filter wheel 1	Ks
Filter wheel 2	open
Instrument Mode	LARGE_FIELD_IMAGING
Combined Offset? (T/F)	F
Return to origin? (T/F)	T
RA offset list (arcsec)	50 0 50 0
Dec offset list (arcsec)	50 50 0 50

C.1.3 SOFI_img_obs_AutoJitterOffset :

Table C.7: SOFI_img_obs_AutoJitterOffset

Parameter signature	Value
Exposure Name	NGC6118
DIT	20
NDIT	3
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Number of Exposures?	10
Filter wheel 1	Ks
Filter wheel 2	open
Instrument Mode	LARGE_FIELD_IMAGING
Combined Offset? (T/F)	F
Jitter Box Width (arcsec)	20
Return to origin? (T/F)	T
Sky Offset Throw (arsec)	600.
Rotate Pupil ?	T

The SOFI_img_obs_AutoJitterOffset template allows you to observe extended objects and to take sky frames. You define the sky offset: the offset will be defined randomly in a circle defined by `Sky Offset Throw`. Moreover, to avoid bad pixel or problem of the detector, jitter is done around the position: your object won't be exactly in the same position, but stays inside the box you define by `Jitter Box Width`.

In this case, the sky is taken at 600 arcsec of the object, and a small jitter of 20 arcsec is done. The number of exposures corresponds to the TOTAL number of exposures, that means SCIENCE exposures + SKY exposures. So here, you will have 5 images of your objects, and 5 images of the sky. Each image is the average of 3 (`NDIT`) exposures of 20 s (`DIT`).

C.1.4 SOFI_img_obs_Jitter :

Table C.8: SOFI_img_obs_Jitter

Parameter signature	Value
Exposure Name	NGC6118
DIT	20
NDIT	3
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Number of Exposures?	5
Filter wheel 1	Ks
Filter wheel 2	open
Instrument Mode	LARGE_FIELD_IMAGING
Combined offset? (F/T)	T
Return to origin? (T/F)	T
RA offset list (arcsec)	0 -50 0 100 0
DEC offset list (arcsec)	0 -50 100 0 -100

This template simply allows to do expositions at different positions, defined by the offset lists.
You can guide: `Combined offset = TRUE`, and you can return to the origin at the end of the sequence (`return to origin = TRUE`). This example gives to you 5 images at 5 different positions. Each image is the average of 3 (`NDIT`) exposures of 20 s (`DIT`).

C.1.5 SOFI_img_obs_GenericImaging :

Table C.9: SOFI_img_obs_GenericImaging

Parameter signature	Value
Exposure Name	NGC6118
DIT	20
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Number of Exposures?	7
List of NDIT	3 2 3 2 3 2 3
Filter wheel 1	Ks
Filter wheel 2	open
Instrument Mode	LARGE_FIELD_IMAGING
Return to origin? (T/F)	T
RA offset list (arcsec)	0 -150 140 150 -140 -250 250
DEC offset list (arcsec)	0 -150 140 150 -140 -250 250
Obs Type (O or S)	O S O S O S O
Guiding (N B S)	B

This template works on the same way than SOFI_img_obs_Jitter, but you have different options to guide.
In this example, you have 7 offsets with the option to guide `Box to star`(other options are `Star to Box`and `No Guiding`. The object is always observed with a `NDIT` equal to 3, whereas the sky is always observed with `NDIT` equal to 2.
At the end you will have 4 images for the object, each of them is the average of 3 (`NDIT`) expositions

of 20 (`DIT`) seconds.
And 3 images of the sky, each of them is the average of 2 (`NDIT`) expositions of 20 (`DIT`) seconds.

C.2 Polarimetric Template:

Table C.10: SOFI_img_obs_Polarimetry

Parameter signature	Value
Exposure Name	NGC6118
DIT	20
NDIT	3
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Number of Exposures?	5
Filter wheel 1	Ks
Filter wheel 2	open
Instrument Mode	LARGE_FIELD_IMAGING
Combined offset? (F/T)	Y
Return to origin? (T/F)	T
X offset list (arcsec)	0 -50 0 100 0
Y offset list (arcsec)	0 -50 100 0 -100
Rotator offset?	

This template is quite simple, as it works as imagery template. The number of exposures must correspond to the number of offsets you define. You specify the set up of the instrument, and the most important you decide which angle you want: you should observe the same object several angles to determine the Stokes parameters (cf. section 2.4).

C.3 Spectroscopic templates

C.3.1 SOFI_spec_obs_AutoNodOnSlit :

The template SOFI_spec_obs_AutoNodOnSlit allows to observe an object on two different positions along the slit (position A and B): you "nod" between the two positions, and so the space between A and B is defined by the parameter `Nod Throw`. Moreover, you can jitter around each position, to avoid bad pixels. The width between two jittered positions is defined by the parameter `Jitter Box Width` .
In this example, you take 2 (`NINT`) spectra in each position. Each spectrum is the average of 2 (`NDIT`) exposures of 40 seconds (`DIT`). You do 3 times the cycle : so you will have ABBAAB.
At the end you will have NINT * Number of cycles * 2 images = 12 images.

Table C.11: SOFI_spec_obs_AutoNodOnSlit

Parameter signature	Value
Exposure Name	NGC6118
DIT	40
NDIT	2
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Spectro Mode	LONG_SLIT_BLUE
Which slit	long_slit_1
Combined offset? (F/T)	Y
Jitter Box Width (arcsec)	20
Return to origin? (T/F)	T
Nod Throw (arcsec)	100.
NINT	2
Number of AB or BA cycles	3

C.3.2 SOFI_spec_obs_AutoNodNonDestr :

Table C.12: SOFI_spec_obs_AutoNodNonDestr

Parameter signature	Value
Exposure Name	NGC6118
DIT	50
NDIT	2
NSAMP	30
NSAMPPIX	4
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Spectro Mode	LONG_SLIT_BLUE
Which slit	long_slit_1
Combined offset? (F/T)	Y
Jitter Box Width (arcsec)	20
Return to origin? (T/F)	T
Nod Throw (arcsec)	100.
NINT	3
Number of AB or BA cycles	3

This template uses the Non destructive readout mode. So you have to define `NSAMP` and `NSAMPIX` (as explained the section 3.4.1).
Otherwise, it's the same thing that SOFI_spec_obs_AutoNodOnSlit. According to the `NINT` and number of cycles you will have a 3x3x2 = 18 files, each of them corresponding to the average of the `DIT` x `NDIT`.

C.3.3 SOFI_spec_obs_GenericSpectro :

If you want to do specific offsets to observe your object and some sky, you can use this template: SOFI_spec_obs_GenericSpectro. You define the offsets in X (along the slit) and in Y (to move out of the slit the object for example). Again the number of exposures must correspond to the number of offsets.

Table C.13: SOFI_spec_obs_GenericSpectro

Parameter signature	Value
Exposure Name	NGC6118
DIT	40
NDIT	2
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Number of Exposure	6
Spectro Mode	LONG_SLIT_BLUE
Which slit	long_slit_1
Return to origin? (T/F)	T
X offset list (arsec)	0 -15 0 30 0 -15
Y offset list (arcsec)	0 0 10 -10 10 -10
Guiding (N B S)	S

In this example, you observe 1- the object at the acquisition position; 2- the object in an offset position (-15 arcsec); 3- the sky : you put away the object of the slit; 4- the object but at an offset position; 5- the sky; and 6- the object at the original position.

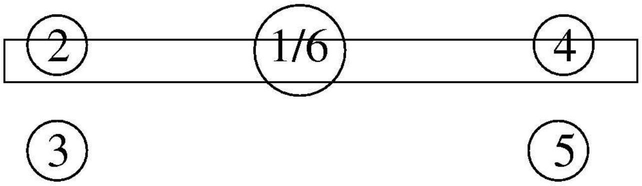


Figure C.1: Positions of the offsets in the slit

At the end, you will have 6 files, each of them is the average of 2 (`NDIT`) exposures of 40 seconds (`DIT`). The guiding option asks to put the star to the box.

C.3.4 SOFI_spec_obs_GenSpecNonDestr :

Same thing than for the SOFI_spec_obs_GenericSpectro, but with the non destructive readout mode.

Table C.14: SOFI_spec_obs_GenSpecNonDestr

Parameter signature	Value
Exposure Name	NGC6118
DIT	40
NDIT	2
NSAMP	4
NSAMPPIX	10
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Number of exposures	4
Spectro Mode	LONG_SLIT_BLUE
Which slit	long_slit_1
Return to origin? (T/F)	T
X offset list (arcsec)	
Y offset list (arcsec)	
Obs Type (O or S)	
Guiding (N B S)	

C.3.5 SOFI_ima_obs_StandardStar:

Table C.15: SOFI_ima_obs_StandardStar

Parameter signature	Value
Exposure Name	S9104
DIT	2
NDIT	5
Number of columns	1024
Number of rows	1024
First column of window	1
First row of window	1
Number of Exposures?	5
Filter Wheel 1	J
Filter wheel 2	open
Instrument mode	Large_field
Combined offset? (F/T)	Y
Return to origin? (T/F)	T
X offset (arcsec)	0 45 -90 0 90
Y offset (arcsec)	0 45 0 -90 0

The SOFI_img_cal_StandardStar is really simply as it does 5 expositions : the first on the acquisition position and the other defined by the list of offsets. At the end you have a “star” pattern.

General comments: The *Auto* templates choose for you the offsets randomly whereas you have to enter which offsets you want for the other templates.

If you want more information, you can read the Template Signature File Parameter Reference Guide, available on the SOFI web page.

Appendix D

Frame Types

There are several basis frame types, which are identified by three keywords in the FITS header. The full list is given in Table D.1.

Keyword	Value	Type
`DPR CATG`	SCIENCE	Exposure on target (object)
`DPR CATG`	OTHER	Exposure off target (sky)
`DPR CATG`	CALIB	Calibration frame
`DPR TECH`	IMAGE	Exposure in imaging mode
`DPR TECH`	SPECTRUM	Exposure in spectroscopic mode
`DPR TECH`	POLARIMETRY	Exposure in polarimetric mode
`DPR TYPE`	LAMP	Arc spectrum (comparison lamp)
`DPR TYPE`	DARK	Dark frame
`DPR TYPE`	STD	Standard Star
`DPR TYPE`	FLAT	Flat Field Frame

Table D.1: FITS header keywords defining the content of the images

___oOo___