LWS OBSERVER'S MANUAL

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CONTENTS

1. INTRODUCTION

This document is meant to tell observers what the Long-Wavelength Spectrometer (LWS) is, how it works and how to use it: it says what astronomical observation templates (AOTs) should be used to achieve particular astronomical goals and shows how the time needed to achieve these goals can be estimated. A list of acronyms, a glossary and an index are provided at the end of the document.

Astronomical spectroscopy has two main objectives. The first is to detect the presence of lines and measure their strengths; in particular, the astronomer is often interested in the *ratio* of the strengths of lines of different species or of lines arising from different levels of the same species. For this, moderate spectral resolving power - which gives relatively high sensitivity - is often satisfactory (although the detection of lines above a strong continuum can prove difficult). The other main objective is the study of the *shapes* of individual lines or blends of lines, often in order to determine the kinematics of the source. For this, the astronomer wants the highest possible resolving power consistent with retaining adequate sensitivity. Inevitably, a compromise has to be made and we chose to design the LWS to operate in two modes: in its moderate-resolution mode, it achieves an average resolving power of about 200, corresponding to a velocity-resolution of some 1500 km s^{-1}; in high-resolution mode, its resolving power is about 10^4 - corresponding to 30 km s^{-1} - with a reduction in sensitivity to continuum or resolved features by a factor of about 500.

2. DESCRIPTION OF THE INSTRUMENT

2.1 Overall design

The LWS consists of three main components, the focal plane unit (FPU);, operating at liquid-helium temperatures, and two warm units: the analogue processing unit (APU); - which drives the various mechanisms and powers the detectors in the FPU, as well as processing the resulting signals - and the digital processing unit (DPU, which commands the LWS via the APU and interfaces with the spacecraft computer.

The FPU itself consists of three main subsystems: the optical subsystem, the detector subsystem and the Fabry-Perot subsystem. The optical subsystem comprises a collimator, a grating, and re-focusing optics which feed the detector subsystem. The Fabry-Perot subsystem, which is situated in the parallel part of the beam, consists of a Fabry-Perot wheel carrying two Fabry-Perot interferometers. The wheel can be set in any of four positions: in one of these, the beam passes through the subsystem un-hampered whilst in another, the beam is completely obscured. In the remaining two positions, one or other Fabry-Perot is placed in the beam and modulates it spectrally.

2.2 Optical

Figure 1 shows the optical train of the LWS superimposed on a photograph of the instrument taken before the integration of the Fabry-Perot subsystem. The f/15 beam from the telescope is folded by mirror (1) and comes to a focus on the field mirror (2), which restricts the field of view on the sky to 1.65 arcmin - the diffraction limit of the telescope at 118 μm. From mirror (2), the beam passes to the collimating mirrors (3) and (4) before reaching the grating via the plane mirrors (5) After passing through the Fabry-Perot subsystem, the beam is reflected by plane mirrors (6) and (7) on to the grating, which has a Schmidt profile to correct for spherical aberration. Finally, on leaving the grating, the radiation is focused by mirror (8) on to the cylindrical surface of the detector block.

The optical subsystem is designed to satisfy the Jaquinot criterion for the resolution of the instrument, minimise the diameter of the beam at the position of the FP etalons, and match the spectral resolution achieved by the grating to the order-sorting needs of the FPs.

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Figure 1. The optical train of the LWS

2.3 The Grating

The grating is ruled with 7.9 lines per millimetre at a blaze angle of 30^{o} on a rotationally symmetric Schmidt profile. With the grating in its rest position, the radiation is incident at an nominal angle of 60^{o}. It can be scanned, by means of a servo-controlled drive mechanism, through ±7.0^{o}. The grating is used in second order for the wavelength range ~43-90 µm and in first order for the wavelength range ~90-197 µm. The grating was originally intended to scan through ±3.5^{o} in normal operation; this range was chosen so that the nominal range of wavelengths covered by one detector channel overlapped that covered by the adjacent detector. An extended scanning range of ±7^{o} allowed - at the cost of a small increase in power dissipated in the focal plane - the nominal wavelength range of any detector channel to be covered by its two neighbours, thus providing redundancy in the case of a failed detector. This increase of the scanning range also extended the long-wavelength coverage out to about 197 µm. In order to maximise the sensitivity of the instrument at all wavelengths, however, it is now likely that the extended scanning range will be used in normal operation (cf. §5.3.3).

The operation of the instrument is described more fully in §3.

2.4 Detectors and Cold Electronics

Figure 2. Drawing of the LWS detector block.

Figure 2 is a drawing of the detector block, which contains ten detectors: five of these cover the short-wavelength range ~43-90 μm in nominally 10 μm-wide channels while the others cover the long-wavelength 90-197 μm in nominally 20 μm-wide channels. As we shall explain in more detail below, radiation in the long-wavelength range - coming from the grating in first order of diffraction - is focused on to the same range of positions on the detector block as is radiation in the short-wavelength range, coming from the grating in the second order of diffraction. Alternate detectors are therefore made to respond to long and short wavelengths respectively, the selection of wavelength being made not only by the intrinsic spectral responses of the detectors but also with efficient band-pass and blocking filters.

The LWS uses three different types of photoconductive detector to cover the required range of wavelengths. The shortest wavelength channel SW1 (nominally 43-50 μm) uses a beryllium-doped germanium (GeBe) detector. The next five channels in wavelength-space (SW2: 50-60, SW3: 60-70, SW4: 70-80, SW5: 80-90 and LW1: 90-110 μm) use GeGa detectors whilst stressed GeGa is used for the four longest-wavelength channels (LW2: 110-130, LW3: 130-150, LW4: 150-170 and LW5: 170-190 μm).

In view of the measured performance of the detectors the *actual* range of wavelengths covered by each channel is adjusted to optimise the sensitivity of the instrument at all wavelengths (cf. §5.3.3). This results in channel SW2's being used over a narrower range of wavelengths than it was designed for and in channel LW4's not being used at all in normal operations.

Figure 3. Mount of a stressed detector.

The mount of a stressed detector is shown in figure 3; the mount of an un-stressed detector is similar. The detector is mounted in an integrating cavity to increase its absorption efficiency. This detector is fed by a horn designed to couple efficiently with the radiation leaving the spherical mirror (8) in figure 1. The stress, which is applied by a screw, reduces the gap between the acceptors and the valence band, thus reducing the energy needed for excitation of carriers into the band. This reduction in energy-gap, however, also allows more carriers to be *thermally* excited into the band; in order to keep their dark-currents to acceptable levels, therefore, the stressed detectors have to be operated at the lowest temperature available, that of the helium tank at 1.8 K. The unstressed detectors in contrast, behave poorly at 1.8 K and are therefore operated at about 3.5 K. Operating the two types of detector at different temperatures is achieved by mounting them on separate bars. The unstressed detectors are mounted on the upper of two bars in the detector block shown in figure 2. This bar, which accommodates a heater and a thermometer operating in a servo loop, has a weak thermal link to the lower bar. The lower bar, accommodating the stressed detectors (shaded) is thermally shorted to the helium tank with a high-conductance copper strap.

The photo-current in a detector element is accumulated on the input capacitance of an FET in a JF-4 integrating amplifier supplied by Infrared Laboratories; these amplifiers can be seen below the detectors in figure 2. To reduce stray thermal emission from the FETs, which are heated to about 60 K within their TO5 cans, the amplifier section is enclosed by a copper cover, not shown in the figure. Also visible in figure 2 are the five infrared illuminators, again provided by Infrared Laboratories, which are used to monitor and calibrate the stability of response of the detectors.

2.5 Fabry-Perots

For use in high-resolution mode, the LWS contains two Fabry-Perot interferometers mounted on a wheel driven by a pinion engaging gear-teeth on the rim of the wheel: a new type of cryogenic motor was especially developed to drive the wheel. The short-wavelength Fabry-Perot covers the wavelength range 43-70 µm while the long-wavelength Fabry-Perot deals with the remaining 70-197 µm. Rotation of the wheel brings successively into the parallel part of the beam, between mirrors (5) and (6) of figure 1: an open aperture, so that the LWS can be used in moderate-resolution mode as a grating spectrometer; the short-wavelength Fabry-Perot; a blanking plate for dark-current measurements; and the long-wavelength Fabry-Perot.

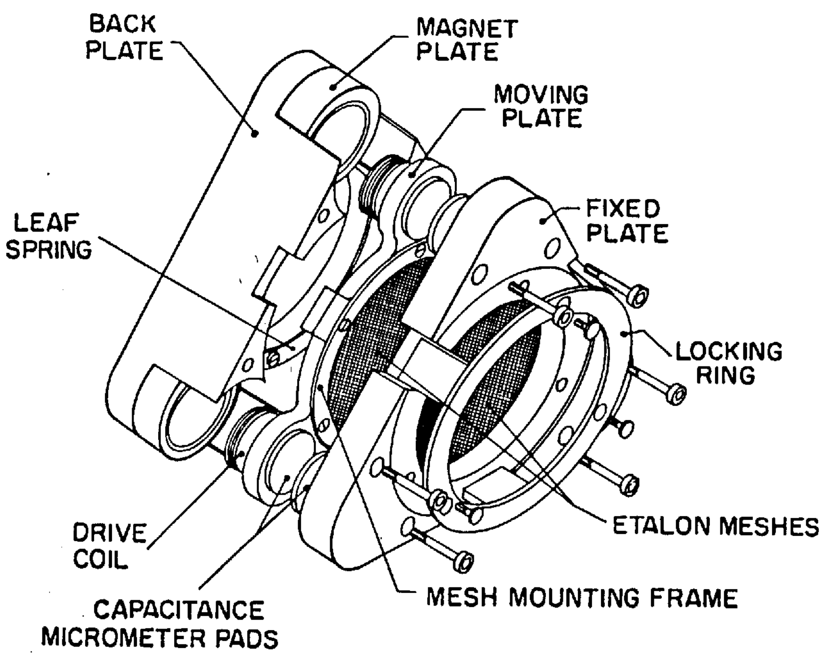

Figure 4. The construction of a Fabry-Perot etalon

The construction of the Fabry-Perot etalons is shown in figure 4. The Moving Plate is suspended on Leaf-Springs between the Back Plate and the Fixed Plate. Each corner of the moving plate carries a loudspeaker-like Drive Coil which operates in a gap surrounding a permanent magnet in the Back Plate. The position of each corner, relative to the Fixed Plate, is determined by measuring the charge on the Capacitance Micrometer, formed by pads on the Moving and Fixed Plates. The position of each corner is controlled by a servo mechanism which supplies sufficient current to the Drive Coil to make the measured charge equal to a control value. Initially, the two plates of the etalon are made parallel by applying offset signals to two of the three drive circuits. The moving etalon is then scanned as a whole by applying the same additional driving signal to all three coils.

The fixed and moving plates carry the reflecting elements, made of free-standing nickel meshes supplied by Heidenhain: these meshes are affixed to the Mesh-Mounting Frames which are attached to the plates. The meshes consist of a rectangular grid of rectangular section: the thickness of the meshes is 3 µm, the width of the "bars" of which the meshes are composed is 6 µm, and the periods of the grid are 19 µm for the long-wavelength Fabry-Perot and 15.5 µm for the short-wavelength Fabry-Perot. The narrow tolerance allowed on these dimensions is critical to the performance of the instrument.

3. How the Instrument Works

3.1 Grating (Moderate Resolution) Mode

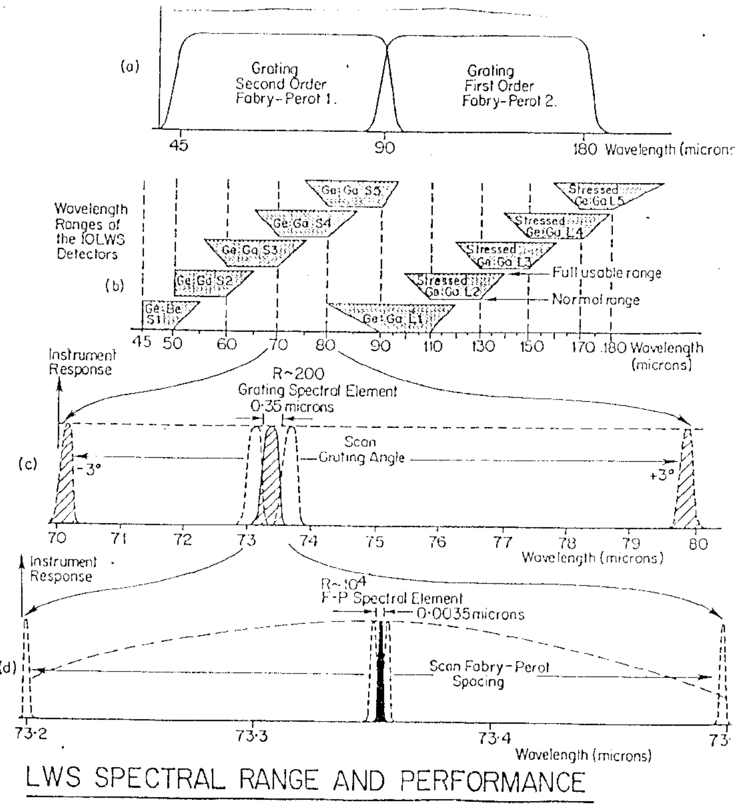

Figure 5. How the LWS works[1].

We refer to figure 5 to describe the operation of the instrument[1]. Consider first figure 5(c) which shows the nominal range of wavelengths covered by the unstressed GeGa detector SW4. When the grating is in its rest position, the central wavelength falling on this detector is 75 µm. The middle hatched region - representing the grating's spectral response function - shows the range of wavelengths falling on the detector when the grating is at an angle of about -1.2°. The resolution, of about 0.29 µm, is determined by the width of the detector aperture in the dispersion direction.

By scanning the grating between -3.5° and +3.5°, the centre of the grating response function can be moved from about 70 µm to about 80 µm. Detector SW3 therefore nominally covers the spectral range 70-80 µm, as shown in figure 5(b). Considering each detector in turn in the same way, we build up the total coverage of 45-180 µm shown in figure 5(b) and again in figure 5(a), where it is shown that the range 45-90 µm is covered with the grating operating in second order whilst the range 90-180 µm uses the grating in first order. It should be clear that, as the grating is moved between -3.5° and +3.5°, the whole spectral range of the LWS is covered, all detectors being scanned over their nominal wavelength range simultaneously. There is therefore ten-fold multiplexing in grating mode.

It is important to remember that wavelength λ in first order is diffracted at the same angle as wavelength $\lambda/2$ in second order and as wavelength $\lambda/3$ in third order, etc. With the grating in its

[1] Since this drawing was prepared, the wavelength ranges and resolutions have changed slightly. In particular, it has been found possible to extend the normal coverage down to 43µm and up to 197µm. Nevertheless, this section accurately describes the principles behind the instrument's operation.

central position, therefore, detector SW4 not only receives its "own" 75 µm radiation in second order but also 150 µm radiation in first order and 37.5 µm radiation in third order, etc. It must be prevented from responding to these extraneous orders by bandpass filters, which are shown schematically in figure 5(b) by the trapezia around each detector. This becomes very critical at the shortest wavelengths where, for example, detector SW1 has to respond to 40 µm radiation (in second order), when the grating is at an angle of -3.5^{o}, but reject radiation at 38 µm (in third order), when the grating is at an angle of +7.0^{o} (cf. §3.3). This demand on the bandpass filter are therefore high.

3.2 Fabry-Perot (High Resolution) Mode

The operation of the instrument in Fabry-Perot mode is illustrated in figure 5(d). With the grating at angle of -1.2^{o} the central wavelength falling on the detector is about 73.35 µm. If the Fabry-Perot - whose resolving power is about 10^4 - is tuned to this wavelength and is brought into the beam, the bandpass falls to about 0.0073 µm, as shown in figure 5(d). Since the response of the grating does not fall off significantly between 73.2 and 73.5 µm, the Fabry-Perot can be scanned between these wavelengths to give a high-resolution spectrum[2].

A Fabry-Perot set to respond to wavelength λ will also respond to wavelengths $\lambda \pm r\Delta\lambda$, where $\Delta\lambda$ is its free spectral range and r = 0, 1, 2,... . The free spectral range is given by λ/n, where n is the order of interference in the Fabry-Perot. Its resolving power, on the other hand is given by nF, where F is its finesse. In order to achieve a resolving power of 10^4 with the available finesses of about 100, we need to operate in orders of around 100, so that the ratio of the wavelength to the free spectral range is also about 100. If the grating is to avoid spectral contamination, by preventing adjacent spectral orders reaching the Fabry-Perots, its resolving power must therefore also be about 100. It was the need for the grating to order-sort for the Fabry-Perot which set the requirement on the resolving power of the grating.

3.3 Extended Mode of Operation

In order to provide some redundancy in case one of the detectors should fail, the grating was designed to be scanned over an extended range of ±7.0^{o}, at the expense of a small increase in the power dissipated into the focal plane. This meant that any detector's wavelength range could have been covered by its neighbours; in figure 5, for example, if SW4 - which covers the range 70-80 µm - should fail, the range 70-75 µm can be covered by SW3 whilst SW5 will cover the range 75-80 µm. This extended scanning of the grating also means that the long-wavelength limit can be pushed out to about 197 µm.

In practice, however, this redundant coverage is not complete over the full wavelength range (cf. §5.3.3) and, as described in §2.4, the extended range of scanning will be used to maximise the sensitivity of the instrument.

[2]In practice, the grating will be rotated during the taking of a spectrum so as to keep the maximum of its response function close to the Fabry-Perot setting.

4. Overview of Modes of Operation and AOTs

4.1 Summary

The LWS has two *operational* modes, *grating (low-resolution) mode* and *Fabry-Perot (high-resolution) mode*. It has six different *observational* modes which can be accessed *via* four astronomical observation templates (AOTs). This is summarised in figure 6.

Grating mode, in which only the grating is used, provides moderate spectral resolving power of about 0.29 μm in the short-wavelength channels (SW1-SW5) and 0.6 μm in the long-wavelength channels (LW1-LW3, LW5) - corresponding to a resolving power of between 100 and 300 - depending on the wavelengths being investigated. Because of the multiplexing describe in §3.1, usable data are obtained from all ten detectors simultaneously. Whether or not these data are useful to the observer depends upon the range of wavelengths selected.

Fabry-Perot mode, in which one of the two Fabry-Perots is used in combination with the grating, provides high spectral resolving power between 8 10^3 and 10^4. Although radiation in different orders of the Fabry-Perot will be falling on detectors other than the one selected for the wavelength of interest, it is unlikely that any of these date will be useful. There are two reasons for this. First, there may not be spectral lines in the other orders. Secondly, and more importantly, the grating will be set so that it has peak transmission at the order of interest. Other orders will fall on the (uncalibrated) wings of the grating's spectral response function.

In both grating and Fabry-Perot modes, scans are carried out at one of a set of standard detector integration times. The total integration time is then achieved by varying the number of scans.

4.2 Medium-Resolution Spectroscopy

4.2.1 Medium-Resolution Wavelength Range.(LWS01)

This grating-mode AOT results in a medium-resolution spectrum covering a wavelength range, specified by the user, up to the full range of the LWS in medium-resolution mode (43.0-196.7 μm). There is a minimum to the range covered, corresponding to 1.25 μm for the short-wavelength channels (SW1-SW5) and 2.5 μm for the long-wavelength channels (LW1-LW3, LW5). Data will be recorded from all ten detectors while the specified range is being scanned. The observer has a choice, in fractions of a resolution element, of the spectral sampling interval.

4.2.2 Medium-Resolution Line Spectrum.(LWS02)

This AOT produces medium-resolution spectra around up to 10 wavelengths, specified by the observer. Data will be recorded from all ten detectors while the specified ranges are being scanned. The observer has a choice, in fractions of a resolution element, of the spectral sampling interval.

4.3 High-Resolution Spectroscopy

4.3.1 High-Resolution Wavelength Range.(LWS03)

This AOT results in a high-resolution spectrum covering a wavelength range, specified by the user, up to the full range of the LWS (47-196.7 μm) in high-resolution mode. Data will be recorded from only one detector at a time. The observer has a choice, in fractions of a resolution element, of the spectral sampling interval. Note that a *full* spectral scan in high resolution mode takes a very long time!

4.3.2 High-Resolution Line Spectrum (LWS04)

The AOT produces high-resolution spectra around up to 10 wavelengths, specified by the observer. Data will be recorded from only one detector at a time. The observer has a choice, in fractions of a resolution element, of the spectral sampling interval.

Figure 6. Modes of the LWS

4.4 Rapid Scanning

Normally, the LWS is scanned so that the required integration time is obtained at each point of the spectrum before the grating or the Fabry-Perot is moved to a new position. In some cases, though, it may be desirable to scan through the spectrum as rapidly as possible, building up the integration time by repeatedly scanning over the spectrum An obvious example is the observation of a weak line on a strong background. The observer may chose this option for any of the above AOTs.

4.5 Narrow-Band Photometry (LWS02)

This is an under-sampled medium-resolution spectrum over the full wavelength range of the LWS (43-196.7 μm): it provides ten photometric points - one in each channel - at a resolution of about 0.29 μm in the short-wavelength channels (SW1-SW5) and 0.6 μm in the long-wavelength channels (LW1-LW3, LW5). For technical reasons, this is not implemented by a separate AOT but by specifying zero-width scan in the medium-resolution line-spectrum AOT (LWS02). The result is that the grating is not scanned but remains at a fixed position.

5. PERFORMANCE OF THE INSTRUMENT

5.1 Introduction

The figures presented here are based on the performance of the LWS as measured under the relatively benign conditions of the laboratory. Although we have made our best attempt to foresee the consequences of changing backgrounds and radiation hits, and to prepare to remove them during the processing of the data, only experience in orbit will tell us if our assumptions are justified.

5.2 Characterising the Performance of the LWS

Suppose the telescope is illuminated with flux-density F_ν at frequency ν. The signal-to-noise ratio *SNR* obtained after integrating for time *t* is given by

$$SNR = \frac{F_\nu}{\left[\frac{4}{\eta(\nu)\tau(\nu)\tau_f(\nu)}\frac{h\nu F_\nu}{A} + \left(\frac{NEFD_{Instr}(\nu)}{\tau_f(\nu)}\right)^2\right]^{1/2}}(2t)^{1/2}, \tag{5.1}$$

where

$\eta(\nu)$		is the quantum efficiency of the detector;
$\tau(\nu)$		is the transmission of the instrument in grating mode;
$\tau_f(\nu)$		is: unity in grating mode or the transmission of the Fabry-Perot in Fabry-Perot mode;
A		is the effective collecting area of the telescope;
$NEFD_{Instr}$		is the noise-equivalent flux-density of the instrument in grating mode.

The first term in the denominator of equation 5.1 takes account of the shot-noise in the photon stream and generation-recombination noise in the photo-current. The second term arises from noise intrinsic to the detector, mainly shot- and generation-recombination noise in the detector's dark-current. These terms make equal contributions to the total noise when

$$F_\nu = \frac{\eta}{4}\frac{\tau(\nu)}{\tau_f(\nu)}A\frac{NEFD^2_{Instr}(\nu)}{h\nu}, \tag{5.2}$$

in which case the signal-to-noise ratio is given by

$$SNR = \frac{\eta(\nu)\tau(\nu)}{4\sqrt{2}}A\frac{NEFD_{Instr}(\nu)}{h\nu}(2t)^{1/2}. \tag{5.3}$$

In all realistic circumstances, the signal-to-noise ratio given by equation 5.3 exceeds one hundred. As we shall explain in §6 below, predicted signal-to-noise ratios much above a hundred are misleading in practice. In what follows, therefore, we restrict our attention to the regime in which the performance is limited by intrinsic detector noise. In this regime we have, from equation 5.1,

$$SNR \approx \frac{F_\nu}{\left[\frac{NEFD_{Instr}(\nu)}{\tau_f(\nu)}\right]}(2t)^{1/2}. \tag{5.4}$$

The use of flux-densities is appropriate for an unresolved line. If a resolved line - or a continuum - is being observed, the spectral flux-density S_ν is the quantity of interest:

$$S(\nu) := \frac{F_\nu}{\Delta\nu} = R(\nu)\frac{F_\nu}{\nu} = \frac{\lambda^2}{c}\frac{F_\lambda}{\Delta\lambda}, \quad (5.5)$$

where $\Delta\nu$ is the resolution of the spectrometer at frequency ν, $R(\nu)$ is the resolving power at that frequency and λ and $\Delta\lambda$ are the corresponding wavelength and wavelength resolution. Corresponding to equation 5.4, we have

$$SNR = \frac{S(\nu)}{\left[\dfrac{NESD_{Instr}(\nu)}{\tau_f(\nu)}\right]}(2t)^{1/2}, \quad (5.6)$$

where the noise-equivalent spectra-density $NESD_{Instr}(\nu)$ is given by

$$NESD_{Instr}(\nu) = R(\nu)\frac{NEFD_{Instr}(\nu)}{\nu} = \frac{\lambda^2}{c}\frac{NEFD_{Instr}(\nu)}{\Delta\lambda}. \quad (5.7)$$

It is clear from the above equations that both the $NEFD_{Instr}$ and the $NESD_{Instr}$ are frequency dependent. In grating-mode, however, $\Delta\lambda$ is roughly constant for a given order and λ varies linearly whilst, in Fabry-Perot mode, $R(\nu)$ is roughly constant and ν varies linearly. Hence, the biggest contribution to the variation of $NEFD_{Instr}$ and $NESD_{Instr}$ within a given channel is caused by the intrinsic properties of the detectors and their filters. There is also a discontinuity in $\Delta\lambda$ between first and second order use of the grating and in $R(\lambda)$ between the short-wavelength Fabry-Perot FPS and the long-wavelength Fabry-Perot FPL.

5.3 Measured Performance

5.3.1 Transmission Efficiency

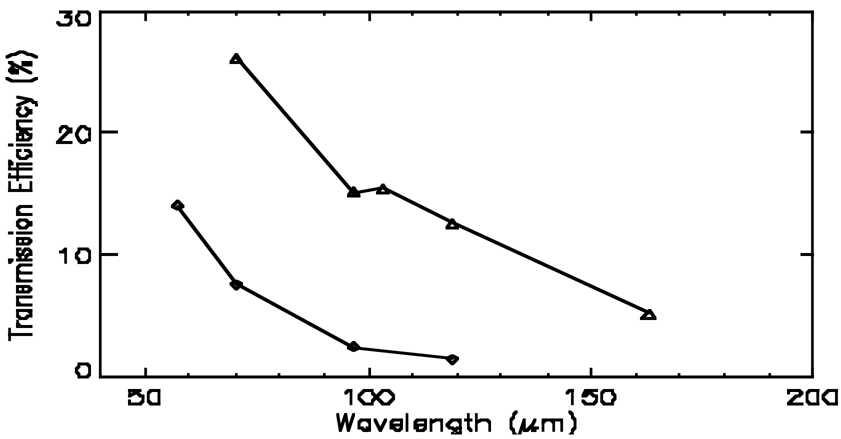

Figure 7. The transmission efficiency of the short- (FPS) and long- (FPL) wavelength Fabry-Perots.

The transmission efficiency of the optics/grating combination is difficult to establish independently, although estimates show it to be close to the design model. We avoid the need to know this figure by referring all sensitivity figures in grating mode to the entrance aperture of the instrument. We do need to know the transmission efficiency of the Fabry-Perots and this can be measured independently. The results are shown in figure 7.

5.3.2 Spectral Resolution

5.3.2.1 Grating Mode

In grating mode, the spectral resolution is limited by the entrance apertures of the detectors and is roughly constant for a given order. In the short-wavelength channels (SW1-SW5) it is about 0.29 µm and in the long-wavelength channels (LW1-LW3, LW5) it is about 0.6 µm

5.3.2.2 Fabry-Perot Mode

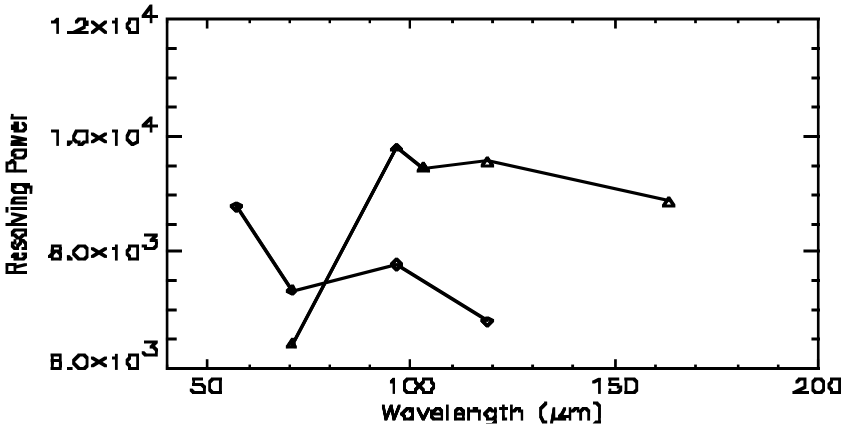

Figure 8. Resolving power in Fabry-Perot mode.

In Fabry-Perot mode, the resolving power is, of course, determined by the performance of the Fabry-Perots themselves; it is shown in figure 8 as a function of wavelength.

5.3.3 Photometric Sensitivity

5.3.3.1 Measurements of un-Resolved Lines

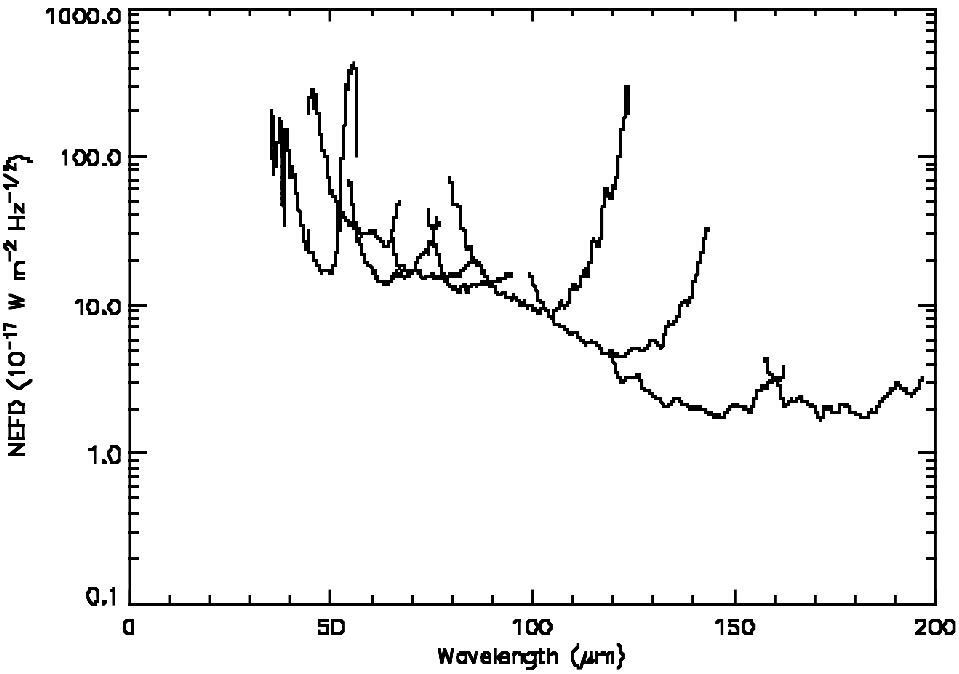

Figure 9. Noise-equivalent flux-density of the LWS in grating mode.

For un-resolved lines, the signal-to-noise ratio obtained in a single integration of time t is given by equation 5.4. In *grating mode*, $\tau_f(\nu)$ is set to unity and the sensitivity of the instrument is therefore determined directly by the $NEFD_{Instr}$, which is plotted as a function of wavelength in figure 9. The individual curves correspond to the different channels (detectors).

It is clear that, in several cases, a detector is less sensitive than an adjacent detector over part of its nominal range. In these cases, the grating will be used in its extended scanning range so as to maximise the sensitivity at any given wavelength. The extreme cases are channels SW2 and LW4, the latter not being shown in the figure. The noise-equivalent power of the detector in channel SW2 is a factor of about three worse than those of its neighbours SW1 and SW3 ($10\ 10^{-18}$ W $Hz^{-1/2}$ and $6\ 10^{-18}$W $Hz^{-1/2}$ respectively). This is exacerbated by the difficulty of producing the order-sorting filters at these short wavelengths, resulting in no overlap of channels SW1 and SW3. Channel SW2 will, therefore be used only over the range of wavelengths, between about 51 µm and 57 µm. where it is clearly more sensitive than channels SW1 and SW2. The sensitivity in this wavelength range is significantly lower than in adjacent ranges. [It is possible that the excess noise found on detector SW2 is caused by pickup in the laboratory and may disappear in orbit. For the moment, though, these figures should be used to estimate integration times.]

The noise-equivalent power of the detector in channel LW4 too, whilst being good in absolute terms ($1.9\ 10^{-18}$W $Hz^{-1/2}$), is about a factor of two worse than those of its neighbours. Consequently, channels LW3 and LW5 will be used to cover the wavelength range nominally assigned to LW4.

The curve of $NESD_{Instr}$ shown in figure 9 reflects the significant spectral structure which exists in the transmission of the instrument. This structure is retained in the software used to reduce the data but it unnecessarily complicates the estimation of integration times. For convenience, therefore, we have divided the wavelength channels into sub-channels roughly 8 resolution elements wide; each sub-channel is therefore about 2 µm wide for channels SW1-SW5 and 4 µm wide for channels LW1 to LW5. We have taken an average value of $NEFD_{Instr}$ and $NESD_{Instr}$ in each of these sub-channels; the values are given in table 3 of §6.

In **Fabry-Perot mode**, $\tau_f(\nu)$ is set to the transmission of the Fabry-Perot.; the sensitivity of the instrument is therefore determined by the $NEFD_{Instr}/\tau_{FP}(\nu)$. Because the FPL has a significantly better transmission than FPS in the wavelength range where the measurements overlap (cf. figure 7), FPL will be used for the wavelength range 70-196.7 µm. Also, because of order-sorting difficulties at the shortest wavelengths, FPS will be used only over the range 47-70 µm. The *NEFD* and *NESD* of the instrument in Fabry-Perot mode are given in table 6 of §6.

5.3.3.2 Measurements of Resolved Lines or Continua

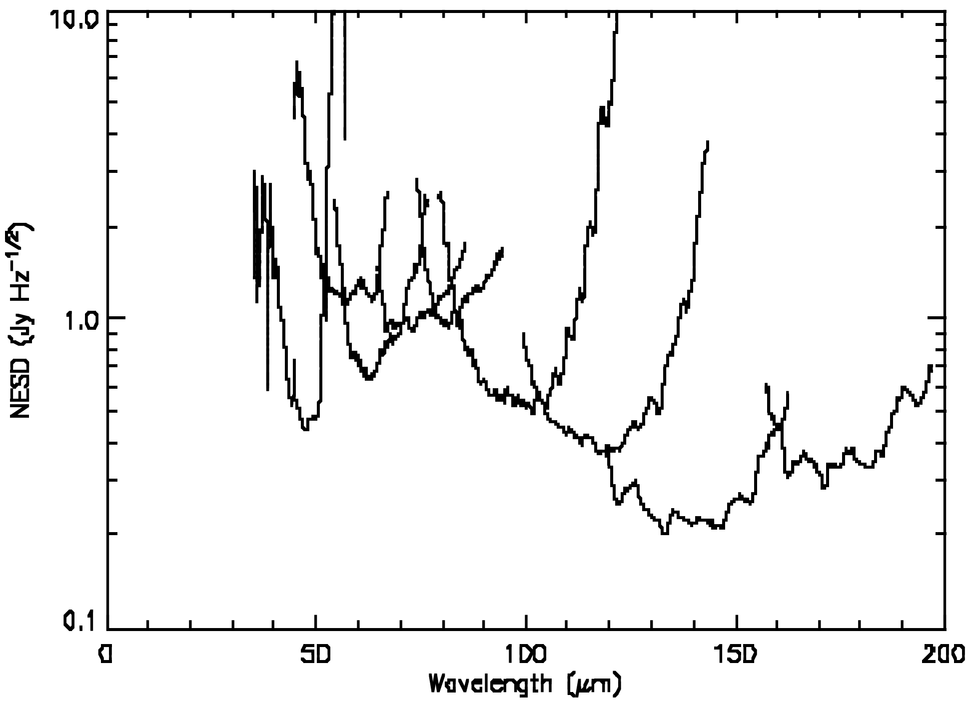

Figure 10. Noise-equivalent spectral-density of the LWS in grating mode.

For resolved lines or continua, the signal-to-noise ratio obtained in a single integration of time t is given by equation 5.6. In **grating mode**, $\tau_f(\nu)$ is set to unity and the sensitivity of the instrument is therefore determined directly by the $NESD_{Instr}$ given by equation 5.7, with $\Delta\lambda$ the resolution in grating mode. This is plotted as a function of wavelength in figure 10 and table 3 gives average values of $NESD_{Instr}$ over the sub-channels described above.

Finally, in **Fabry-Perot mode**, the performance is given by equations 5.6 and 5.7 with the appropriate Fabry-Perot values of $\tau(\nu)$ and $R(\nu)$. The resulting $NESD_{Instr}$ is tabulated in table 6 of §6.

You should appreciate that the above figures are for a *single point* in a spectrum. To obtain the time needed for a complete spectrum, you must multiply the times by the number of points in the spectrum, paying careful attention to the need to sample the spectrum fully. It will also be essential, in general, to repeat the spectrum off the source and perform a subtraction; all times should therefore be doubled. Finally, no account is taken these figures of any instrumental overheads. All these points are discussed in §6 below.

6. COOKERY BOOK

6.1 Astronomical Considerations in Use of the Instrument

The choice of AOT will obviously be dictated by the astronomical objectives. There are two general consideration which apply to all observations, however. The design of the LWS means that it is comparatively difficult to establish a zero level for spectra. In cases where the astronomical interest lies only in the strengths and structures of spectral lines, and where these line lie on measurable continua, this may not be important. In general, however, **we regard it is as mandatory that every observation on a source is repeated at a neighbouring position off the source**.

Secondly, the effective dynamic range of the LWS is about 1000:1, corresponding to 10 effective bits in the analogue-to-digital converter. It **is therefore impossible** to measure a **resolved line** whose spectral density is much less 1% of the continuum on which it may sit. Similarly, **it is impossible** to measure an **unresolved line** sitting on a continuum which, in the spectral resolution element, contributes much more than 100 times the flux of the line.

6.2 Grating-Mode Observations - LWS01, LWS02

This section describes the observing modes dedicated to medium-resolution observations with the grating. It contains a description of each AOT, of the observing parameters and of the standard data products. Section 6.2.4 summarises the performance at medium resolution. Narrow-band photometry, described in §4.5 above, is carried out with the same AOT as medium resolution line-spectra, using a zero-length scan.

6.2.1 DESCRIPTIONS

There are two AOTs available for observations with the grating:

LWS01: Medium-Resolution Wavelength Range: This AOT takes the spectrum of an object over a specified *range of wavelengths* lying between 43.0 μm and 196.7 μm.

LWS02: Medium-Resolution Line Spectrum. This AOT takes the spectrum of an object around a *number (1 to 10) of specified wavelengths* lying between 43.0 μm and 196.7 μm. Its main purpose is the detection of line emission.

The spectral-resolution element - the full width to half power (FWHP) of the spectral response function - is roughly constant at 0.29 μm between 43.0 μm and 90.5 μm and at 0.6 μm between 90.5 μm and 196.7 μm; the resolving *power* varies with wavelength between about 150 and 300 in each channel.

Using LWS01, any range of wavelength up to the full LWS range may be specified; a full grating scan is about 65 spectral elements long. The range actually covered, however, will not be less than 4 spectral-resolution elements.

A line spectrum using LWS02 is obtained by scanning the grating over each specified range. No account is taken of possible overlap of wavelength-coverage nor of the intrinsic multiplexing provided by the instrument. If several lines are to be covered, use of LWS01 over the full wavelength range of the LWS may incur very little increase - and could mean a decrease - in the total time needed to carry out the observation. Unfortunately, it is impossible to give a simple algorithm to assess this[3]. As a rough rule of thumb, observers should use LWS01 over the full wavelength range if the total number of spectral elements to be covered approaches about:

30 in the wavelength range 57.0 μm$<\lambda<$120.5 μm

60 otherwise.

At appropriate intervals, illuminator flashes are inserted between sets of scans to provide a relative photometric calibration of the detectors. Data are taken from all the detectors while the

[3]Users of the LWS Observing-Time Calculation Aid can investigate this by trial and error.

specified wavelength ranges are being scanned and these data will be processed. The signal-to-noise ratio specified by the user is only guaranteed, however at the specified *exposure wavelengths* (see below).

For each AOT, the observer may use the rapid scanning mode instead of the normal mode (cf. §4.4). This mode is recommended for observations in which the line-to-continuum ratio is less than 1:50. It may also be used to reduce the observation time, by a factor of up to 4, for a source brighter than about 50 Jy in the LWS wavelength range (cf. §6.4.3)

In narrow-band photometry, carried out with LWS02, the grating remains at a fixed position. In this mode spectro-photometry can be obtained at 10 fixed wavelengths between 43.0 μm and 196.7 μm.

All these observations can be performed at a single sky position or in a celestial raster.

With these AOTs, atomic and molecular lines can be sought in a variety of objects. One goal which can be pursued with medium resolution observations is to detect lines and compare their strengths in order to analyse abundances and ionisation conditions. Also, the continuum energy distribution in the far infrared can be studied in detail.

6.2.2 OBSERVING PARAMETERS

6.2.2.1 General

In both AOTs, the observer can choose between a single pointing (one target position) or a raster. If a raster is to be made, the observer provides the number of steps M(≤32) per line of the raster, the number of raster lines N(≤32), the angular distance dM (between 2 and 180 arcsec) on the sky between each raster step, the angular distance dN (between 0 and 180 arcsec) on the sky between each raster line and the orientation of the raster on the sky (degrees, from north to east) (cf. ISO Observer's Manual).

6.2.2.2 Medium-Resolution Wavelength Range - LWS01

A wavelength range is specified by the *start* and *end wavelengths.* A number (≥1) of *references exposures* must be specifies, for each of which the *wavelength* and the expected *continuum* or *line flux* has to be specified. If the line flux corresponds to a spectrally resolved feature, the *width* of the line must be given.

The *spectral sampling interval* is the number of spectral samples per resolution element. It can be 1, 2, 4 or 8. For wavelengths between 43.0 μm and 90.5 μm, these numbers correspond to samples taken approximately 0.29, 0.15, 0.08 and 0.04 μm apart respectively; for the wavelength range 90.5 μm to 196.7 μm, the corresponding figures are 0.6, 0.3, 0.15 and 0.07 μm.

If rapid scanning is desired, the *fast scan* flag has to be set. This option is described in §4.4 above. [Because the grating does not move in narrow-band photometry, the fast scan flag is not applicable to this mode.]

The observer can **either** specify the *signal-to-noise ratio* required at the reference lines **or** the *integration time* per spectral element.

The full list of parameters is given in table 1.

6.2.2.3 Medium-Resolution Line Spectrum - LWS02

The *number* of lines to be observed has to be specified. For each line, the *wavelength* and the expected *continuum* or *line* flux must be given.

The *spectral scan width* defines the width of the spectral scan, in multiples of the spectral resolution element, on either side of the line centre; it can have values 0, 2, 3 or 4. The total width of a scan over a line, expressed as number of resolution elements, is given by: 1 (the line centre) + 2 * (spectral scan width) and therefore has values 1, 5, 7 or 9 resolution elements. Setting the spectral scan width equal to zero automatically gives narrow-band photometry.

The *spectral sampling interval* is the number of spectral samples per resolution element. It can be 1, 2, 4 or 8. For wavelengths between 43.0 μm and 90.5 μm, these numbers correspond to samples taken approximately 0.29, 0.15, 0.07 and 0.04 μm apart respectively; for the wavelength range 90.5 μm to 196.7 μm, the corresponding figures are 0.6, 0.3, 0.15 and 0.07 μm.

For any specified line, the *actual line width* has to be given. If appropriate, it can be set to zero.

If rapid scanning is desired, the *fast scan* flag has to be set. This option is described in §4.4 above. [Because the grating is not move in narrow-band photometry, the fast scan flag is not applicable to this mode.]

The observer can **either** specify the *signal-to-noise ratio* required at the specified lines **or** the *integration time* per spectral element.

The full list of parameters is given in table 2.

6.2.3 Data Products

For each spectral sample, the observer will be given (i) the wavelength of the sample, (ii) the flux (W m^{-2}) integrated over the resolution element, and (iii) the spectral resolution element (μm).

6.2.4 Sensitivity Figures

The sensitivity of the instrument is encapsulated in the *noise-equivalent flux density (NEFD)* and the *noise-equivalent spectral density (NESD)*. These have been given graphically in §5 but these graphs contain more detail than is justified for calculating integration times. We have therefore averaged the sensitivity figures over bins roughly sixteen spectral elements wide: the results are given in table 3.

Table 1. Parameters for AOT LWS01

Parameter	Type	Values	Units	Description
M	Num(I)	<32	-	No of points in line of raster scan.
N	Num(I)	<32	-	No of lines in raster.
dM	Num(FP)	2 to 180	arcsec	Angular distance between points in raster line.
dN	Num(FP)	0 to 180	arcsec	Angular distance between raster lines.
THETA	Num(FP)	0 to 360	degree	Orientation of the raster on the sky, from north to east.
WAVES	Num(FP)		µm	Spectrum start wavelength.
WAVEE	Num(FP)	<WAVES	µm	Spectrum end wavelength.
INTERVAL	Num(I)	1, 2, 4, 8	-	Spectral sampling interval expressed as the number of spectral samples per spectral resolution element.
FAST	Logical	Y, N	-	Flag indicating whether individuals scans are to be carried out as quickly as possible.
NEXP	Num(I)	1 to 10	-	Number or reference exposure values. These are used to calculate the integration time needed to achieve the specified signal-to-noise ratios at each of the given wavelengths. For **each** exposure value:
WAVE	Num(FP) array. NEXP values	>WAVES <WAVEE	µm	Wavelengths for exposure values.
CFLUX	Num(FP) array. NEXP values.	≥0	Jy	Continuum flux for the object at each exposure-value wavelength. May only be zero if LFLUX is non-zero.
LFLUX	Num(FP) array. NEXP values.	≥0	$W\ m^{-2}$	Integrated line flux for the object at each exposure-value wavelength. May only be zero if CFLUX is non-zero.
WIDTH	Num(FP) array. NEXP values.	≥0	µm	Width of line for each exposure value. This parameter is needed only if the LFLUX value refers to a spectrally resolved line. If not, WIDTH should be set equal to zero.
SN	Num(FP) array. NEXP values.	≥1 or 0	-	Signal-to-noise ratio required, per spectral INTERVAL, at each exposure wavelength. This parameter must be set equal to zero if TINT is non-zero.
TINT	Num(FP) array. NEXP values.	>0 or 0	s	Integration time required, per spectral INTERVAL, at each exposure wavelength. This parameter must be set equal to zero if SN is non-zero.

Num() = Numeric. (FP) = Floating point. (I) = Integer.

Table 2. Parameters for AOT LWS02

Parameter	Type	Values	Units	Description
M N dM dN THETA	Num(I) Num(I) Num(FP) Num(FP) Num(FP)	<32 <32 2 to 180 0 to 180 0 to 360	- - arcsec arcsec degree	No of points in line of raster scan. No of lines in raster. Angular distance between points in raster line. Angular distance between raster lines. Orientation of the raster on the sky, from north to east.
NLINES	Num(I)	1 to 10	-	Number of lines to be scanned. For each line:
WAVE	Num(FP) array. NLINES values		μm	Wavelength at which the line is expected to be *observed* in the solar rest-frame.
NSPEL	Num(I) array. NLINES values	0, 2, 3, 4	-	Spectral scan-width, expressed as the number of spectral resolution elements to be scanned on *either side* of the central sample. If zero is specified, an under-sampled spectrum is obtained.
INTERVAL	Num(I) array. NLINES values	1, 2, 4, 8	-	Spectral sampling interval expressed as the number of spectral samples per spectral resolution element.
FAST	Logical	Y, N	-	Flag indicating whether individuals scans are to be carried out as quickly as possible. Must be set "N" if NSPEL is set equal to zero.
CFLUX	Num(FP) array. NLINES values.	≥0	Jy	Continuum flux for the object at each exposure-value wavelength. May only be zero if LFLUX is non-zero.
LFLUX	Num(FP) array. NLINES values.	≥0	$W\ m^{-2}$	Integrated line flux for the object at each exposure-value wavelength. May only be zero if CFLUX is non-zero.
WIDTH	Num(FP) array. NLINES values.	≥0	μm	Width of line for each exposure value. This parameter is needed only if the LFLUX value refers to a spectrally resolved line. If not, WIDTH should be set equal to zero.
SN	Num(FP) array. NLINES values.	≥1 or 0	-	Signal-to-noise ratio required, per spectral INTERVAL, at each exposure wavelength. This parameter must be set equal to zero if TINT is non-zero.
TINT	Num(FP) array. NLINES values.	>0 or 0	s	Integration time required, per spectral INTERVAL, at each exposure wavelength. This parameter must be set equal to zero if SN is non-zero.

Num() = Numeric. (FP) = Floating point. (I) = Integer.

TABLE 3: Sensitivity of the LWS in Medium-Resolution Mode

Channel No.	Wavelength Range (μm)	Spectral-Resolution Element (μm)	NEFD (10^{-17} W m^{-2} $Hz^{-1/2}$)	NESD (Jy $Hz^{-1/2}$)
SW1	43.0 - 47.0	0.29	27	0.63
	47.0 - 51.0	0.29	20	0.56
SW2	51.0 - 53.5	0.29	50	1.6
	53.5 - 57.0	0.29	40	1.4
SW3	57.0 - 61.5	0.29	18	0.73
	61.5 - 66.0	0.29	14	0.64
	66.0 - 70.0	0.29	16	0.83
SW4	70.0 - 74.3	0.29	16	0.96
	74.3 - 78.5	0.29	15	1.0
SW5	78.5 - 82.5	0.29	13	1.0
	82.5 - 86.5	0.29	14	1.1
	86.5 - 90.5	0.29	14	1.3
LW1	90.5 - 95.5	0.60	14	0.65
	95.5 - 101.5	0.60	11	0.59
LW2	101.5 - 111.0	0.60	6.6	0.42
	111.0 - 120.5	0.60	4.9	0.37
LW3	120.5 - 128.5	0.60	3.4	0.29
	128.5 - 136.5	0.60	2.2	0.21
	136.5 - 144.5	0.60	2.0	0.22
	144.5 - 152.5	0.60	2.0	0.25
	152.5 - 161.2	0.60	2.8	0.38
LW5	161.2 - 168.2	0.60	2.5	0.38
	168.2 - 175.2	0.60	2.0	0.33
	175.2 - 182.2	0.60	2.2	0.40
	182.2 - 190.2	0.60	2.4	0.47
	190.2 - 196.7	0.60	2.9	0.60

6.3 Fabry-Perot Observations - LWS03, LWS04

This section describes the observing modes dedicated to high-resolution observations with the Fabry-Perot. It contains a description of each AOT, of the observing parameters and of the standard data products. Section 6.3.4 summarises the performance at high resolution.

6.3.1 DESCRIPTIONS

As for grating-mode observations, there are two AOTs for use in Fabry-Perot mode.

LWS03: High-Resolution Wavelength Range: This AOT takes the spectrum of an object over a specified *range of wavelengths* lying between 47.0 µm and 196.7 µm.

LWS04: High-Resolution Line Spectrum. This AOT takes the spectrum of an object around a *number (1 to 10) of specified wavelengths* lying between 47.0 µm and 196.7 µm. Its main purpose is the study of line emission.

The *resolving power*, defined as the ratio of the wavelength to the resolution element, is some 8,000 or more, corresponding to a resolution element of less than 0.025 µm over the entire LWS wavelength range.

A spectrum is obtained by performing a series of Fabry-Perot scans, each with the grating held at a fixed calibrated position. In the case of LWS03, the scans are arranged to overlap in wavelength so as to provide a complete spectrum. For LWS04, the grating is set to the nearest calibrated position for each line and a Fabry-Perot scan is performed about that line. At appropriate times, illuminator flashes are inserted between sets of scans to provide a relative photometric calibration of the detectors. Data are processed only for the channel covering the current wavelength range or spectral line.

The observer may use the rapid scanning mode, instead of the normal mode (see §4.4), for either AOT. This mode is recommended for observations in which the line-to-continuum ratio is estimated to be less than 1:50.

High resolution observations can be performed at a single sky position or in a celestial raster.

These AOTs can be used to explore spectral features (in relatively bright objects) which are unresolved at medium resolution. Profiles of lines originating in high temperature environments or in high velocity outflows can therefore be studied.

6.3.2 OBSERVING PARAMETERS

6.3.2.1 General

In both AOTs, the observer can choose between a single pointing (one target position) or a raster. If a raster is to be made, the observer provides the number of steps M(≤32) per line of the raster, the number of raster lines N(≤32), the angular distance dM (between 2 and 180 arcsec) on the sky between each raster step, the angular distance dN (between 0 and 180 arcsec) on the sky between each raster line and the orientation of the raster on the sky (degrees, from north to east) (cf. ISO Observer's Manual).

6.3.2.2 High-Resolution Wavelength Range - LWS03

A wavelength range is specified by the *start* and *end wavelengths.* A number (≥1) of *references exposures* must be specifies, for each of which the *wavelength* and the expected *continuum* or *line flux* has to be specified. If the line flux corresponds to a spectrally resolved feature, the *width* of the line must be given.

The *spectral sampling interval* is the number of spectral samples per resolution element. It can be 1, 2, 4 or 8.

If rapid scanning is desired, the fast *scan* flag has to be set. This option is described in §4.4 above.

The observer can **either** specify the *signal-to-noise ratio* required at the reference lines **or** the *integration time* per spectral element.

The full list of parameters is given in table 4.

6.3.2.3 High-Resolution Line Spectrum - LWS04

The *number* of lines to be observed has to be specified. For each line, the *wavelength* and the expected *continuum* or *line* flux must be given.

The *spectral scan width* defines the width of the spectral scan, in multiples of the spectral resolution element, on either side of the line centre; it can have values 3, 4 or 5. The total width of a scan over a line, expressed as number of resolution elements, is given by: 1 (the line centre) + 2 * (spectral scan width) and therefore has values 7, 9 or 11 resolution elements. Setting the spectral scan width equal to zero automatically gives narrow-band photometry.

The *spectral sampling interval* is the number of spectral samples per resolution element. It can be 1, 2, 4 or 8.

For any specified line, the *actual line width* has to be given. If appropriate, it can be set to zero.

If rapid scanning is desired, the fast *scan* flag has to be set. This option is described in §4.5 above.

The observer can **either** specify the *signal-to-noise ratio* required at the specified lines **or** the *integration time* per spectral element.

The full list of parameters is given in table 5.

6.3.3 DATA PRODUCTS

For each spectral sample, the observer will be given (i) the wavelength of the sample, (ii) the flux (W m^{-2}) integrated over the resolution element, and (iii) the spectral resolution element (µm).

6.3.4 SENSITIVITY FIGURES

The sensitivity of the instrument is encapsulated in the *noise-equivalent flux density (NEFD)* and the *noise-equivalent spectral density (NESD)*. We have averaged these sensitivity figures over the same bins as used in table 6.

Table 4. Parameters for AOT LWS03

Parameter	Type	Values	Units	Description
M	Num(I)	<32	-	No of points in line of raster scan.
N	Num(I)	<32	-	No of lines in raster.
dM	Num(FP)	2 to 180	arcsec	Angular distance between points in raster line.
dN	Num(FP)	0 to 180	arcsec	Angular distance between raster lines.
THETA	Num(FP)	0 to 360	degree	Orientation of the raster on the sky, from north to east.
WAVES	Num(FP)		μm	Spectrum start wavelength.
WAVEE	Num(FP)	<WAVES	μm	Spectrum end wavelength.
INTERVAL	Num(I)	1, 2, 4, 8	-	Spectral sampling interval expressed as the number of spectral samples per spectral resolution element.
FAST	Logical	Y, N	-	Flag indicating whether individuals scans are to be carried out as quickly as possible.
NEXP	Num(I)	1 to 10	-	Number or reference exposure values. These are used to calculate the integration time needed to achieve the specified signal-to-noise ratios at each of the given wavelengths. For **each** exposure value:
WAVE	Num(FP) array. NEXP values	>WAVES <WAVEE	μm	Wavelengths for exposure values.
CFLUX	Num(FP) array. NEXP values.	≥0	Jy	Continuum flux for the object at each exposure-value wavelength. May only be zero if LFLUX is non-zero.
LFLUX	Num(FP) array. NEXP values.	≥0	W m^{-2}	Integrated line flux for the object at each exposure-value wavelength. May only be zero if CFLUX is non-zero.
WIDTH	Num(FP) array. NEXP values.	≥0	μm	Width of line for each exposure value. This parameter is needed only if the LFLUX value refers to a spectrally resolved line. If not, WIDTH should be set equal to zero.
SN	Num(FP) array. NEXP values.	≥1 or 0	-	Signal-to-noise ratio required, per spectral INTERVAL, at each exposure wavelength. This parameter must be set equal to zero if TINT is non-zero.
TINT	Num(FP) array. NEXP values.	>0 or 0	s	Integration time required, per spectral INTERVAL, at each exposure wavelength. This parameter must be set equal to zero if SN is non-zero.

Num() = Numeric. (FP) = Floating point. (I) = Integer.

Table 5. Parameters for AOT LWS04

Parameter	**Type**	**Values**	**Units**	**Description**
M	Num(I)	<32	-	No of points in line of raster scan.
N	Num(I)	<32	-	No of lines in raster.
dM	Num(FP)	2 to 180	arcsec	Angular distance between points in raster line.
dN	Num(FP)	0 to 180	arcsec	Angular distance between raster lines.
THETA	Num(FP)	0 to 360	degree	Orientation on the sky, from north to east.
NLINES	Num(I)	1 to 10	-	Number of lines to be scanned. For each line:
WAVE	Num(FP) array. NLINES values		μm	Wavelength at which the line is expected to be *observed* in the solar rest-frame.
NSPEL	Num(I) array. NLINES values	3, 4, 5	-	Spectral scan-width, expressed as the number of spectral resolution elements to be scanned on *either side* of the central sample. If zero is specified, an under-sampled spectrum is obtained. One spectral element should be allowed for the effect of the velocity of the satellite with respect to the solar rest-frame.
INTERVAL	Num(I) array. NLINES values	1, 2, 4, 8	-	Spectral sampling interval expressed as the number of spectral samples per spectral resolution element.
FAST	Logical	Y, N	-	Flag indicating whether individuals scans are to be carried out as quickly as possible.
CFLUX	Num(FP) array. NLINES values.	≥0	Jy	Continuum flux for the object at each exposure-value wavelength. May only be zero if LFLUX is non-zero.
LFLUX	Num(FP) array. NLINES values.	≥0	$W m^{-2}$	Integrated line flux for the object at each exposure-value wavelength. May only be zero if CFLUX is non-zero.
WIDTH	Num(FP) array. NLINES values.	≥0	μm	Width of line for each exposure value. This parameter is needed only if the LFLUX value refers to a spectrally resolved line. If not, WIDTH should be set equal to zero.
SN	Num(FP) array. NLINES values.	≥1 or 0	-	Signal-to-noise ratio required, per spectral INTERVAL, at each exposure wavelength. This parameter must be set equal to zero if TINT is non-zero.
TINT	Num(FP) array. NLINES values.	>0 or 0	s	Integration time required, per spectral INTERVAL, at each exposure wavelength. This parameter must be set equal to zero if SN is non-zero.

Num() = Numeric. (FP) = Floating point. (I) = Integer.

TABLE 6: Sensitivity of the LWS in High-Resolution Mode

Fabry -Perot	Channel No.	Wavelength Range (μm)	Resolving Power	Resolution Element (nm)	NEFD (10^{-17} (W m^{-2} $Hz^{-1/2}$)	NESD (Jy $Hz^{-1/2}$)
FPS	SW1	47.0 - 51.0	8594	5.7	100	150
	SW2	51.0 - 53.5	8514	6.1	300	440
		53.5 - 57.0	8431	6.6	270	420
	SW3	57.0 - 61.5	8343	7.1	140	230
		61.5 - 66.0	8226	7.8	130	230
		66.0 - 70.0	8112	8.4	180	340
FPL	SW4	70.0 - 74.3	6852	10.5	64	110
		74.3 - 78.5	7842	9.7	65	130
	SW5	78.5 - 82.5	8607	9.3	61	140
		82.5 - 86.5	9172	9.2	66	170
		86.5 - 90.5	9559	9.2	74	210
	LW1	90.5 - 95.5	9782	9.5	75	230
		95.5 - 101.5	9748	10.1	66	210
	LW2	101.5 - 111.0	9612	11.1	46	160
		111.0 - 120.5	9526	12.1	41	150
	LW3	120.5 - 128.5	9432	13.2	32	130
		128.5 - 136.5	9335	14.2	24	100
		136.5 - 144.5	9226	15.2	27	120
		144.5 - 152.5	9107	16.3	31	140
		152.5 - 161.2	8969	17.5	50	230
	LW5	161.2 - 168.2	8829	18.7	51	250
		168.2 - 175.2	8696	19.7	45	220
		175.2 - 182.2	8553	20.9	53	270
		182.2 - 190.2	8390	22.2	60	310
		190.2 - 196.7	8230	23.5	71	370

6.4 How to Estimate Observing Times

6.4.1 Calculation of Number of Spectral Samples

6.4.1.1 Medium-Resolution Wavelength Range

For medium-resolution mode, $\Delta\lambda$ is constant over the five short-wavelength channels (SW1-SW5) and over the four long-wavelength channels (LW1-LW3, LW5). You should therefore calculate the number $N_{s(S,L)}$ of spectral samples needed to cover the specified wavelength range as follows:

$$N_s(S,L) = \min\left\{\frac{[WAVES - WAVEE]}{\Delta\lambda(S,L)},\ Samples_{\max}\right\} \times INTERVAL, \tag{6.1}$$

where $\Delta\lambda\ (S,L)$ is the resolution element in the short-wavelength channels (S) or the long-wavelength channels (L); it is given in table 3. $\mathrm{Samples}_{\max}$ is the maximum numbers of samples in a full grating scan:

$$Samples_{\max} = \begin{cases} 35 & 43.0\mu\mathrm{m} \le \lambda \le 90.5\mu\mathrm{m} \\ 65 & 90.5\mu\mathrm{m} \le \lambda \le 196.7\mu\mathrm{m} \end{cases} \tag{6.2}$$

If the wavelength range *[WAVEE-WAVES]* spans both the short-and long-wavelength channels, you should split it into the two appropriate sub-ranges and calculate N_s separately for each. The total N_s is then the sum

$$N_s = N_s(S) + N_s(L) \tag{6.3}$$

Note that, as discussed in §6.2 **for grating-mode only**, if N_t approaches about

30 in the wavelength range 57.0 µm<λ<120.5 µm

60 otherwise,

you should consider carrying out a scan over the full wavelength range of the LWS using LWS01.

6.4.1.2 High-Resolution Wavelength Range

For high-resolution mode, it is the resolving *power* which is roughly constant over the ranges of the short- and the long-wavelength Fabry-Perots. You should therefore calculate $N_s(S,L)$ as follows:

$$N_s(FPS,FPL) = \frac{[WAVEE - WAVES]}{\min\left[\Delta\lambda_{FPS,FPL}\right]} \times INTERVAL, \tag{6.4}$$

where

$$\min\left[\Delta\lambda_{FPS,FPL}\right] \tag{6.5}$$

is the minimum resolution element over the specified range (cf. table 6 of §6). As before, if the wavelength range *[WAVEE-WAVES]* spans the ranges of both the short- and long-wavelength Fabry-Perots, you should split it into two sub-ranges, calculate $N_s(FPS,FPL)$ for each and take the total:

$$N_s = N_s(FPS) + N_s(FPL) \tag{6.6}$$

You should note that a full spectral scan in Fabry-Perot mode is 15,000 spectral elements!

6.4.1.3 Medium- and High-Resolution Line Spectrum

You should therefore calculate the number N_s of spectral samples needed to cover the specified lines:

$$N_s = NLINES \times [1 + 2 \times NSPEL] \times INTERVAL, \tag{6.7}$$

6.4.2 Estimation of Integration Times per Spectral Sample

6.4.2.1 Isolated Unresolved Lines

This is the simplest example. For each specified exposure value (wavelength range AOT) or for each specified line (line-spectrum AOT) you should calculate the integration time needed per spectral sample according to equation 5.4:

$$t_n = \frac{1}{2}\left[SN \times \frac{NEFD}{LFLUX_n}\right]^2, \tag{6.8}$$

where $LFLUX_n$ is the integrated line flux-density at each of the specified exposure values (wavelength range AOT) or specified lines (line-spectrum AOT). The values of *NEFD* are taken from table 3 or table 6, depending on whether medium or high resolution mode is being used. The integration time t_s to be used, per spectral sample, is then given by

$$t_{sample} = \max[t_n]. \tag{6.9}$$

6.4.2.2 Continuum or Isolated Resolved Lines

For each specified exposure value (wavelength range AOT) or for each specified line (line-spectrum AOT) you should calculate the integration time needed per spectral sample according to equation 5.6:

$$t_n = \frac{1}{2}\left[SN \times \frac{NESD}{CFLUX_n}\right]^2, \tag{6.10}$$

where $CFLUX_n$ is the spectral flux-density at each of the specified exposure values (wavelength range AOT) or specified lines (line-spectrum AOT). The values of *NESD* are taken from table 3 or table 4, depending on whether medium or high resolution mode is being used. The integration time t_s to be used, per spectral sample, is then given by

$$t_{sample} = \max[t_n]. \tag{6.11}$$

6.4.2.3 Resolved Lines on Continua

This is more complicated. The software used in the Ground Segment calculates signal-to-noise ratios on the basis of the *total* power - line plus continuum - falling on the detector. The observer, on the other hand, is often more interested in the signal-to-noise ratio SN_{line} **obtained on the line**, measured *above* the continuum. We have

$$CFLUX = CFLUX_{line} + CFLUX_{continuum} \tag{6.12}$$

so that

$$\begin{aligned} SN &:= \frac{CFLUX}{Noise} = \frac{CFLUX_{line} + CFLUX_{continuum}}{Noise} \\ &= \frac{CFLUX_{line}}{Noise}\left[1 + \frac{CFLUX_{continuum}}{CFLUX_{line}}\right] \\ &= SN_{line}\left[1 + \frac{CFLUX_{continuum}}{CFLUX_{line}}\right] \end{aligned} \tag{6.13}$$

If you wish to achieve a given signal-to-noise ratio on the line, therefore, you should separately estimate the spectral flux-density for the line and the continuum and then use equation 6.13 to estimate the total signal-to-noise ratio *SN* needed. [Note: If the ratio of the continuum spectral density to the line spectral density exceeds about 50, you should use rapid scanning (cf. §4.4)].

To use equation 6.13, you should first estimate the spectral flux density $S(\nu)$ of the line at its centre:

$$S(\nu) = \frac{F_\nu}{\Delta\nu} = \frac{\lambda^2}{c}\frac{F_\nu}{\Delta\lambda} \tag{6.14}$$

where $S(\nu)$ is $CFLUX_{line}$ and F_ν is $LFLUX_{line}$. $\Delta\lambda$ is the line width.

Having estimated the signal-to-noise ratio SN_n required for each specified exposure value (wavelength range AOT) or for each specified line (line-spectrum AOT) you should calculate the overall signal-to-noise ratio required according to

$$SN = \max[SN_n] \tag{6.15}$$

and then the integration time needed per spectral sample according to equation 5.6, as before:

$$t_n = \frac{1}{2}\left[SN \times \frac{NESD}{CFLUX_n}\right]^2, \tag{6.16}$$

where $CFLUX_n$ is the *total* spectral flux-density at each of the specified exposure values (wavelength range AOT) or specified lines (line-spectrum AOT). The values of *NESD* are taken from table 3 or table 6, depending on whether medium or high resolution mode is being used. The integration time t_s to be used, per spectral sample, is then given by

$$t_{sample} = \max[t_n]. \tag{6.17}$$

6.4.2.4 Un-Resolved Lines on Continua

This follows the previous case but is yet more complicated. We now have

$$CFLUX = \frac{LFLUX_{line}}{\Delta\lambda} + CFLUX_{continuum}, \tag{6.18}$$

where $\Delta\lambda$ is the spectral resolution element at the given wavelength. Equation 6.13 is now modified to

$$SN = SN_{line}\left[1 + \frac{CFLUX_{continuum}\Delta\lambda}{LFLUX_{line}}\right]. \tag{6.19}$$

If you wish to achieve a given signal-to-noise ratio on the line, therefore, you should separately estimate the flux-density for the line and the spectral flux-density for the continuum and then use equation 6.19 to estimate the total signal-to-noise ratio *SN* needed. [Note: If the ratio of the continuum spectral density to the line spectral density exceeds about 50, you should use rapid scanning (cf. §4.4)].

Having estimated the signal-to-noise ratio SN_n required for each specified exposure value (wavelength range AOT) or for each specified line (line-spectrum AOT) you should calculate the overall signal-to-noise ratio required according to

$$SN = \max[SN_n] \tag{6.20}$$

and then the integration time needed per spectral sample according to equation 5.6, as before:

$$t_n = \frac{1}{2}\left[SN \times \frac{NESD}{CFLUX_n}\right]^2, \tag{6.21}$$

where $CFLUX_n$ is the *total* spectral flux-density at each of the specified exposure values (wavelength range AOT) or specified lines (line-spectrum AOT). The values of *NESD* are taken from table 3 or table 6, depending on whether medium or high resolution mode is being used. The integration time t_s to be used, per spectral sample, is then given by

$$t_{sample} = \max[t_n]. \tag{6.22}$$

6.4.3 Estimation of Total Observing Time

Having estimated the total number of spectral samples N_s and the integration time t_s needed per sample you could now estimate the total time T_{obs} needed to make the observation by

$$T_{obs} = 2 \times N_s \times \max\left[\frac{t_s}{\varepsilon},\ 3\text{s}\right] \times (M \times N) \tag{6.23}$$

where *(MxN)* is the number of point in the raster and ε is an efficiency factor which take account of instrumental overheads. The factor 2 is needed for repeating the observation off the source (cf. §6.1). The expression

$$\max\left[\frac{t_s}{\varepsilon},\ 3\text{s}\right]$$

is needed because, for technical reasons, the minimum value of t_s/ε is 3 seconds. Use of the fast-scanning mode, however, can reduce the time needed to observe sources brighter than about 50 Jy by a factor of up to 4 (cf. §6.2.1).

Although instrumental overheads are taken account of in the Ground Segment software, it is impossible to give a simple algorithm for estimating ε. Our experience is that in the worst case (bright sources, short integration times) ε is 40-45% and in the best case (faint sources, long integration times) ε is about 90%. Since the worst case implies a short observation anyway, we suggest that you use a standard figure of 75% for all observations. We believe that this will also give adequate margin to include the time taken to move between raster points: this is usually very small compared with the time needed for integration at each point.

6.5 Worked Examples

The examples given in this section are actual observations from the LWS Central Programme.

6.5.1 Grating range scan.

The proposed observation is a full grating scan (43 to 190 μm) of an AGB star. The reference wavelengths are 60 and 100 μm, with continuum fluxes of 24 and 9.7 Jy respectively. The spectrum is to be taken with 4 samples per resolution element, and the signal-to-noise ratio required is 50 at both wavelengths.

First step is the calculation of the number of steps in the scan (§ 6.4.1.). Since we are doing a full scan, the number of resolution elements for the full spectral range is equal to the maximum number of resolution elements to cover the range of one detector. This maximum is about 65 for detector LW3. The number of samples is thus (equations 6.1 and 6.2):

$$N_s = 65 \times 4 = 260.$$

The factor 4 arises because of the 4 samples per resolution element.

Secondly we have to calculate the integration time per step needed to obtain the signal-to-noise ratio required. We use formula 6.10 for each reference wavelength.

60 μm: detector SW3, with NESD = 0.73 Jy $Hz^{-1/2}$. The required integration time to get signal-to-noise ratio=50 for a flux of 24 Jy is 1.16 sec.

100 μm: detector LW1, with NESD = 0.59 Jy $Hz^{-1/2}$. The required integration time to get signal-to-noise ratio=50 for a flux of 9.7 Jy is 4.62 sec.

The second reference wavelength gives the larger integration time, and should therefore be used for calculating the total integration time.

The total time for on- and off-source observation is then (equation 6.23):

$$T_{obs} = 2 \times 260 \times \frac{4.62}{0.75} \text{ s} = 3203 \text{ s}$$

or about 53 minutes.

6.5.2 GRATING LINE SCAN.

The proposed observation is a grating line scan of the [CII] 158 micron line in an active galaxy. The continuum flux of this source is about 150 Jy at 158 μm and the expected flux of the [CII] line is 6 10^{-17} W m^{-2}.

The line is 0.5 μm wide, and is therefore unresolved. The signal-to-noise ratio required on the line is 10, and the scan width is 3 elements on either side with 4 samples per element. The line falls onto detector LW3, with NESD=0.38 Jy $Hz^{-1/2}$ and a resolution element width of 0.6 μm. The number of samples in this scan is therefore (equation 6.7):

$$N_s = 4 \times (1 + 2 \times 3) = 28$$

The equivalent spectral density for the unresolved line at 158 μm is CFLUX(line)=6 10^{-17}/0.5=1.2 10^{-16} W m^{-2} μm^{-1}, which is equivalent to about 1 Jy. Since this is about 1/150 of the continuum flux, this observation probably is best done with fast scanning. The signal-to-noise ratio on the total flux at 158 μm has to be calculated next. The continuum flux at 158 μm (150 Jy) is equivalent to 1.8 10^{-14} W m^{-2} μm^{-1}. The signal-to-noise ratio on the total flux is (equation 6.19):

$$SN = SN_{line} \times \left(1 + \frac{CFLUX_{cont} \times \Delta\lambda}{LFLUX_{line}}\right)$$
$$= 10 \times \left(1 + \frac{1.8 \times 10^{-14} \times 0.6}{6 \times 10^{-17}}\right) = 1810$$

Note that a very high SN on the continuum is required to get SN=10 on the weak line!

The integration time needed to achieve this signal-to-noise ratio is (equation 6.16):

$$t_{\text{int}} = \frac{1}{2}\left[SN \times \frac{NESD}{CFLUX_n}\right] = 0.5 \times \left(1810 \times \frac{0.38}{151}\right)^2 \text{ s} = 10.4 \text{ s}$$

This means the total integration time, on- and off-source, is (equation 6.23):

$$T_{obs} = 2 \times 28 \times 10.4 \text{ s} = 582 \text{ s},$$

or about 10 minutes.

6.5.3 FP WAVELENGTH RANGE SCAN.

The proposed observation is a FP scan over the NH_3 band at about 84 µm in a planet. The scan should run from 82.6 to 86.2 µm. The continuum flux at this wavelength is about 95,000 Jy, and the requested signal-to-noise ratio on the continuum is 500. The spectrum should be taken with 2 samples per resolution element.

The scan falls in the SW5 range. At this wavelength the resolving power of the instrument is about 9170. This gives for the number of spectral samples in the scan (equation 6.4):

$$N_s = \frac{(86.2 - 82.6)}{0.0092} \times 2 = 783$$

The SW5 detector has a NESD of about 170 Jy $Hz^{-1/2}$. This means that in order to get signal-to-noise ratio=500 on the continuum we need (equation 6.10):

$$t_{\text{int}} = 0.5 \times \left(500 \times \frac{170}{95000} \right)^2 \text{s} = 0.40 \text{ s}$$

The estimated observing time is less than three seconds so we replace the estimated time divided by the efficiency by 3 s (cf. §6.4.3). The total observing time on- and off-source will then be given by (equation. 6.23):

$$T_{obs} = 2 \times 783 \times \ 3.0 \text{ s} = \ 4698 \text{ s}$$

or about 1 hour 18 minutes.

6.5.4 FP LINE SCAN.

The proposed observation is an FP line scan of the 63 µm [OI] line in a star-forming region. The estimated line flux is 5 10^{-15} W m^{-2}. The continuum flux at 60 µm is 373 Jy. The scan is to be over 4 resolution elements on either side of the line with 4 samples per resolution element. The expected line width is 100 km s^{-1}, or 0.02 µm, so the line is resolved. The requested signal-to-noise ratio on the line is 10.

The line falls in the range of detector SW3. The resolution in this range is about 8200, and one resolution element is about 0.0078 µm wide. The total number of samples in the scan is equal to

$$N_s = 4 \times 9 = 36$$

The integrated line flux is equivalent to a continuum flux of

$$CFLUX_{line} = \frac{5 \times 10^{-15}}{0.02} = 2.5 \times 10^{-13} \text{ W m}^{-2} \ \mu\text{m}^{-1}$$

This is equivalent to a flux of 330 Jy. The total flux thus is

$$CFLUX = 330 + 373 = 703 \text{ Jy}$$

is The signal-to-noise ratio required on the total flux to achieve the signal-to-noise ratio on the line then (equation 6.13)

$$SN = SN_{line} \times \left(1 + \frac{CFLUX_{cont}}{CFLUX_{line}} \right)$$
$$= 10 \times \left(1 + \frac{373}{330} \right) = 21$$

The integration time needed to achieve this signal-to-noise ratio is, using that the *NESD* for detector SW3 is 230 Jy $Hz^{-1/2}$ (equation 6.16):

$$t_{\mathrm{int}} = 0.5 \times \left(SN \times \frac{NESD}{CFLUX} \right)^2$$

$$= 0.5 \times \left(21 \times \frac{230}{703} \right)^2 \mathrm{s} = 23.6\ \mathrm{s}$$

This gives for 36 samples a total observation time, on- and off-source, (equation. 6.23):

$$T_{obs} = 2 \times 36 \times \frac{23.6}{0.75}\ \mathrm{s} = 2266\ \mathrm{s}$$

or about 38 minutes.

7. ACRONYMS

AOT	Astronomical Observation Template
APU	Analogue Processing Unit
DPU	Digital Processing Unit
FET	Field-effect transistor
FIR	far-infrared (>20 µm)
FPU	Focal Plane Unit
FWHP	Full width to half power
IRAS	Infrared Astronomical Satellite
ISO	Infrared Space Observatory
ISOCAM	ISO instrument: camera, also abbreviated CAM
LWS	ISO instrument: long-wavelength spectrometer
ISOPHOT	ISO instrument: imaging photo-polarimeter, also abbreviated PHT
SWS	ISO instrument: short-wavelength spectrometer
FP	Fabry-Perot
KAO	Kuiper Airborne Observatory
MIR	mid-infrared (5-20 µm)
NEFD	Noise-equivalent flux density (for line fluxes)
NESD	Noise-equivalent spectral density (for continuum fluxes)
NIR	near-infrared (<5 µm)
PAH	polycyclic aromatic hydrocarbons
PGA	Proposal Generation Aids
PHT	ISO instrument: imaging photo-polarimeter, also abbreviated ISO
SN or SNR	Signal-to-noise ratio
TBC	to be confirmed
TBD	to be determined

8. Glossary

Airy disc:

The circular diffraction image inside the first minimum of the point spread function.

Astronomical Observation Template (AOT):

Representation of an instrument observing mode in the proposal generation aids software (PGA). By selecting a specific template and filling in the variable parameters with specific values an astronomical observation of the target is defined.

Background

Celestial emission towards the direction of the source. The contributions are: Zodiacal Light, diffuse galactic emission and local diffuse emission in the vicinity of the source.

Drift:

Temporal variation of detector response.

Integration Time:

The time during which the target is observed. This is calculated per spectral sample.

Observational Mode or Observing mode:

An instrument mode dedicated to a specific type of astronomical observation. The representation of an observing mode *vis-à-vis* the observer is an AOT.

Observation Time or Observing Time:

Time needed to carry out an observation specified with one AOT. It is the sum of integration times over all spectral point and, in the case of a celestial raster, over all raster points.

Operational Mode

A mode in which the instrument can be operated; i.e. medium resolution (grating) mode or high resolution (Fabry-Perot) mode.

Overhead:

Time to prepare the spacecraft and instrument for an observation, e.g. detector heating, wheel positioning and spacecraft slews.

Point spread function:

The intensity distribution of an ideal point source in the focal plane resulting from the diffraction by the telescope optics.

Pointing:

Positioning of spacecraft at a required sky position.

Raster:

A series of regularly spaced pointed observations, where at each position the observation is repeated. It is defined by the central position, the number of raster legs and raster positions along one leg, the step sizes along the leg and between different legs, and the orientation on the sky.

Resolution Element:

The width in wavelength corresponding to the resolution of the grating or the Fabry-Perot.

Sampling Interval or Spectral Sampling Interval:

Number of spectral points sampled per resolution element.

Scan or Spectral Scan:

A series of spectral points obtained by moving the grating, and the Fabry-Perot in the case of high resolution observations, through a particular number of positions.

Scan Width:

The wavelength range covered by a scan. It is expressed in number of resolution elements.

Schmidt Profile:

A profile of a reflecting surface that corrects for spherical aberration over a large area.

Spectral Point:

Sample of the spectrum observed with a single grating position and, if applicable, with a single position of Fabry-Perot etalons.

Stressed Detectors:

Detectors mounted under stress.

Subsystem or Sub-instrument:

Specific part of the instrument; e.g. optics, Fabry-Perot or detectors.

Target dedicated time:

The time spent for the observation of a source in an observing mode including integration time and overhead times.

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