

ASTRONOMICAL SPECTROMETRY IN THE
NEAR-INFRARED

BY

Charles Mattias Mountain
BSc, ARCS

Astronomy Group
Blackett Laboratory
Imperial College of Science and Technology
London SW7

A thesis submitted for the degree of
Doctor of Philosophy of the University of London
and for the
Diploma of Membership of the Imperial College

December 1982

ABSTRACT

ASTRONOMICAL SPECTROMETRY IN THE NEAR-INFRARED

C. M. Mountain

Descriptions of two related projects are presented. The first is the design and construction of a $1\ \mu\text{m} - 5\ \mu\text{m}$ cooled grating spectrometer for astronomical work. Second, this thesis reports the measurement of the absolute flux from Vega in the J, K, L and M photometric bands.

The cooled grating spectrometer, with a resolution $R = 10^2 - 10^3$, was designed for work using the 1.5 m I.R.F.C. in Tenerife. The importance of longterm stability and accurate wavelength registration in such an instrument is stressed. A description of the control and data acquisition electronics is given and results from a first commissioning run are shown.

The absolute flux from Vega has been measured by comparison with a standard furnace. The results show a systematic disagreement with current Stellar Models in the K and L bands. Attempts to measure the flux in the M band are severely limited in accuracy by uncertainties in the atmospheric extinction.

To try and overcome this a theoretical atmospheric transmission model has been used to make first order corrections. It is concluded that the only accurate way to measure the $5\ \mu\text{m}$ flux, to confirm this systematic trend seen at K and L, is to use a cooled grating spectrometer. A spectrophotometric scheme is proposed based on a preliminary attempt made in Tenerife.

Appendix E contains a paper describing the problems of atmospheric extinction at $5\ \mu\text{m}$ with relevance to both photometry and spectrometry. In Appendix F a paper is presented on the possibility of detecting the cosmologically significant molecule HD in the near-infrared.

*The Universe is sacred.
You cannot improve it.*

*How do I know the Universe
is like this?*

By looking!

*Lao Tsu
(circa. 500 B.C.)*

LIST OF CONTENTS

	Page
ABSTRACT	2
PREFACE	8
ACKNOWLEDGEMENTS	10
LIST OF TABLES	12
LIST OF FIGURES	13
CHAPTER ONE <i>Astronomical Spectrometry in the Near-Infrared</i>	16
1.1 Introduction	16
1.2 Requirements for Infrared Spectrometer	19
1.2.1 Cooled or Uncooled Instrument	19
1.2.2 Detector noise versus Background shot noise	21
1.3 Type of Spectrometer	23
1.3.1 Prism or Grating	23
1.3.2 Luminosity, Resolution and Telescope Size	25
1.3.2.1 Point sources	26
1.3.2.2 Extended sources	28
1.3.3 Fabry-Perot Spectrometer	30
1.3.4 Multiplex Spectrometers	32
1.4 Conclusion	36
CHAPTER TWO <i>Design, Construction and Operation of Cooled Grating Spectrometer</i>	37
2.1 Optical Configuration	37

	Page
2.2 Mechanical Design	41
2.2.1 Materials	42
2.2.2 Optical Supports	42
2.2.3 Grating drive and Rotation	44
Encoding	
2.2.4 Cryostat	47
2.3 Alignment and Positioning of Detector	47
2.4 Data Acquisition and Control Electronics	51
2.4.1 Shaft Encoder	51
2.4.2 Control and Data Acquisition	51
2.4.3 Detector and Preamplifier	58
2.5 Performance	58
 CHAPTER THREE <i>Absolute Calibration of Vega</i>	 63
3.1 Introduction	63
3.2 The Method	66
3.2.1 Previous Calibrations	66
3.2.2 Our Method	67
3.3 Experimental Procedure	70
3.3.1 Detector Stability and Linearity	70
3.3.2 Seeing fluctuations	73
3.3.3 Mirror Reflectivities	74
3.3.4 Pin hole area	74
3.3.5 Telescope Focus	74
3.3.6 Furnace Flux and Attenuation	76
3.3.6.1 MgO diffuser	76
3.3.6.2 Low Temperature Furnace	76
3.3.6.3 Attenuators	78

	Page
3.3.7 Atmospheric Extinction and Wavelength Definition	78
3.4 Results and Discussion	82
CHAPTER FOUR <i>The Quantitative Assessment of Atmospheric Extinction</i>	85
4.1 Program IRTANS	85
4.1.1 Atmospheric Parameters	86
4.1.2 Transmission Spectra	88
4.2 Absolute Calibration Revised	89
4.2.1 AMOS.FOR	92
4.2.2 Results for Absolute Calibration Filters	93
4.2.3 1.2 μm and 2.2 μm Corrections	95
4.2.4 Correction at 3.76 μm	97
4.2.5 4.6 μm correction	97
4.3 Conclusions	98
CHAPTER FIVE <i>Spectrophotometry in the Near-Infrared</i>	101
5.1 Introduction	101
5.2 Absolute Calibration Using the Cooled Grating Spectrometer	102
5.3 Extending the Absolute Calibration Beyond 3 μm	106
5.4 Conclusions	108

	Page
APPENDIX A 'NOVA' Data Logging PROGRAM	112
APPENDIX B Program ATMOS.FOR	113
APPENDIX C Program EXTINC.FOR	116
APPENDIX D IRTANS parameters for UKIRT	118
APPENDIX E Paper for the XVith ESLAB Symposium	119
"Extinction Corrections in Ground-Based Infrared Spectrometry"	
APPENDIX F Paper for the XVith ESLAB Symposium	123
"The Strength of HD Infrared Emission in Orion"	
REFERENCES	126

PREFACE

The work reported in this thesis was carried out by the author in the Astronomy Group at Imperial College, under the supervision of Dr. M. J. Selby. It describes two related projects undertaken on the 1.5 m I.R.F.C. Tenerife. The first is the design, construction and operation of a cooled grating spectrometer for the near-infrared. The second is a project to measure the absolute flux from Vega (at near-infrared wavelengths) and has been undertaken in collaboration with the Department of Astrophysics, University of Oxford. Initially both projects were started independently but it soon became apparent that they were inextricably related and are now described under the title, 'Astronomical Spectrometry in the Near-Infrared'.

Chapter one makes the case for using the cooled grating spectrometer in infrared astronomical spectrometry and Chapter two describes this instrument in detail. Special attention is paid to the control and data acquisition system as this was designed and built by the author. Chapter three reports on the absolute calibration experiment and in Chapter four a detailed discussion of the atmospheric corrections needed is presented with reference to a theoretical atmospheric model. The final chapter (Chapter five) looks in more detail at atmospheric extinction in the near-infrared. It is through this route that it becomes apparent that using a cooled grating spectrometer is potentially the most accurate way to measure absolute fluxes. This correspondingly leads to a possible method establishing an absolute standard essential for accurate spectrophotometry.

The appendices contain listings of programs written for these projects. Also included are two papers for the ESLAB Symposium discussing

the problems of extinction in the 5 μ m window and on the possibility of detecting HD in the near-infrared for which the calculated line positions are given.

ACKNOWLEDGEMENTS

I am indebted to Mike Selby who supervised and cajoled me throughout this project, and to Professor Jim Ring for providing such a stimulating environment in which to work. I must also thank Carlos Sanchez and his colleagues at the I.A.C. for never flagging in their encouragement during some of the gloomier trips in Tenerife.

The mechanical and electronic workshops of course played a vital role in this thesis and I would particularly like to thank Bill Stannard (who has patiently weathered some of my madder ideas) and Victor de Menezes could always be relied upon to find the last minute 'forgotten' component.

A major proportion of this thesis would have been impossible without the Department of Astrophysics, Oxford. I would like to thank my friends and colleagues there, Professor Blackwell, Sandy and David for such an engaging and stimulating collaboration (even if the cooking got a little complicated).

The Science and Engineering Research Council has supported me throughout these years.

I would like to thank Dr. W. Traub for providing a copy of his program IRTRANS and the enthusiastic staff of the UCL Starlink node for their help in its implementation.

Finally, I thank all my friends and colleagues at Imperial College (especially Richard Wade and Tony Jones in those formative years) for help and guidance throughout. Pat Kerridge has stayed many late nights typing this and still manages to cope with my spelling.

Above all I am grateful to my Family and Phuong, and other dear friends for putting up with me these last six months (and probably the preceding years as well).

ooo000ooo

LIST OF TABLES

	Page
1.1 Comparison between warm and cooled spectrometer	20
1.2 Shot noise from warm spectrometer	22
2.1 Expected wavelength resolution at 5" and 15" sky entrance apertures as a function of wavelength grating order n and angle θ	39
3.1 Results of previous calibrations	63
3.2 Results from 1979, 1980 and 1981 absolute calibration experiments	82
4.1 Values of E, Δ and ϕ calculated for the filters used in the absolute calibration	94
4.2 Extinction measured in the absolute calibration experiment	94
4.3 Theoretical values for absorption and scattering coefficients	96

LIST OF FIGURES

	Page
1.1 a) 'Warm' infrared spectrometer	20
b) 'Cooled' infrared spectrometer	20
1.2 Resolution as a function of NEP and wavelength	23
1.3 Relative luminosity of Grating and prism as a function of wavelength	24
1.4 Astronomical Grating spectrometer matched to a telescope of diameter D	25
1.5 Detector size as a function of telescope size and source extension	31
1.6 Example of a Felement Hadamard cyclic mask and associated coding matrix	34
2.1 Optical configuration of the cooled Grating spectrometer	38
2.2 Input optics, focal ratio converter and field lens	40
2.3 a) Grating Cell	43
b) Collimator Cell	43
2.4 The 'noise' that can be generated by dividing a mismatched absorption profile	46
2.5 Spectrometer Cryostat	48
2.6 a) 0.5 mm dia. InSb detector on mounting disc	49
b) Equivalent perspex disc with 0.5 mm dia. alignment aperture	49
c) View through 0.5 mm alignment aperture showing the image of the circular 15" input aperture and exit slit	49
2.7 Circuit to generate COUNTS (x 4) and DIRECTION from shaft encoder	52
2.8 Spectrometer system 'over-view'	53

	Page
2.9 General Interface Box	54
2.10 Flow diagram of AIM65 machine code Initilization Module	56
2.11 Flow diagram of AIM65 machine code scanning control program	57
2.12 Cooled scans of 1.08 μm Helium Line	60
2.13 a) Cooled Spectrometer Scan in H and K windows of Vega	61
b) Scans of Vega in the L window (uncorrected for Vega flux $T \sim 10^4$)	61
3.1 Application of the I.R. Flux Method to γSer	65
3.2 Infrared reimaging system for absolute calibration experiment	69
3.3 The Absolute Calibration system	71
3.4 Beam profile of the infrared photometer	75
3.5 Method for measuring the telescope focal length using stellar transit time	75
3.6 Extinction curves measured with	80
a) 2.2 μm filter	80
b) 3.76 μm filter	80
3.7 Extinction curve measured using 4.6 μm filter	81
4.1 Calculated atmospheric transmission for Tenerife (2.38 km with 4 mm H_2O) for	90
a) 'J' and 'H' windows	90
b) 'K' window	90
c) 'L' window	90
d) 'M' window	90

	Page
4.2	Calculated atmospheric transmission for UKIRT (4.2 km with 2.3 mm H ₂ O)
	91
a)	'J' and 'H' windows
	91
b)	'K' window
	91
c)	'L' window
	91
d)	'M' window
	91
4.3	Calculated extinction curve using a broad band filter 4.5 μ m - 5.4 μ m
	93
4.4	Transmission through a 2-metre column of air at 2.38 km (4.6 μ m filter)
	99
4.5	Results from the absolute calibration experiment (1980, 1981) compared with the stellar model of Dreiling and Bell
	100
5.1	a) The dependance of extinction upon water vapour
	103
	b) The corresponding dependance of extrapolation error Δ on water vapour
	103
5.2	a) 2 μ m scan of Procyon
	105
	b) Equivalent D.C. 2 μ m scan of 1253 K calibration furnace
	105
5.3	Original Absolute Calibration apparatus using the spectrometer
	110
5.4	Proposed scheme for Absolute spectrophotometric calibration
	110
5.5	Transmission and corresponding extinction calculated for the 10 μ m window (UKIRT)
	111

CHAPTER ONE

'I write about molecules with great diffidence, having not rid myself of the tradition that atoms are physics, but molecules are chemistry, but the new conclusion that hydrogen is abundant seems to make it likely that the above-mentioned elements H, O, and N will frequently form molecules'.

Eddington (1937)

1.1 INTRODUCTION

Chemists have long known that the infrared region of the electromagnetic spectrum provides a fruitful hunting ground for molecular lines. In the two decades of temperature which roughly spans 10 K - 1000 K molecules can absorb and emit radiation in quantum levels associated not with electronic transitions, but with degrees of freedom unique to molecules; rotation and vibration. The nuclei in a molecule, with their larger masses, move slowly compared with the electrons and these additional radiative mechanisms have characteristic energies which predominantly fall in the millimetre to infrared wavelengths. Molecules in the interstellar medium have been discovered in cool cloud complexes, opaque to visible and ultraviolet radiation, but visible by their emission at radio wavelengths. It is in these dense interstellar clouds that star formation is probably taking place. The molecular line emission provides a powerful and unique diagnostic tool. However as Dalgarno (1976) has pointed out, molecules are *".. much more than diagnostic tools. Energy is lost from clouds by infrared and millimetre emissions from molecules and the thermal structure of the clouds is profoundly influenced by molecular composition. It is probable that the*

formation of molecules leads to dynamic and thermal instabilities which cause the cloud to break into fragments that collapse to produce stars".

The detection in Orion of the 2 μm vibration-rotation quadrupole emission from molecular hydrogen, which has no radio spectrum has shown that infrared techniques previously only applied in the laboratory can now be used to probe the interstellar medium. (Gautier 1976).

The Ground Based I.R. Astronomy Group at Imperial College has chosen to restrict its range of attention to the near-infrared (1 μm - 5 μm). There are several advantages in this region,

- 1) A single and highly sensitive detector technology can be used to span 1 μm to 5 μm . InSb photovoltaic detectors have N.E.P.'s approaching $\sim 10^{-17} \text{ W H}_2^{-\frac{1}{2}}$ with quantum efficiencies of $\sim 75\%$.
- 2) The atmospheric windows (J, H, K, L, M) can be exceptionally transparent at good ground based observatories. In certain portions of the K (2 μm) window atmospheric extinctions of only $\sim 3\%$ have been measured. (This thesis).

This choice does not prove particularly restrictive or lacking in astrophysical content. Molecular hydrogen (the vibration-rotation bands fall in the 2 μm window) has proved a sensitive probe into the heating of the Orion Molecular Cloud and as an indication, as well as a diagnostic, of shocks (Beckwith 1981). It has now been seen in other HII regions, Planetary Nebulae and even in Seyfert galaxies, (Beckwith 1981). CO, with bands at 3 μm , is a well established component of cool late type stars and the cosmologically significant molecule HD may prove more accessible in the near infrared (Appendix F).

It is not only molecular lines that fall in the near-infrared. Recombination lines of Hydrogen (B_{γ} 2.17 μm , $B\alpha$ 4.05 μm) or Helium (HeI 2.06 μm) are used to measure the temperatures, emission measures, kinematics and reddening in HII regions. (Lacy, 1981, Willner 1983). With the steady maturing of infrared astronomy, it is not only line radiation that is of interest.

HII regions show continuous free-free emission, as well as broad band "dust" emission. It is ever more necessary to have the ability to measure the continuous spectra of sources, rather than just assume distributions from the extrapolation of single point photometry.

An example is in the development of the Infrared Flux Method (Blackwell, 1979). Potentially this is the most accurate way to determine stellar angular diameters (θ) and effective temperatures (T_{eff}), but Blackwell (1979) has reported that some stars show anomalies when θ is plotted as a function of photometric colour. To determine θ as a function of continuous wavelength would be a sensitive procedure for the detection of weak absorption bands and emission features.

This would give enormous insight into the method and may prove a powerful diagnostic of stellar atmospheres.

It is also becoming apparent, if absolute photometric accuracy is the goal (2% or better*), this can only be done using the narrow and well defined bandwidths of an Infrared Spectrometer.

* At present, the accuracy of the Infrared Flux Method is limited by the absolute calibration of infrared fluxes.

1.2 Requirements for Infrared Spectrometer

The target wavelength resolution of the proposed instrument was $R(\lambda/\delta\lambda) \sim 100-1000$ over $1 \mu\text{m} - 5 \mu\text{m}$. (This was compared with, at the start of the project, Circular Variable Filter photometers (C.V.F.'s) working with resolutions of $R \sim 50-80$.)

1.2.1. Cooled or Uncooled Instrument

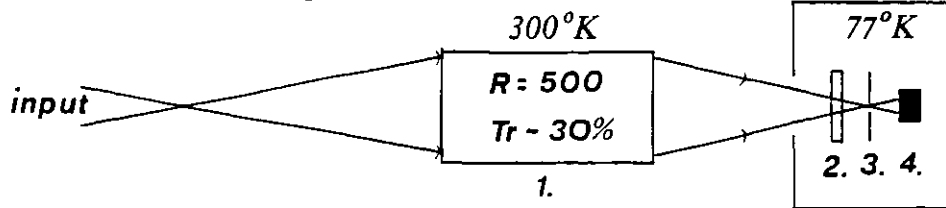
The most important consideration was whether it is necessary to cool part or all of the spectrometer. So as not to swamp the detector with the background photon shot noise from the instrument itself, two possible approaches are shown in Fig. 1.1a, b. One imagines a simple realizable spectrometer with $R = 500$ and a typical transmission of 30%. The detector can view either a cooled or warm spectrometer through a set of cooled blocking filters and field stop.

Table 1.1 shows the comparison of the sky emission as seen through the spectrometer ($R = 500, 1000$) to that of the emission from the instrument. The spectrometer emission is equivalent to black-body of 0.7 emissivity. (The blocking filters are chosen to cover the useful portions of the IR windows).

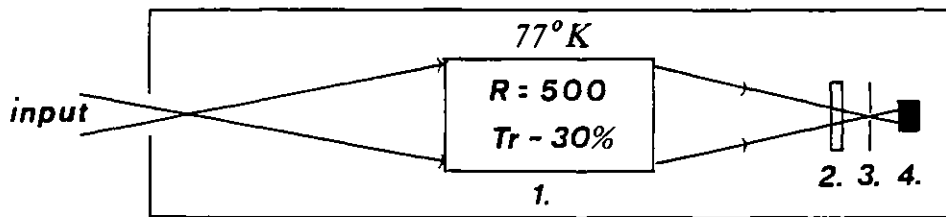
For any wavelengths from the K band and longward, the dominant background source would be the room temperature spectrometer. As the resolution is increased to 1000, this also becomes true for the H band. To be dominated solely by the sky background, over the $1 \mu\text{m} - 5 \mu\text{m}$ windows, it is necessary to cool the spectrometer. This is most conveniently done by putting it in the same cryostat with the detector. (Fig. 1.1b).

Figure 1.1

a) 'Warm' infrared spectrometer



b) 'Cooled' infrared spectrometer



1. spectrometer 2. blocking filter 3. field stop 4. detector

TABLE 1.1

	λ_o (μm)	$\Delta\lambda$ (μm)	Emission of Spectrometer seen by detector		Sky Emission* seen through Spectrometer	
			(a) 300° K 70% Black-Body ($\text{W m}^{-2} \text{ sr}^{-1}$)	(b) 80° K 70% Black-Body ($\text{W m}^{-2} \text{ sr}^{-1}$)	R = 500 ($\text{W m}^{-2} \text{ sr}^{-1}$)	R = 1000 ($\text{W m}^{-2} \text{ sr}^{-1}$)
J	1.2	.2	3.0 E-11	4.0 E-54	8.9 E-05	4.5 E-05
H	1.6	.3	2.3 E-07	4.5 E-43	4.5 E-07	2.3 E-07
K	2.2	.4	2.2 E-04	2.1 E-30	2.3 E-06	1.2 E-06
L	3.8	.6	2.1 E-02	1.8 E-16	6.5 E-04	3.0 E-04
M	5.0	.8	5.4 E-01	5.2 E-12	6.7 E-03	3.3 E-03

* adapted from measurements made on the 1.5 m I.R.F.C. Tenerife

(MacGregor, 1977).

1.2.2 Detector noise versus Background shot noise

In the above example it is assumed the dominant contribution to the noise of the system comes from the photon shot noise of the backgrounds. At present this is not the case at all wavelengths. MacGregor has shown (MacGregor 1977) that the Noise Equivalent Power (NEP) from an InSb detector in a transimpedance amplifier is given by,

$$\text{NEP}(\text{w H}_z^{-\frac{1}{2}}) = \frac{7.5 \cdot 10^{-11}}{(Z_{11})^{\frac{1}{2}} \eta \lambda} \quad \dots (1.1)$$

where η = quantum efficiency $\sim .74$

λ = wavelength (μm)

and Z_{11} = the parallel resistance of the detector Z_D
and feedback resistor Z_R ,

Presently we are achieving $Z_{11} \sim 5 \times 10^9 \Omega$

$$(Z_R \sim Z_D \sim 10^{10} \Omega)$$

which gives an NEP $\sim 5 \times 10^{-16} \text{ w H}_z^{-\frac{1}{2}}$.

The background shot noise on a background of P_B watts μm^{-1} is given by (MacGregor 1977)

$$N_B = \left(\frac{2 \cdot 10^{-19} P_B}{R} \right)^{\frac{1}{2}} \text{ w H}_z^{-\frac{1}{2}} \quad \dots (1.2)$$

where $R = \frac{\lambda}{\Delta \lambda}$

Table 1.2 shows the calculated shot-noise from the background of a "warm" spectrometer. (Figure 1.1(a) 300 K black-body of 0.7 emissivity seen through cooled blocking filters).

TABLE 1.2

	Shot noise ($w H_z^{-\frac{1}{2}}$)
J	2.2E-19
H	1.6E-17
K	2.9E-16
L	3.2E-15
M	1.4E-14

(cf. Detector/preamp. NEP $\sim 5E-16 w H_z^{-\frac{1}{2}}$)

Examining Table 1.2 at the apparent "cross-over point" between a cooled and uncooled instrument (Table 1.1) at 2 μm , shows the dominant noise source is not background shot noise (whether cooled or uncooled) but the detector/preamp. system noise. However as detector systems improve and spectrometer resolutions increase it becomes increasingly advantageous to use a cooled spectrometer

Present InSb detectors (.25 mm diameters) now have impedences of $Z_D \sim 10^{12} \Omega$ in principle allowing NEP's of $\sim 10^{-17} w H_z^{-\frac{1}{2}}$ realizable. ($Z_{11} > 10^{12} \Omega$). Because of inherent FET gate leakage and the inability to find sufficiently resistive feed-back resistors with $Z_R > 10^{10}$, *it is the preamplifier which is limiting the systems noise performance.*

Assuming the spectrometer is cooled, so the dominant background is the sky/telescope shot noise, (data taken from MacGregor 1977). figure 1.2 shows the resolution as a function of NEP and wavelength at which the spectrometer becomes detector/preamp. noise limited.

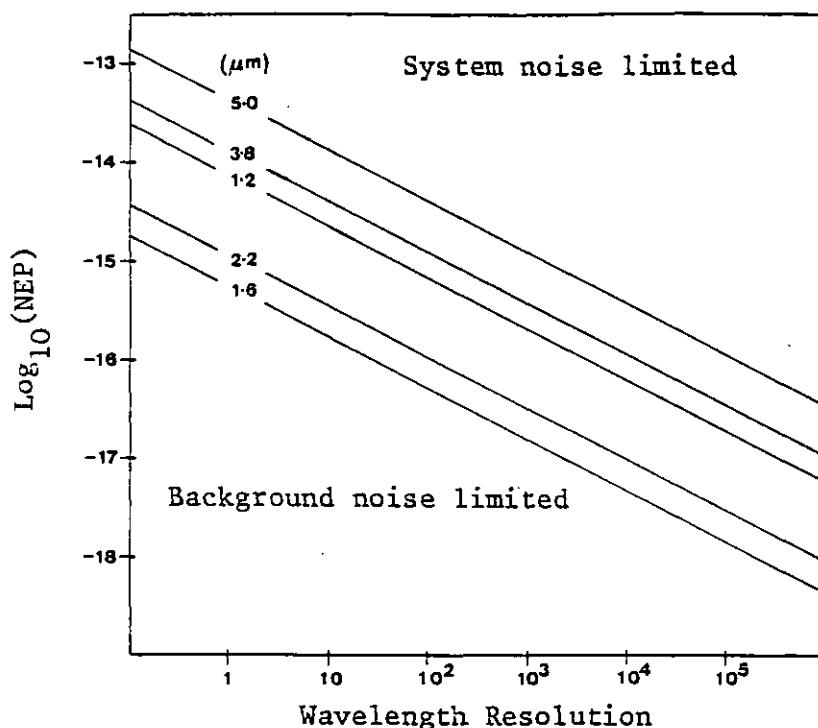


Figure 1.2 Resolution as a function of NEP and wavelength

It should be noted that even at $3.8 \mu\text{m}$ with our present $\text{NEP} \sim 5 \times 10^{-16} \text{ w H}_z^{-1/2}$, the spectrometer will be detector/preamp. noise limited at $R \sim 1000$. If an NEP of $3.6 \times 10^{-17} \text{ w H}_z^{-1/2}$ is realized ($R_D \sim 10^{12} \Omega$), the spectrometer will remain background noise limited up to a resolution of ~ 20000 .

1.3 Type of Spectrometer

The general constraints on the infrared spectrometer are different from those on a visible instrument. Principally it must be compact and relatively simple as it must fit into a cryostat and operated at 77 K. The requirement is for an instrument to work over the entire $1 \mu\text{m} - 5 \mu\text{m}$ region able to accept field apertures up to 2.0 mm (equivalent to 20 arcseconds on the 1.5 m I.R.F.C.) with a wavelength resolution of between 100-1000.

1.3.1 Prism or Grating

The simplest spectrometer is either a prism or grating

instrument. Jacquinot (1954) has shown that the relative luminosities (ϕ) of a grating spectrometer of grating area A , used at the Littrow blaze, compared to a prism spectrometer of prism base area A , both with identical wavelength resolutions is,

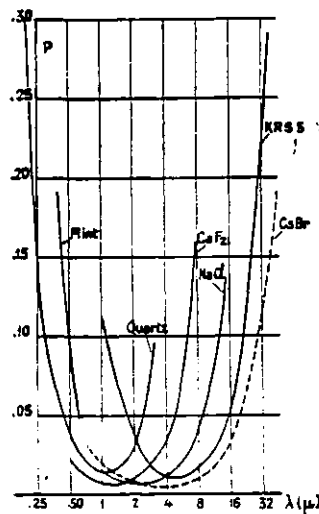
$$P = \frac{\phi(\text{prism})}{\phi(\text{grating})} = \frac{\lambda(d\mu/d\lambda)}{2 \sin \theta}$$

$d\mu/d\lambda$ = dispersion of prism.

Figure 1.3 shows the variation of P for typical prism materials, assuming $\theta = 30^\circ$.

Figure 1.3

Variation, as a function of the wavelength (in logarithmic scale) of the ratio P , of the flux given by a prism to the flux given by a grating of the same size and with the same effective resolving power.

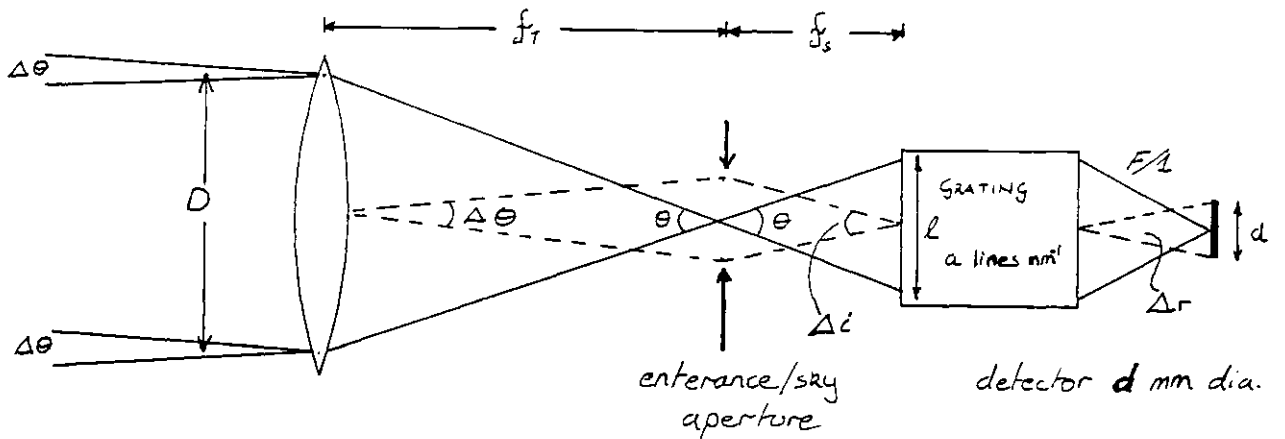


From $1 \mu\text{m} - 5 \mu\text{m}$ P is never greater than 0.1; compared with the visible the dispersion of dielectrics in the infrared is very small. The luminosity of a grating system is the order of 10 times greater than that of an infrared prism spectrometer. Assuming we necessarily have a compact system, it becomes important to determine what in fact limits the luminosity of the spectrometer.

1.3.2 Luminosity, Resolution and Telescope Size

To determine what limits the resolution (R) and luminosity (L) of a simple astronomical spectrometer, it is assumed a grating spectrometer of grating size l is matched to a telescope of diameter D , with a common entrance and sky aperture, viewing a field $\Delta\theta$. The detector is illuminated by an $F/1$ camera.

Figure 1.4 Astronomical grating spectrometer matched to a telescope of diameter D



Using the grating in a Lithrow mount,

$$\frac{n\lambda}{a} = \sin i + \sin r = 2 \sin r$$

$$\Rightarrow \frac{d\lambda}{dr} = \frac{a}{n} \cos r \sim \frac{\Delta\lambda}{\Delta r}$$

$$\text{giving } R = \frac{\lambda}{\Delta\lambda} = \frac{2 \tan r}{\Delta r}$$

The diffraction limited resolving power ($\Delta r = \frac{\lambda}{l}$) is then given by,

$$R_L = \frac{2 \tan r}{\lambda} l \quad \dots (1.3)$$

The telescope sets a limit on the resolution by,

$$\frac{f_T}{f_s} = \frac{\Delta i}{\Delta \theta} = \frac{D}{l}$$

$$\frac{\Delta \theta D}{l} = \Delta i = \Delta r \quad \dots (1.4)$$

so $R_{\text{Telescope}} = \frac{2 \tan r \ l}{D \Delta \theta} \quad \dots (1.5)$

but the detector size d will also constrain the resolution,

$$d = l \Delta r \quad (\text{F/l camera})$$

$$R_{\text{Detector}} = \frac{2 \tan r \ l}{d} \quad \dots (1.6)$$

The performance of any astronomical spectrometer is critically dependent on whether the source is point like or extended.

1.3.2.1 Point sources

For point sources it is sensible to choose $\Delta \theta \approx 3\Delta \theta_s$, where $\Delta \theta_s$ is the seeing angle, making typically $\Delta \theta = 6$ arcseconds ($1.46 \cdot 10^{-5}$ rads.) Normally the resolution is restricted such that $R \approx 3R_L$, the diffraction limited resolution,

$$\Delta \theta > 3\lambda/D$$

With $\Delta \theta = 6''$ limits the smallest telescope that can be used at $5 \mu\text{m}$ to 1 metre. The upper limit on telescope diameter is controlled solely by the detector size d . From Figure 1.4 and equation 1.4.

$$d = l \Delta r \Rightarrow d = D \Delta \theta \quad \dots (1.7)$$

However even for a huge telescope (15 m), the largest detector required is .218 mm. For point sources, detector size is largely unimportant, giving, $R = \frac{2 \tan r \ell}{\Delta \theta D}$ (equation 1.5). A compact spectrometer of $\ell \sim 50$ mm, used on a 1.5 m telescope with $\Delta \theta = 6''$ and $r = 30^\circ$ gives a realizable resolution, $R \sim 2600$. So for a prism spectrometer of comparable luminosity to the grating instrument, could only give an achievable resolution in the infrared of ~ 260 . (Figure 1.3).

The luminosity, or energy throughput, for a point source is given simply by, $L = \frac{\pi}{4} D^2$ (1.8) where the source has a flux given as $w \text{ m}^{-2} \mu\text{m}^{-1}$. The resulting Resolution Luminosity product is therefore proportional to,

$$RL \propto \frac{\tan r \ell}{\Delta \theta} \cdot D \quad \text{where} \quad \Delta \theta = 1.45 \cdot 10^{-5} \text{ rads}$$

For the infrared this RL product is not necessarily a good figure of performance, as the background radiation (αL) can be a significant fraction of the signal. A better measure of performance can be given by a Resolution, Signal to Noise product, $R.(S/N)$, and is a measure of the information throughput of a spectrometer.* Defining the two cases as;

- 1) system noise limited operation ($N_s = \text{constant}$)
- 2) background shot noise limited operation, ($N_B = (L \Delta \lambda)^{\frac{1}{2}}$)

where L is the luminosity per unit wavelength.

For continuum point sources this new $R.(S/N)$ product becomes;

* From information theory, the Information content. I is given by,

$$I = \frac{\mu}{\Delta \mu} \log_2 (S/N) \quad \text{where} \quad \frac{\mu}{\Delta \mu} = \text{number of discernable levels}$$

System NEP
noise limited

$$N_s = \text{constant}$$

$$\begin{aligned} R. \left(\frac{S}{N} \right) &= \frac{R.L.\Delta\lambda}{N_s} \\ &= \frac{R.L.}{N_s} \cdot \frac{\lambda}{R} \\ &= \frac{L\lambda}{N_s} \end{aligned}$$

Background shot
noise limited

$$N_B = (L\Delta\lambda)^{\frac{1}{2}}$$

$$\begin{aligned} R. \left(\frac{S}{N} \right) &= \frac{R.L.\Delta\lambda}{(L\Delta\lambda)^{\frac{1}{2}}} \\ &= R^{\frac{1}{2}} L^{\frac{1}{2}} \lambda^{\frac{1}{2}} \end{aligned}$$

from equations (1.5) and (1.8)

$$R. \left(\frac{S}{N} \right) \propto D^2 \lambda$$

$$R. \left(\frac{S}{N} \right) \propto \left(\frac{\tan r \cdot l}{\Delta\theta} \right)^{\frac{1}{2}} D^{\frac{1}{2}} \lambda^{\frac{1}{2}}$$

For unresolved emission line point sources, an equivalent measure of performance is given simply by the Signal/Noise (S/N)

$$N_s = \text{constant}$$

$$N_B = (L\Delta\lambda)^{\frac{1}{2}}$$

$$\left(\frac{S}{N} \right) \propto D^2$$

$$\left(\frac{S}{N_B} \right) \propto \left(\frac{\tan r \cdot l}{\Delta\theta \lambda} \right)^{\frac{1}{2}} D^{\frac{1}{2}}$$

It should be noted that in the background noise limited case the $R. \left(\frac{S}{N} \right)$ product is proportional to $D^{\frac{1}{2}}$ not D .

1.3.2.2 Extended sources

The resolution of the spectrometer in this case is controlled by the extension of the source $\Delta\theta$, telescope diameter D and ultimately detector size d . From equation (1.7), $\Delta\theta = d/D$ which for a 0.5 mm detector used on a 1.5 m telescope, means for any sources larger than

68th the resolution is totally controlled by the detector size d.
 (For a 3.8 m telescope the limiting $\Delta\theta = 27''$). For the compact
 grating spectrometer of $l = 50$ mm, $r = 30^\circ$ and detector size .5 mm,
 the maximum resolving power possible for such an extended source is

$$R_D = \frac{100.057}{0.5} \quad (\text{from equation 1.6})$$

$$\sim 100$$

The Luminosity from an extended source is given by

$$L = A\Omega$$

$$= \left(\frac{\pi}{4} D\Delta\theta\right)^2$$

where the brightness of the source is given in $w \text{ m}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1}$
 giving the conventional RL product as $\propto \tan r \cdot l \cdot (D\Delta\theta)$ or $\propto \tan r \cdot l \cdot d$
 Looking at the $R \cdot \left(\frac{S}{N}\right)$ product for continuum extended sources gives:

$N_s = \text{constant}$ (NEP limited) $R\left(\frac{S}{N}\right) \propto (D\Delta\theta)^2 \lambda$ (or $\propto d^2 \lambda$)	$N_B = (L\Delta\lambda)^{\frac{1}{2}}$ (background limited) $R\left(\frac{S}{N}\right) \propto (\tan r \cdot l)^{\frac{1}{2}} (D\Delta\theta)^{\frac{1}{2}} \lambda^{\frac{1}{2}}$ (or $\propto (\tan r \cdot l)^{\frac{1}{2}} d^{\frac{1}{2}} \lambda^{\frac{1}{2}}$)
---	---

similarly for extended unresolved emission line sources,

$\frac{S}{N_s} \propto (D\Delta\theta)^2$ (or $\propto d^2$)	$\frac{S}{N_B} \propto \frac{(\tan r \cdot l)^{\frac{1}{2}}}{\lambda^{\frac{1}{2}}} (D\Delta\theta)^{\frac{1}{2}}$ (or $\propto \frac{(\tan r \cdot l)^{\frac{1}{2}}}{\lambda^{\frac{1}{2}}} d^{\frac{1}{2}}$)
---	---

The $R \cdot \frac{S}{N}$ product (or RL product) in all cases is dependent on
 either $D\Delta\theta$ or d . In figure 1.5 $D\Delta\theta = d$ has been calculated as a function

of detector size, telescope diameter and source extension $\Delta\theta$, showing for which regimes of telescope diameter and source extension the $R.(\frac{S}{N})$ product (or RL product) is controlled totally by the detector size d. The $R.(\frac{S}{N})$ product can give a measure of performance, or information through-put for an infrared astronomical spectrometer that is detector/system noise limited and for an equivalent instrument that is background noise limited. The comparable performance figure $(\frac{S}{N})$ gives an equivalent measure for unresolved line emission sources also for both cases.

In conclusion, a spectrometer with a 50 mm grating when matched to a 1.5 m telescope can give the required resolution of between 100 - 1000 without loss in luminosity (or $R.\frac{S}{N}$ product) even with extended sources up to one arcminute. The next chapter describes the detailed design and construction of such a compact cooled spectrometer. It is however useful to compare this instrument with other possible types of spectrometer.

1.3.3 Fabry-Perot Spectrometer

Jacquinet has again demonstrated that the intrinsic luminosity of a single Fabry-Perot (F.P.) Spectrometer can be up to two orders of magnitude greater than that of a comparable grating instrument. However there are some severe drawbacks in using F.P.'s.

- 1) Accurate spectrophotometry is complicated because of the Lorentzian instrumental profile produced by an F.P. (Chabbal 1953)
- 2) To get sufficient through-put, highly reflective coatings have to be used on the mirrors. At present, at least 3 separate F.P.'s would be needed for the $1\text{ }\mu\text{m} - 5\text{ }\mu\text{m}$ windows, as no one coating can cover this range.

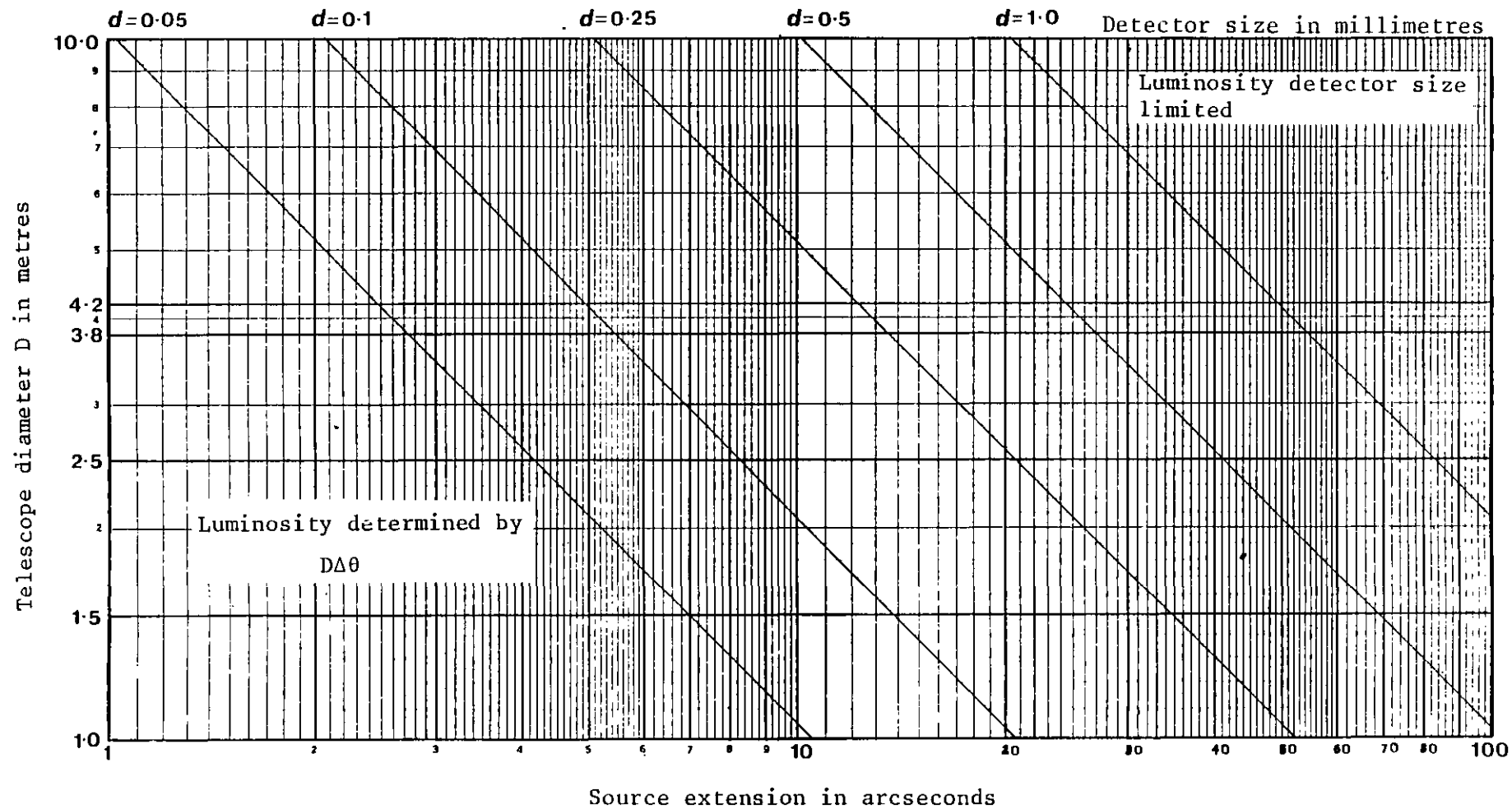


Figure 1.5 Detector size as a function of telescope size and source extension

- 3) It is impossible to multiplex in wavelength, using either detector arrays or coding masks, without using another disperser, such as a grating.

In fact the intrinsic luminosity gain of the F.P. is only applicable when the entrance aperture of the grating spectrometer is limiting the luminosity. In our application at these moderate resolving powers, the majority of sources fall well inside the entrance aperture (20 arc seconds) so giving the F.P. spectrometer no advantages, but some real disadvantages.

1.3.4 Multiplex Spectrometers

As telescope time is a limited commodity and in the J, H, K bands detector noise can be the main noise source, it is interesting to consider various multiplexing schemes for both shot noise limited and detector noise limited cases.

Considering the detector noise limited case, one option is to build a Two-beam Interferometer (Fourier Transform Spectrometer). As with the F.P., the intrinsic luminosity is far in excess of what is needed. Looking only at the multiplex advantage; the power falling on the detector as a function of path difference 2ξ is,

$$S(\xi) = \int_0^{\infty} P(\nu) \cos^2(2\pi\xi\nu) d\nu$$

$P(\nu)$ = spectral density as a function of wave-number ν .

Harwit (1976) shows this can be transformed to a discrete series

$$P(\nu) = 16 \sum_{n=0}^N S(n\Delta) \cos(4\pi\nu n\Delta)\Delta$$

where Δ is the step length ($\Delta = \frac{\lambda_{\min}}{4}$)

N = total number of steps.

defining $\pi(\nu) = \delta P(\nu)$, $\delta = \frac{\nu_{\max} - \nu_{\min}}{N}$

$$\pi(\nu) = \frac{4}{N} \sum_{n=0}^N S(n\Delta) \cos(4\pi\nu\Delta)$$

which can be expressed as the matrix equation

$$\underline{\pi} = \underline{W}^{-1} \underline{S}$$

($\underline{S}$ = column vector of intensities $S(0), S(\Delta) \dots S(N\Delta)$)

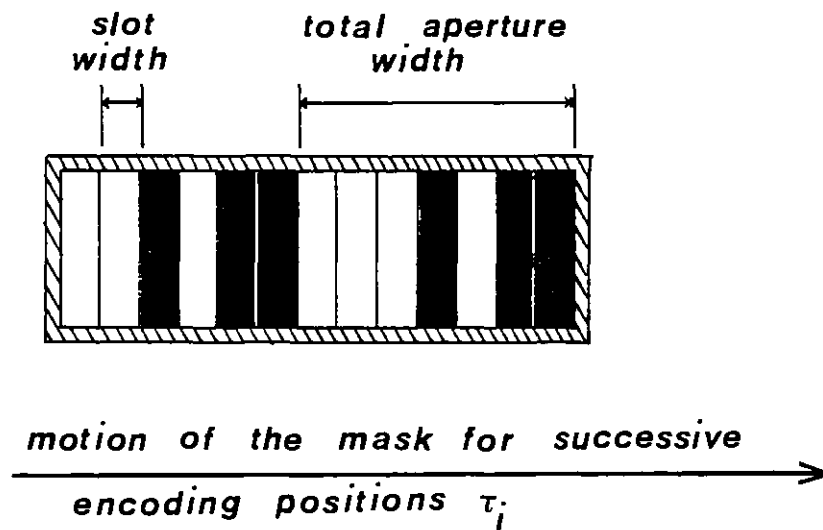
If the detector or system noise per reading has a variance σ^2 , Sloane (1969) has shown the mean square error in the spectrum $\epsilon = \sigma^2 \text{Trace } \underline{W}^{-1} (\underline{W}^{-1})^T$ which for large N ,

$$\frac{\epsilon}{\sigma^2} \sim 8$$

(c.f. single slit scanning spectrometer $\frac{\epsilon}{\sigma^2} = N$).

An alternative multiplexing scheme is to use a grating spectrometer with a series of coding masks in place of exit apertures. Nelson and Fredman (1970) has demonstrated, that in the detector noise limited case, it is possible to maximize the multiplex or Fellgett advantage by using Cyclic Hadamard coding masks. If these masks are intended to sample N spectral elements, the detector will always see $\sim N/2$ elements simultaneously. In figure 1.3 an example of a 7 element cyclic mask is shown with the associated coding matrix $\underline{W}_H$.

Figure 1.6 Example of a 7 element Hadamard cyclic mask and associated coding matrix



$$\underline{W}_H = \begin{pmatrix} 1 & 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 \end{pmatrix}$$

The Spectrometer encodes the spectrum $\underline{K}(\lambda_i)$ as,

$$\underline{S}(\tau_i) = (\underline{W}_H)^T \cdot \underline{K}(\lambda_i)$$

where $\underline{S}(\tau_i)$ is the signal on the detector at successive times τ_i .

applying the same analysis as Sloane on,

$$\underset{\sim}{K} = (\underset{\sim}{W}\underset{\sim}{T})^{-1} \underset{\sim}{S}$$

gives $\frac{\epsilon}{\sigma^2} \sim 4$: for large N.

This spectrometer has a greater multiplex advantage than a Fourier Transform Instrument. Additionally the decoding of a Hadamard spectrum is a simple matrix multiplication of 1's and 0's, easy for a computer, as opposed to a series of cosine transforms of the F.T.S. More importantly it is considerably more difficult to operate a coded FTS instrument because of the interferometric motions required; especially as it has to work on the Cassegrain focus of the Telescope.

None of these multiplex spectrometers gives any advantage in the L and M windows. Here the background shot noise is the dominant noise source. Can there be any multiplex gain for shot noise limited systems?

If we stay with the grating instrument, the coding mask can be replaced with a multielement detector array.

If there are N detectors n_i , each receiving p_i photons/sec,

$$\text{shot noise}_i = \sqrt{p_i}$$

In time T, we get Tp_i photons/element n_i

$$\left(\frac{\text{Signal}}{\text{Noise}}\right)_i \text{ array} = \frac{Tp_i}{\sqrt{Tp_i}} = \sqrt{Tp_i}$$

For a single detector sequentially scanned,

$$\left(\frac{\text{Signal}}{\text{Noise}}\right)_i = \sqrt{\frac{T}{N} P_i} : \text{ each spectral element gets } \frac{T}{N} \text{ pi photons}$$

Sequ-
ential

$$\text{Advantage } \left(\frac{\text{Array } N}{\text{Sequential}}\right) = \sqrt{N}$$

1.4 Conclusion

A small ($L \sim 50 \text{ mm}$) cooled grating spectrometer can be the ideal instrument for near-infrared astronomical spectrometry;

- 1) At these moderate resolutions and for the majority of objects, the instrument is not luminosity limited.
- 2) If a higher resolution is needed, it can be used in conjunction with a Fabry-Perot without subsequent loss in luminosity.
- 3) In the detector noise limited case (longward of $3 \mu\text{m}$), a multiplex or Fellgett advantage can be gained by using a Hadamard coding mask in the plane of the exit aperture.
- 4) If photon shot noise limited, the mask can be replaced by a linear detector array. As detectors improve, this may become the case eventually over the entire $1 \mu\text{m} - 5 \mu\text{m}$ region.

For the future with the advent of large infrared arrays and by using Echelle gratings ($L \sim 100 \text{ mm}$ with $\theta \sim 80^\circ$) it will be possible to achieve resolutions from a cooled instrument $\sim 5 \cdot 10^4$ (equation 1.5). The only other way to increase the resolution on point sources is by reducing $\Delta\theta$, making $\Delta\theta \sim \Delta\theta_{\text{seeing}}$ (i.e. $\Delta\theta = 2 \text{ arcseconds}$). With telescopes such as the Isaac Newton 2.5 m this may now become possible.

CHAPTER TWO

Fitting a grating spectrometer into a cryostat so it can be cooled to 77 K and subsequently operated at the Cassegrain focus of a telescope places major constraints on both the optical and mechanical design.

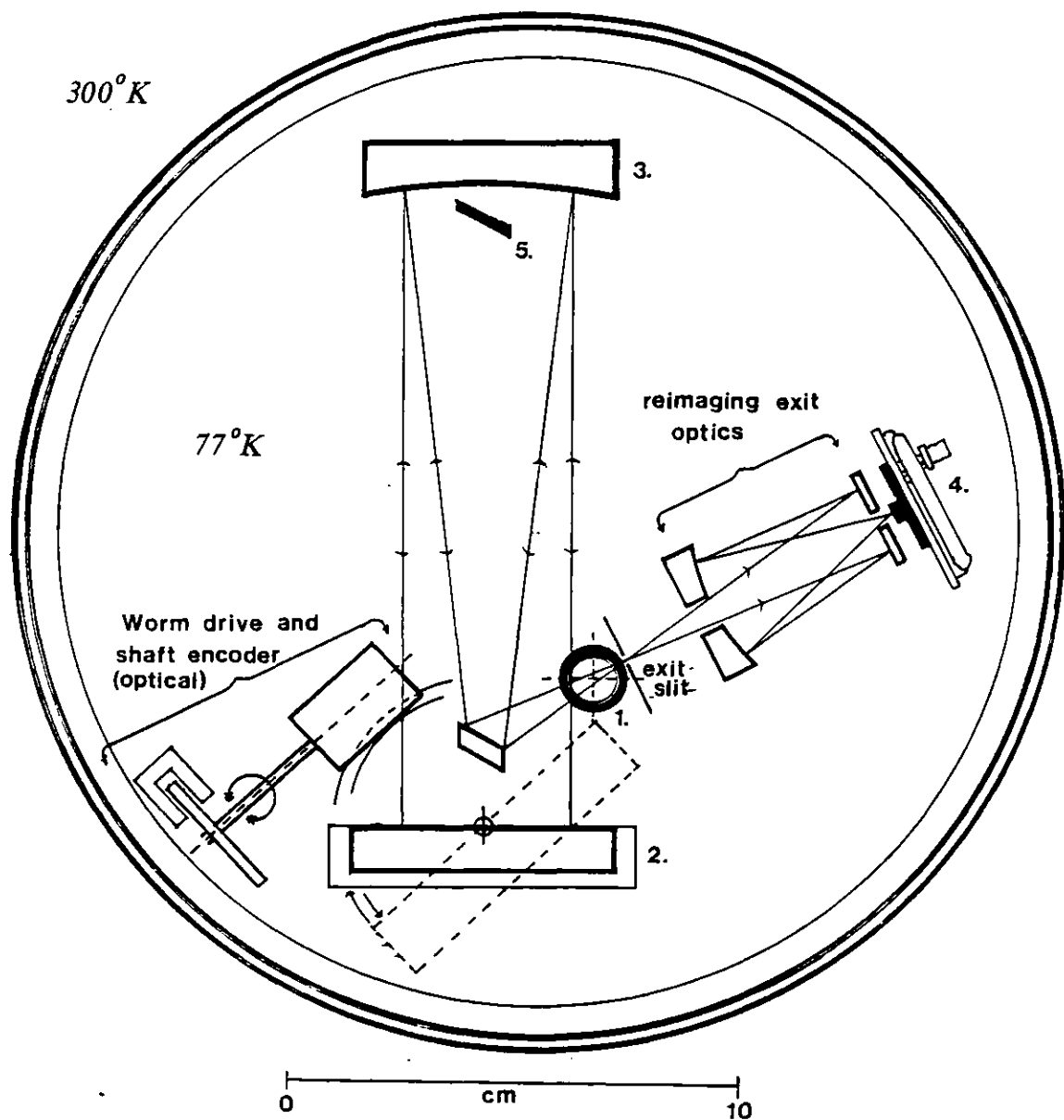
2.1 Optical Configuration

The principle constraint was to keep the optics as compact and as simple as possible.

The configuration chosen was an up-down Newtonian Lithrow mount (Fig. 2.1). This has the advantages of using the grating in its most efficient mode (Jacquinot 1954) and all optical components are used on axis so allowing the use of a simple spherical collimator. The shadowing of the telescope secondary, allowed the Newtonian flat to be introduced into the centre of the beam with no loss in throughput. A cooled central stop is also placed near the collimator so the detector can only see a black 77 K surface in this central 'hole'.

Using a focal ratio of $F/4.28$ and a focal length of 154 mm gives a clear aperture on the grating and collimator of 36 mm. On axis, the spherical collimator produces a circle of least confusion of ~ 0.016 mm, this is compared with the smallest input and exit apertures of 0.15 mm (equivalent to a 15 arcsecond sky aperture).

The first grating used was an aluminium coated Bauch and Lomb replica grating on a glass substrate. This was blazed at $2.5 \mu\text{m}$, with $300 \text{ lines mm}^{-1}$, gave an efficient coverage from $1.6 \mu\text{m} - 4 \mu\text{m}$ in 1st order and $0.9 \mu\text{m} - 1.9 \mu\text{m}$ in 2nd order. It was later replaced



1. Input optics and blocking filters 2. Grating Cell 3. Collimator (spherical)
 4. Detector and Pre-amp. 5. Central stop

Figure 2.1 Optical configuration of the cooled grating spectrometer

replaced by a similar grating but blazed at 4 μm , allowing the complete 1 μm - 5 μm range to be covered. (See Table 2.1).

TABLE 2.1

Table showing the expected wavelength resolution at 5 $^{\wedge}$ and 15 $^{\wedge}$ sky entrance apertures as a function of wavelength, grating order n and angle θ .

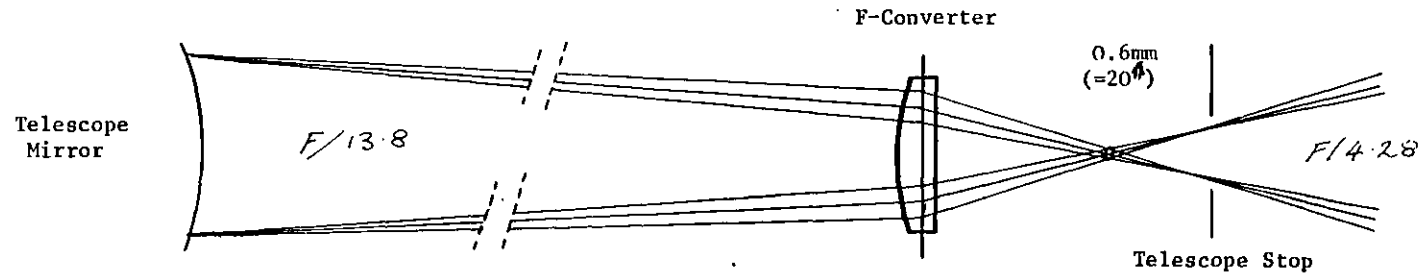
Wavelength				Dispersion $\mu\text{m mm}^{-1}$	Resolution $\lambda/\delta\lambda$	
	(μm)	n	θ		5 $^{\wedge}$ (.15 mm)	15 $^{\wedge}$ (.45 mm)
J	1.1	3	29.7	.0063	1170	390
H	1.6	2	28.7	.0095	1122	374
K	2.2	2	41.3	.0081	1804	601
L	3.8	1	34.7	.0178	1425	475
M	5.0	1	48.6	.0143	2329	776

(Bausch and Lomb 300 lines mm^{-1} , blazed at 4 μm , $f = 154 \text{ mm}$)

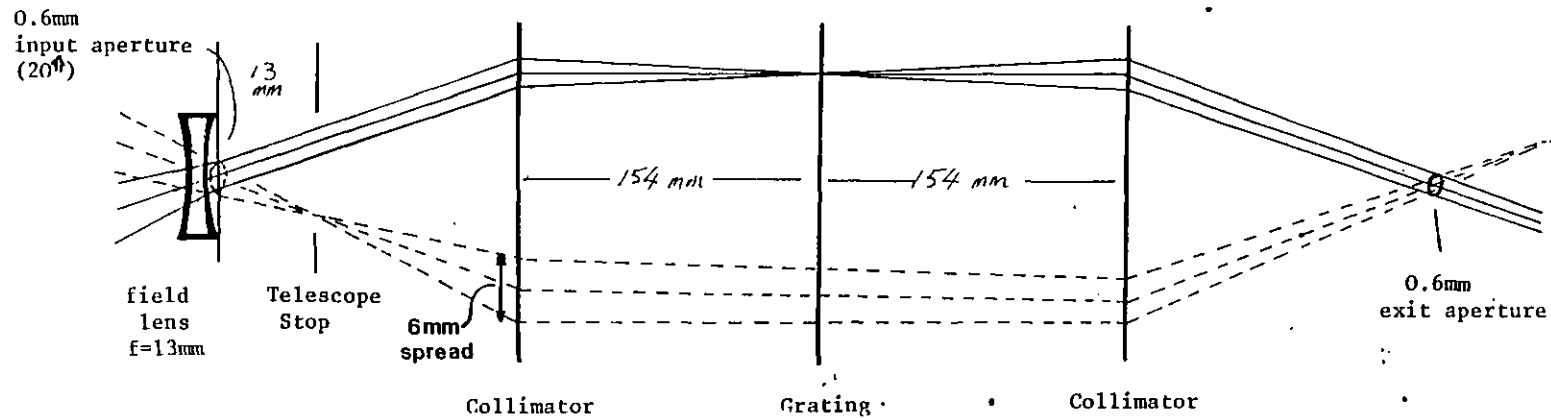
To be compatible with the Imperial College Infrared Photometer in Tenerife, (Jordan 1977) which is designed for a F/13.8 beam, two CaF_2 lenses were used as a simple focal ratio converter and field lens. (Fig. 2.2). (The dispersion of CaF_2 made it necessary to refocus the telescope for each I.R. window, but this is quickly done using a calibrated slide on the guide eyepiece). The resulting F/4.28 beam is brought to a focus on circular input apertures which can be chosen to correspond to 5 $^{\wedge}$, 10 $^{\wedge}$, 15 $^{\wedge}$ or 20 $^{\wedge}$ sky apertures. These are matched by equivalent exit apertures which are reimaged onto the detector at $\sim F/2$ using two mirrors (Fig. 2.1). It was found this reimaging system allowed a 15 $^{\wedge}$ sky aperture to be focussed into a 0.25 mm diameter spot, well inside the 0.5 mm diameter InSb detector. (Fig. 2.6c).

All the mirrors were glass and made in the I.C. Optical Workshop,

Figure 2.2 - Input optics; a) focal ratio converter and
b) field lens



- a) A simple plano-convex CaF lens converts the $F/13.5$ beam to $F/4.28$
 b) Without a field lens the beam will be significantly spread on the collimator and grating (dashed line). The addition of the bi-concave "field lens" produces no spread on the grating (solid line).



then gold coated. In the infrared, the reflectivity of gold mirrors is extremely high (typically > 98%) so the optical design can afford to incorporate a large number of mirrors without a significant loss in throughput. An estimate of the transmission through the spectrometer is given by product of transmissions T_i ,

$$\begin{aligned}
 T_{\text{TOTAL}} &= T(\text{CaF}_2 \text{ window}) \times T(2\text{CaF}_2 \text{ lens}) \times T(\text{Grating}) \times T(7 \text{ gold mirrors}) \\
 &\sim .94 \times .94^2 \times .6 \times .98^7 \times 100 \\
 &\sim 43\%
 \end{aligned}$$

2.2 Mechanical Design

During the cooling from $T \sim 300 \text{ K}$ to 77K the contraction of components and supports can be quite significant. For example, the 60 mm diameter aluminium collimator cell will contract by $\sim .2 \text{ mm}$ while the glass mirror it holds will contract by only $\sim 0.08 \text{ mm}$. Consequently great care was taken in the mounting of mirrors and in the operation of the grating which has to scan over an angle $\sim 40^\circ$; the greatest worry being that this differential contraction would cause the optics to go out of alignment during cooling. On some astronomical sources the spectrometer may have to integrate on faint lines for periods up to 5 hours. It is very desirable to take advantage of the exceptionally stable temperature environment inside a cryostat to maintain the optical stability. This can only be successfully achieved by totally decoupling and isolating the spectrometer from the outer cryostat can. This precludes the use of any direct adjustment on any of the optical components as this may introduce mechanical or thermal strains, so compromising the stability. Consequently, Grating, Collimator and the other components must be mounted such that, when aligned and

clamped, they remain in alignment when the spectrometer is cooled to 77 K. (The spectrometer works at the Cassegrain focus so components must be clamped to withstand telescope vibration and tipping up to 60° from the zenith).

Mechanically the instrument overall is very strong, hence stable, since it is necessarily compact in design.

2.2.1. Materials

As the purpose of cooling the spectrometer is to reduce the radiation seen by the detector, the optics and body of the instrument must actually cool to liquid nitrogen temperatures in a reasonable time. Aluminium and Copper both have good thermal conductivities at 77 K. (Aluminium, $K_c = 1.5 \text{ W cm}^{-1} \text{ K}^{-1}$, Copper, $K_c = 6 \text{ W cm}^{-1} \text{ K}^{-1}$). To save weight aluminium is used for the majority of the mountings and support components while copper is only used for the detector block and instrument base plate. Remarkably, stainless steel is an effective thermal insulation at these temperatures, ($K_c = 0.07 \text{ W cm}^{-1} \text{ K}^{-1}$) and has only been used when this property is required; such as shafts leading through the vacuum jacket.

2.2.2. Optical Supports

The collimator and grating, the largest components, are mounted in individual cells by being sprung hard against 3-point supports. (See Fig. 2.3 a, b).

The collimator cell is clamped to its support using adjustable screws (but no springs). The grating cell is supported by two cross-spring Bendix pivots (Bendix $\frac{3}{16}$ " 5006-800 Flexural

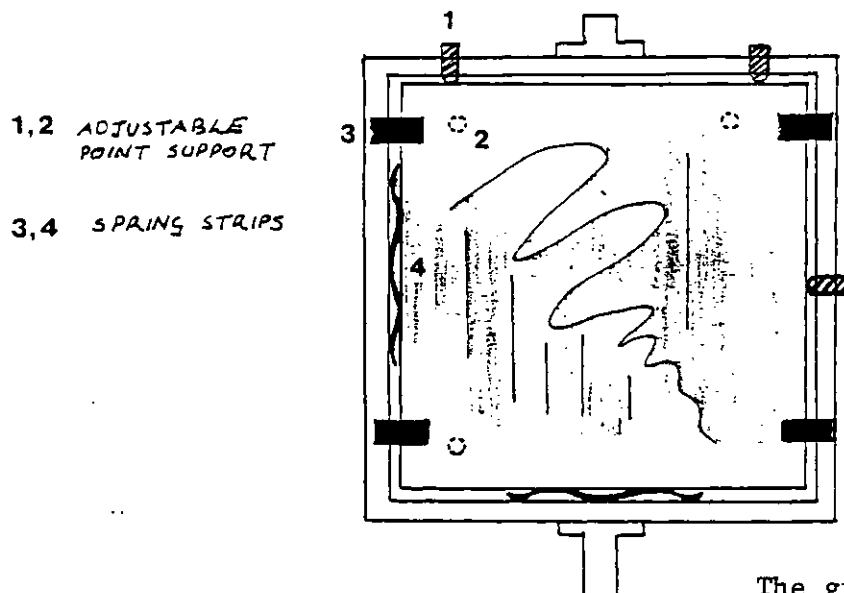


Figure 2.3 (a) - Grating Cell

The grating is held in the cell and laterally by spring strips holding the grating against two sets of adjustable point supports

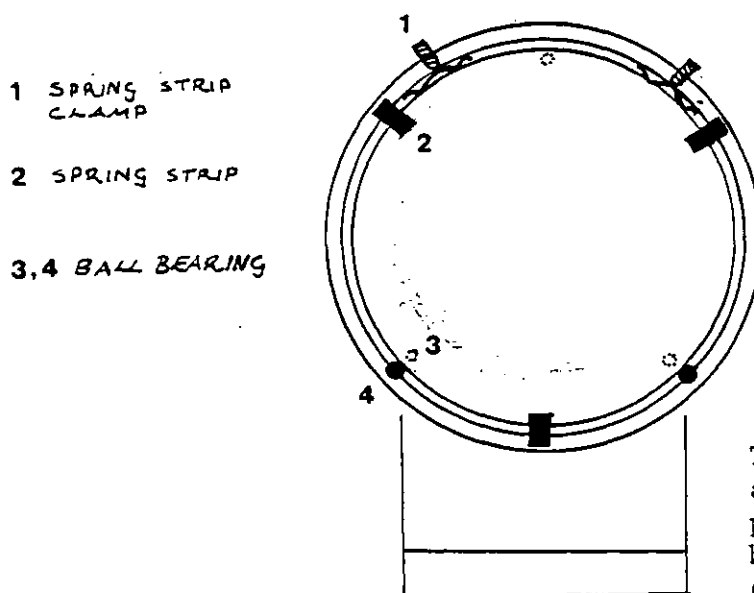


Figure 2.3 (b) - Collimator Cell

The collimator is also sprung against point supports, but here, the whole cell can be adjusted so ball bearings can be used as supports

Pivots). These provide frictionless and accurate rotation centres; essential if the spectrum is to remain within the 0.5 mm detector as the grating rotates. This was found only to be the case if the pivots are mounted and clamped in identical orientations. Using a jig to support the grating cell while clamping ensured there was no risk of any rotational misalignment that would cause differential torsion between the two pivots. During one test, one pivot was accidentally mounted 'back to front' with respect to the other. On cooling, the differential torsion was sufficient to cause the spectrum to miss the detector completely. It is also found necessary to restrict the range of rotation to $\pm 15^\circ$ when cool rather than the quoted $\pm 20^\circ$ to avoid damaging the spring leaves.

The other mirrors are simply glued, using Epoxy, to their individual supports. These are clamped to the main body of the spectrometer using adjustable screws. These mirrors have so far stayed in place over ~ 30 thermal cycles.

Allowance is made for a limited amount of movement in the 'up-down' direction, perpendicular to the dispersion axis, by replacing the circular exit aperture with an equivalent slit.

2.2.3. Grating drive and Rotation Encoding

The grating is rotated using a high precision P.I.C. antibacklash worm and wheel. The rotation position is measured using an incremental encoder on the worm gear shaft inside the spectrometer and cryostat. There are two advantages in having the rotational encoder inside the cryostat:

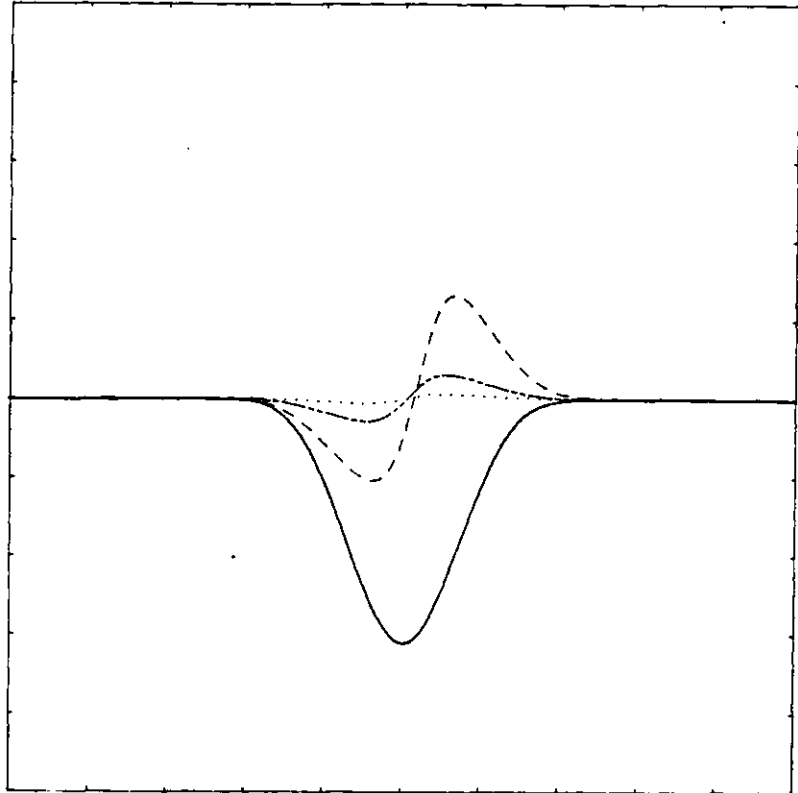
- 1) The worm gear shaft need only be loosely coupled to the external drive motor, so simplifying the coupling through the vacuum jacket and avoiding the risk of any thermal or mechanical strains being transmitted to the grating mount. (As no positioning accuracy is required of the motor, a simple DC motor is used, so avoiding inherently microphonic stepping motors).
- 2) The I.R. atmospheric window can be highly structured in transmission (see Fig. 2.13). To sum consecutive spectra, or extract the continuum by dividing out the atmospheric contribution using a calibration star, the spectra must be matched or aligned in wavelength to far greater precision than the resolution of the instrument. Any mismatch, as figure 2.4 shows, will generate 'noise' over these structured regions. Ideally, to avoid this, the wavelength registration must be reproducible to at least $1/100$ of the resolution in order to be considered utterly negligible.

To achieve this last requirement, implies registration of ~ 1 in 10^4 on the worm gear shaft for our present grating. If the encoder is placed outside the cryostat a rigid shaft is needed through the vacuum jacket. Even the use of flexible bellows couplings proves inadequate. These have inherent "wind-up". (Servometer quote typically 358 arcseconds per inch ounce applied torque). As all internal bearing and worm drive have no lubrication, torques transmitted through the couplings can be high, so compromising the absolute reproducibility of any external encoder.

Figure 2.4

The dotted/hashed lines show the 'noise' that can be generated by dividing a measured absorption feature (solid line) by an identical but mismatched profile. The mismatch is given as a percentage of the instrumental profile;

..... 1%
- - - - - 5%
- - - - - 20%



The disadvantage of such an encoding scheme is trying to find an encoder that will work reliably in a vacuum at 77 K. A great deal of effort was expended in trying to develop such a device (see Plate 2.1). The most successful to date is an optical encoder using L.E.D.'s and a circular disc with an accurate series of holes on the

circumference. To avoid any contamination of the beam, the L.E.D.'s are switched off during the detector integration period. This has the disadvantage that the bandwidth of the detector system requires a long settling time. (~ 1 second).

To get a good photometric accuracy it is desirable to scan the spectrum as fast as possible to attempt to 'freeze' any atmospheric transparency changes across a scan.

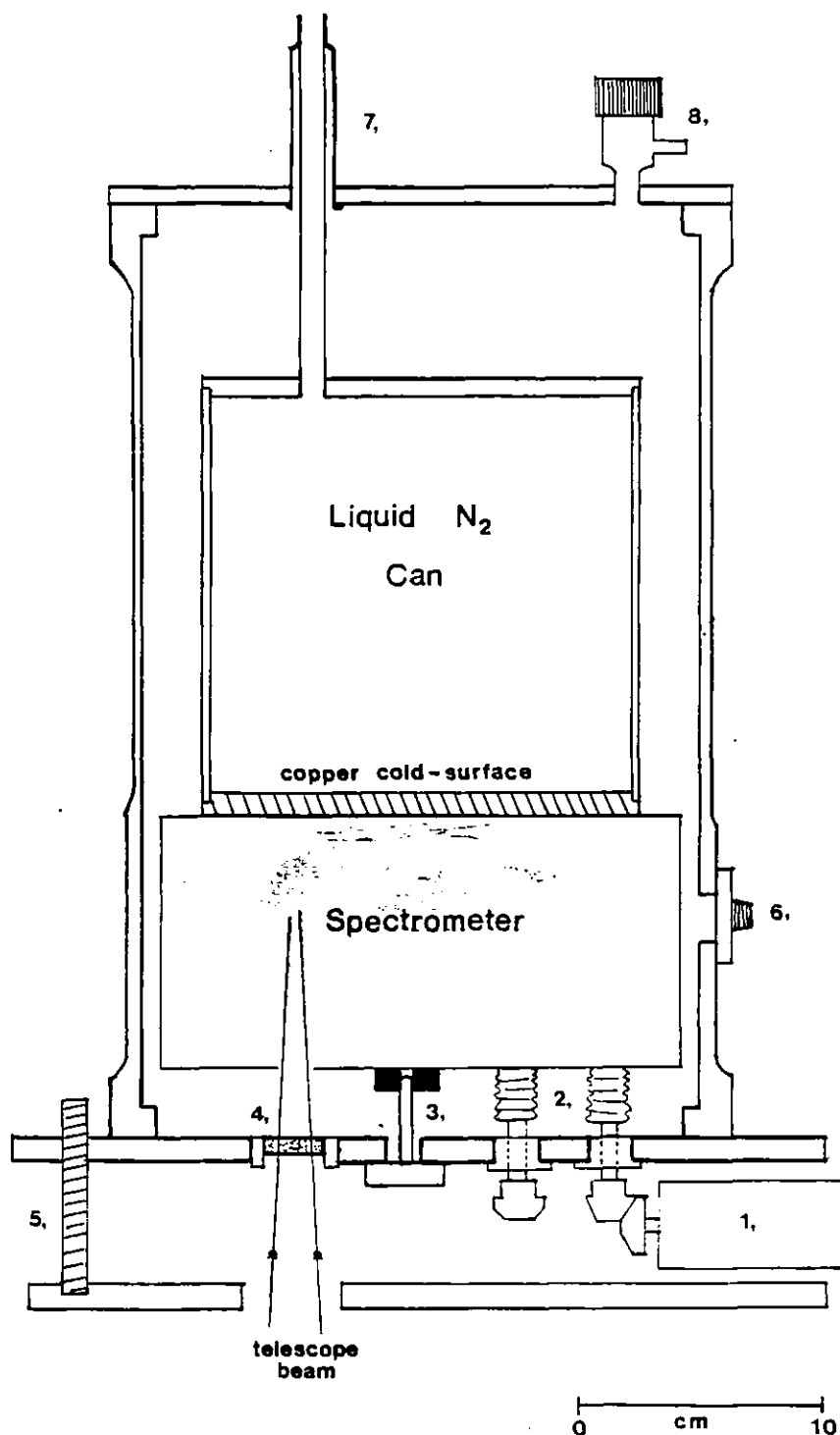
This encoder is now being replaced by a capacitive device, developed by Roger Sidey of Imperial College, which encodes the rotational position absolutely with a precision of 1 in 16000.

2.2.4. Cryostat (Fig. 2.5)

To cool the spectrometer to 77 K a cryostat with a 7 inch work surface was made at Imperial College. The inner Nitrogen can is made of stainless steel supported by three 22 S.W.G. $\frac{3}{8}$ " O.D. fill tubes. The work surface was initially also stainless steel to ease problems of welding. However this did not provide the necessary cooling and was later replaced by a vacuum brazed copper cold-surface. The cryostat outer can is a machined Dural tube. All electrical connections are led out using three 6-way hermetically sealed Amphanol connectors. Both grating drive and filter change are coupled to the spectrometer using 'Servometer' bellows couplings. These shafts are led in through Wilson seals set in the base plate of the cryostat.

2.3 Alignment and Positioning of Detector

As there are no external adjustments on the optical train, great care is taken to align the instrument and position the detector



1. - grating drive motor 2. - flexible 'Bellow Couplings' and corresponding Wilson Seals 3. - centring pin 4. - CaF window 5. - spectrometer tilt and support screws 6. - Amphenol electrical connector 7. - fill tube 8. - vacuum valve

Figure 2.5 - Spectrometer Cryostat

so the entire spectrum falls on the detector over the entire grating rotation.

The InSb detectors are bought mounted only on small sapphire discs. These are then centred, using a travelling microscope and centering jig, and bonded to machined mounting discs (Fig. 2.6a). The detector discs are designed to fit into a machined circular recess on the detector block of the spectrometer. To make sure the spectrometer beam is in the same position as the detector, the detector disc can be interchanged with an identical perspex disc having a .5 mm aperture at the exact position of the detection surface (Fig. 2.6b). Illuminating with a F/13.8 beam from a He/Ne laser, the image position and focus at the detector surface can be viewed from behind the detector mount using a microscope (Fig. 2.6c).

When the alignment is checked over the entire grating range, (using the 1st to 9th order from the .633 μm Laser line), the components are clamped to the cryostat cold-surface. After the alignment is rechecked, the perspex disc is interchanged with detector. If this procedure is followed, the spectrometer remains in alignment when cool over the 1 μm - 5 μm range.

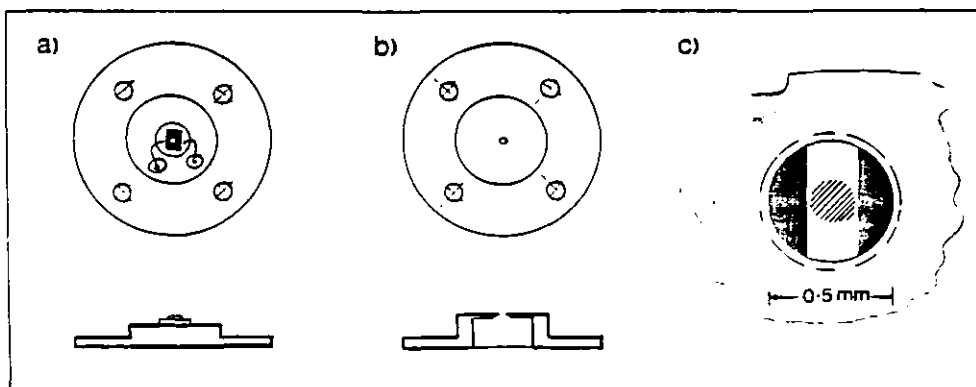
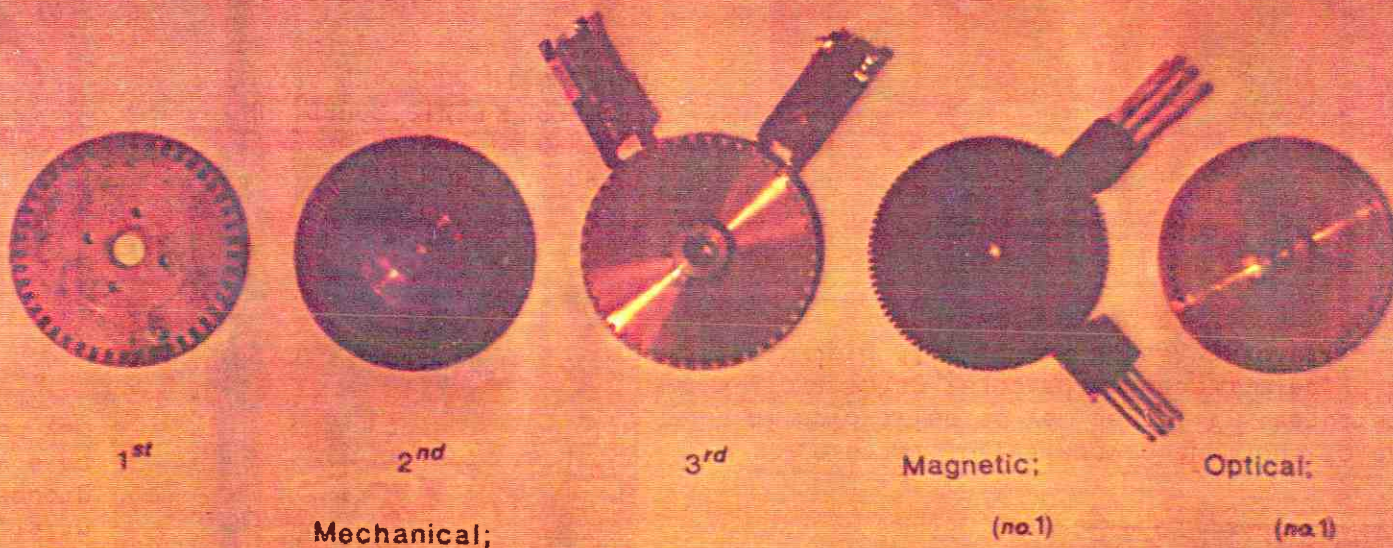


Figure 2.6 (a) - 0.5 mm dia. InSb detector on mounting disc.
(b) - equivalent perspex disc with 0.5 mm dia. alignment aperture.
(c) - View through 0.5 mm alignment aperture showing the image of the circular 15 μm input aperture and exit slit.

1 μ m--5 μ m COOLED GRATING I.R. SPECTROMETER,



SHAFT ENCODERS (77°K)

Plate 2.1 Shaft Encoders used in Cooled Grating Spectrometer

2.4 Data Acquisition and Control Electronics

2.4.1. Shaft Encoder

The shaft encoder mounted on the worm gear shaft is a disc with 90 equidistant 1 mm diameter holes drilled along the circumference, Plate 2.1. A pair of optical switches are used to generate two equal mark-space square waveforms 90° out of phase. By counting at each edge of each waveform 360 counts/rev. are produced. By comparing the relative phases, the direction of rotation is also defined. The circuit designed to do this is shown in Figure 2.7. The output of this decoding circuit is fed to a 4 digit B.C.D. up/down counter.

The reproducibility of the encoder relies on the accuracy of the phase difference and the 1:1 mark space ratio. This in turn relies on the accuracy of the encoder disc machining. In practice this was found to be better than 5% giving a reliable reproducibility of 1:3600.

2.4.2. Control and Data Acquisition

The control and data acquisition is designed to be compatible with the I.C. Infrared photometry system on Tenerife. (Jordan 1977). The general structure of the spectrometer system is shown in Fig. 2.8.

Grating scanning, data logging and telescope control is synchronized and controlled by a Rockwell Advanced Interactive Microprocessor System, AIM65. This allows great flexibility in changing the mode of operation of the spectrometer, a very necessary feature during the first development runs. The General Interface Box

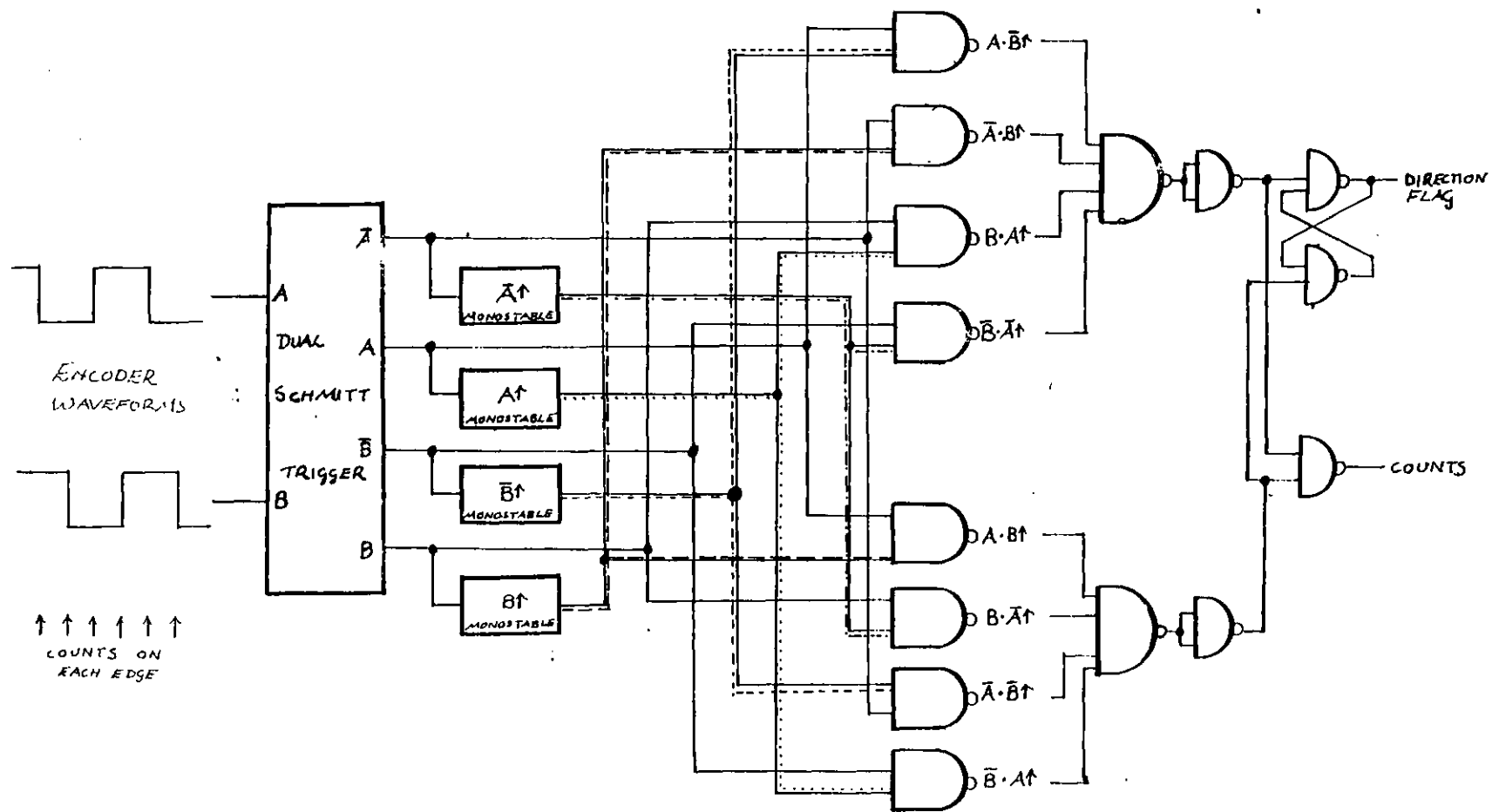


Figure 2.7 Circuit to generate COUNTS (x 4) and DIRECTION from shaft encoder

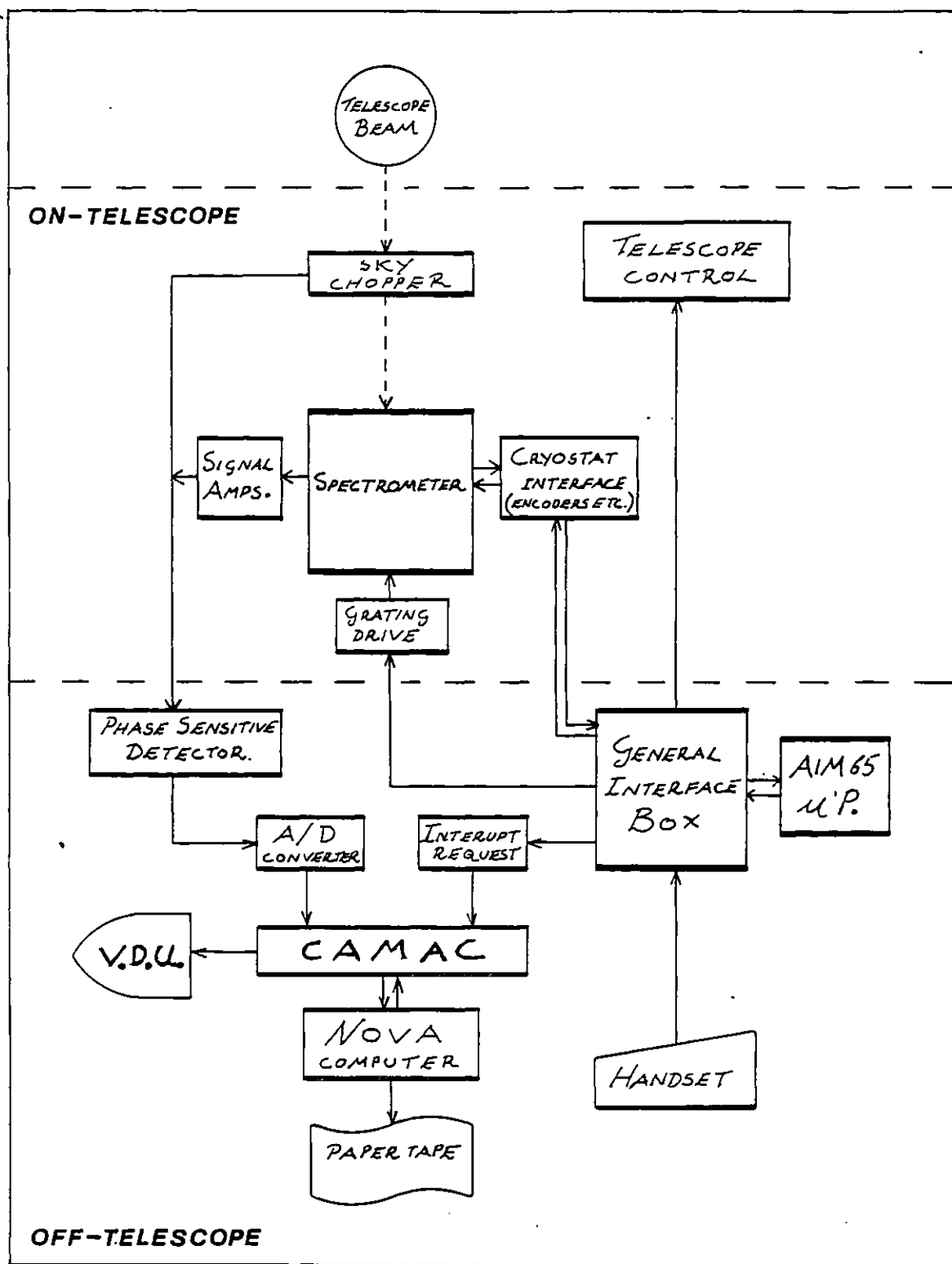


Figure 2.8 Spectrometer system 'over-view'

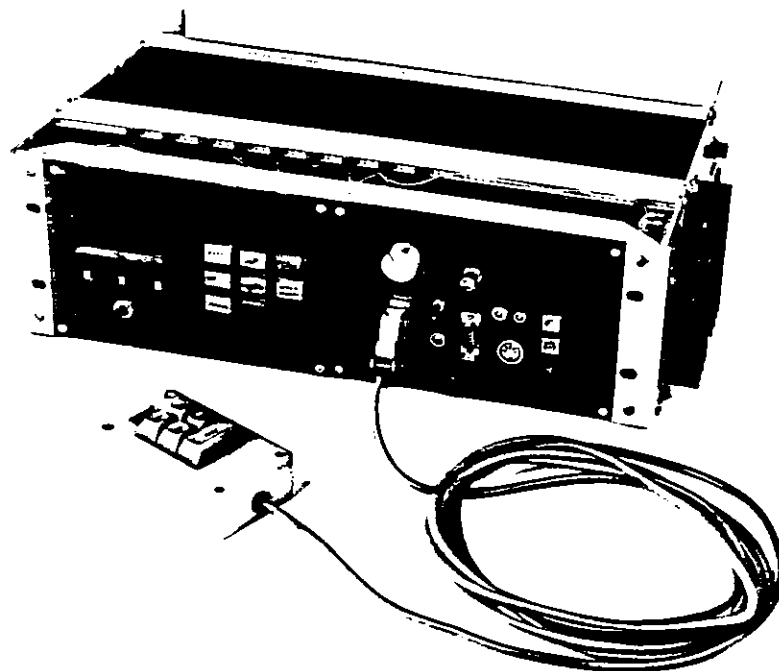
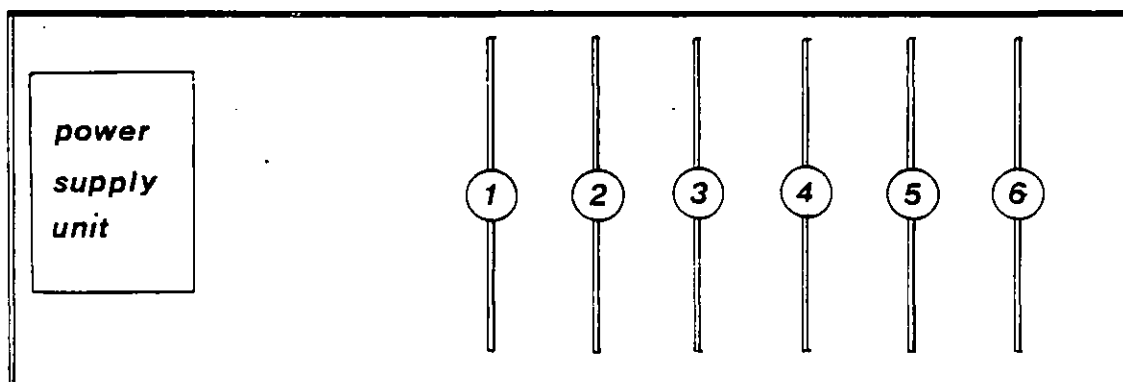


Plate 2.2 General Interface Box



Boards; (1) - counter decode (2) - grating drive control (3) - computer and telescope interface (4) - AIM 65 interface (5) - cryostat interface (6) - Encoder de-code and counter

Figure 2.9 - General Interface Box

(G.I. Box) (Plate 2.2, Fig. 2.9) was built to house all power supplies, switching electronics and decoding circuits for the grating drive and positioning.

It also allows the spectrometer to be manually operated via separate hand set and continuously displays the current grating position. The Nova computer is simply used as an 'intelligent' data logger and gives a real time display of the spectra on a V.D.U. in the Telescope Dome. Each spectral scan is individually stored at present on paper tape for subsequent analysis at I.C. (This is now being replaced by a digital cassette). The Basic program for the data logging on the Nova is given in Appendix A.

The mode of operation of the spectrometer is best illustrated by following the two flow diagrams (Fig. 2.10 and Fig. 2.11) of the machine code routines used to run the AIM65.

The initialization program is simply to find the grating datum position, a 0.005" slotted optical switch attached to the grating mount, and used as the zero position for the encoder counter.

The scanning of spectra is always done in the 'forward direction', defined as moving away from zero order to increasing wavelength. After each scan, the grating is quickly returned to the short position. To remove any mechanical backlash in the couplings, the start position is always approached in the forward direction.

Initialization Module

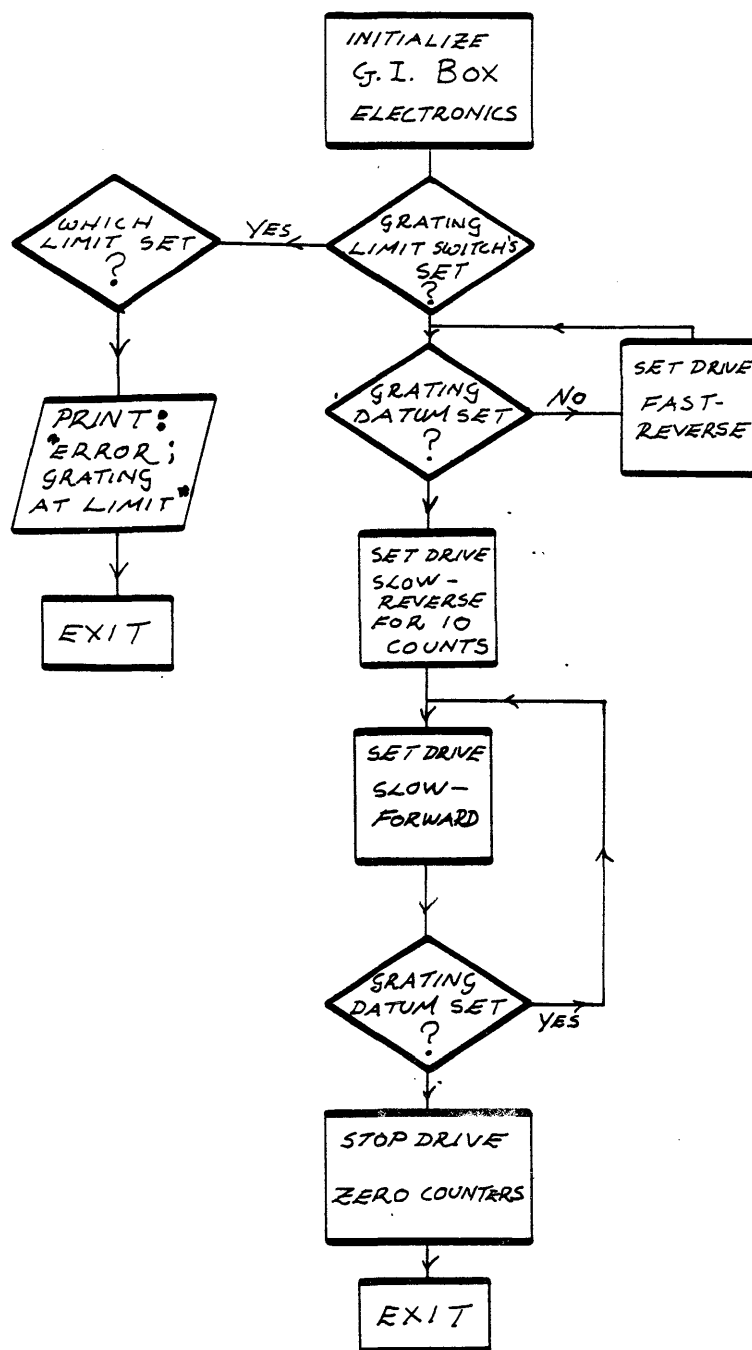
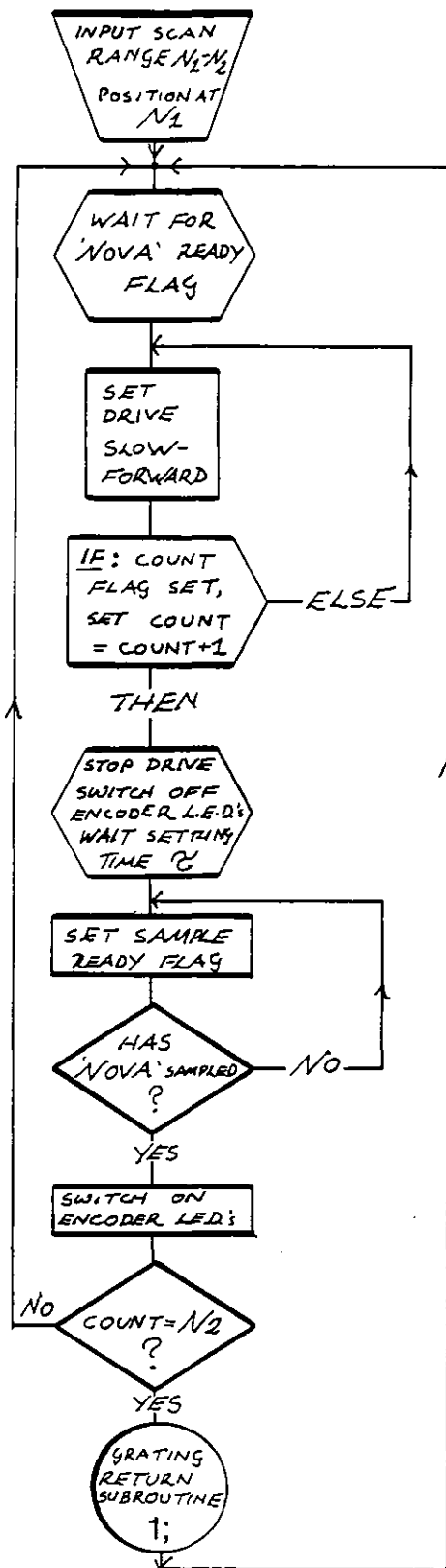


Figure 2.10 Flow diagram of AIM65 machine code initialization module

Scanning Control Program



subroutine 1;

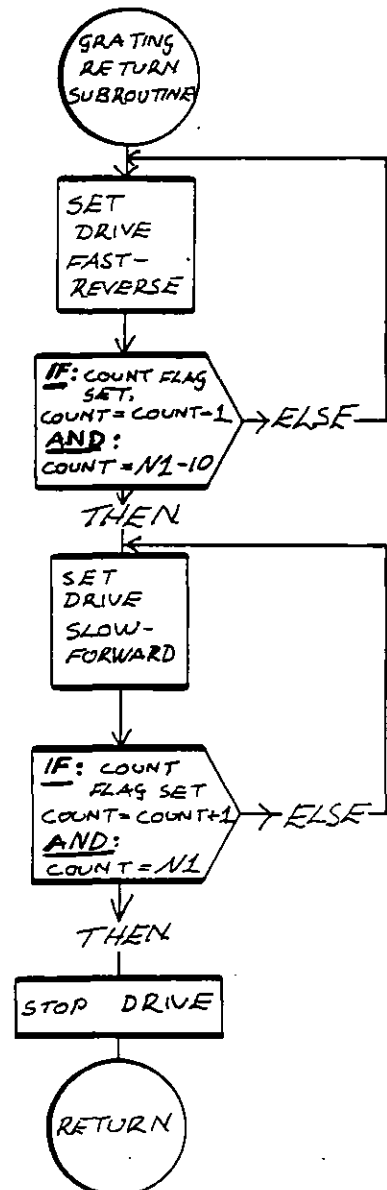


Figure 2.11 Flow diagram of AIM65 machine code scanning control program

2.4.3 Detector and Preamplifier

The single InSb 0.5 mm photovoltaic detector is operated in a transimpedance amplifier of the Hall type, and is extensively described by MacGregor (1976).

A novel feature of this spectrometer is in the hypersensitization, or 'J-flashing' of the detector. This process, which is to flood the detector with 1 μm radiation after it has cooled, is found to subsequently make the detector far more stable and can increase its impedance by up to factors of 10. (This is thought to be the effect of "cleaning out" metastable surface states from the detector). It is done in the spectrometer with a small "pea" bulb, behind a J-filter, from inside the cryostat. The detector can be completely 'J-flashed' with a single 20 second pulse. A normal photometer usually requires a 10 minute 'flash' from an external 60 watt bulb, (with the spectrometer this was found totally ineffective).

2.5 Performance

The first cooled scans of the 1.08 μm Helium line in 1st, 2nd and 3rd order are shown in Figure 2. The measured resolution agrees well with that predicted by the grating equation. ($n\lambda = 2d \sin \theta$; $1/d = 300 \text{ lines mm}^{-1}$). This, combined with good instrumental profiles, shows the spectrometer remains in focus and in alignment when cold. Repeated scanning of these lines over a period of an hour always produced the same count from the encoder (this was using the optical encoder with 10 counts across the instrumental profile). There was initial concern when a least squared fit analysis of grating position to wavelength gave a poor fit. It was subsequently found a 'good fit' was obtained

by using a line spacing of $1/d = 303 \text{ lines mm}^{-1}$ as the grating had contracted by 1%. The through-put of the spectrometer was measured by looking at the signal produced by the flux from a standard furnace and comparing this with the equivalent signal from our photometer. Assuming the InSb responsivities are the same (0.8 W A^{-1}) gave a transmission through the spectrometer of 30%.

The commissioning runs for the spectrometer on the 1.5 m I.R.F.C. have been plagued by bad weather. However the first continuous scans of Vega (using the grating blazed at $2.5 \text{ }\mu\text{m}$) are shown in figure 2.a,b. These scans, taken in poor photometric conditions, have not been corrected for the $\sim 10^4 \text{ K}$ flux distribution of Vega but the detailed structure of the H, H and L windows is clearly visible (c.f. Figure 4.1 a,b).

3.24 μm
R-380

2.16 μm

R-232

1.08 μm
R-105

zero
order

Figure 2.12 - Cooled scans of the
1.08 μm He line in 1st, 2nd (2.16 μm)
and 3rd (3.24 μm) order

Baush and Lomb grating blazed at
2.5 μm with $1/d = 300$ lines mm^{-1} .

λ	n	θ	Expected Resolution ($f = 154$ mm 15° input app.)	Measured
1.08	1	9.3°	112	105
2.16	2	18.9°	234	232
3.24	3	29.1°	380	379

A comparison of the expected resolution,
at order n and angle θ , with that
measured.

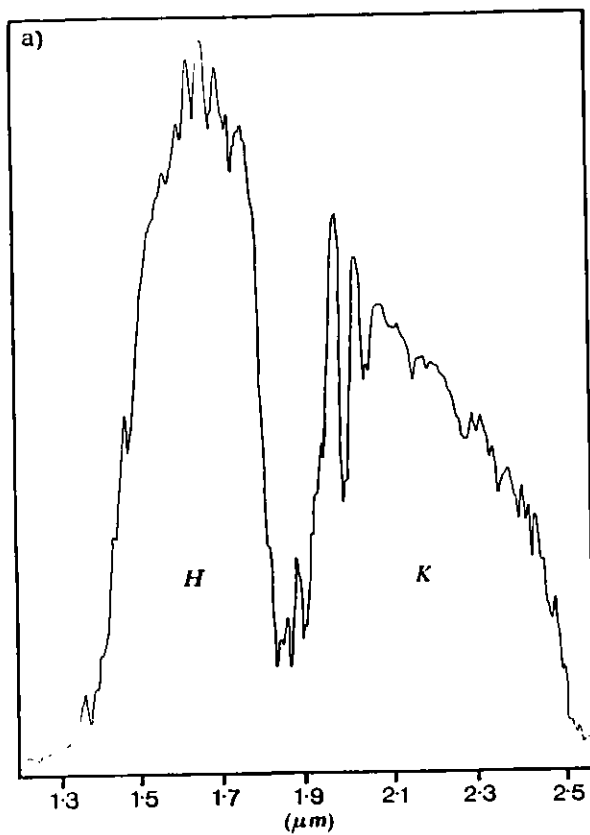
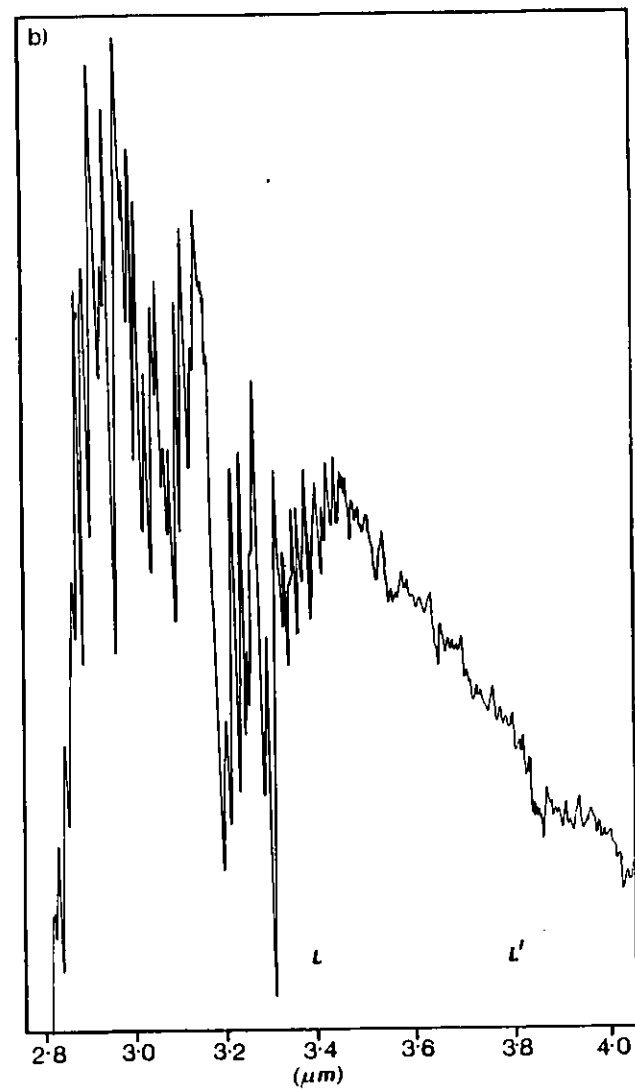


Figure 2.13 a) Cooled spectrometer scan on H and K windows

b) Scans of Vega in the L window
(uncorrected for Vega flux $T \sim 10^4$)



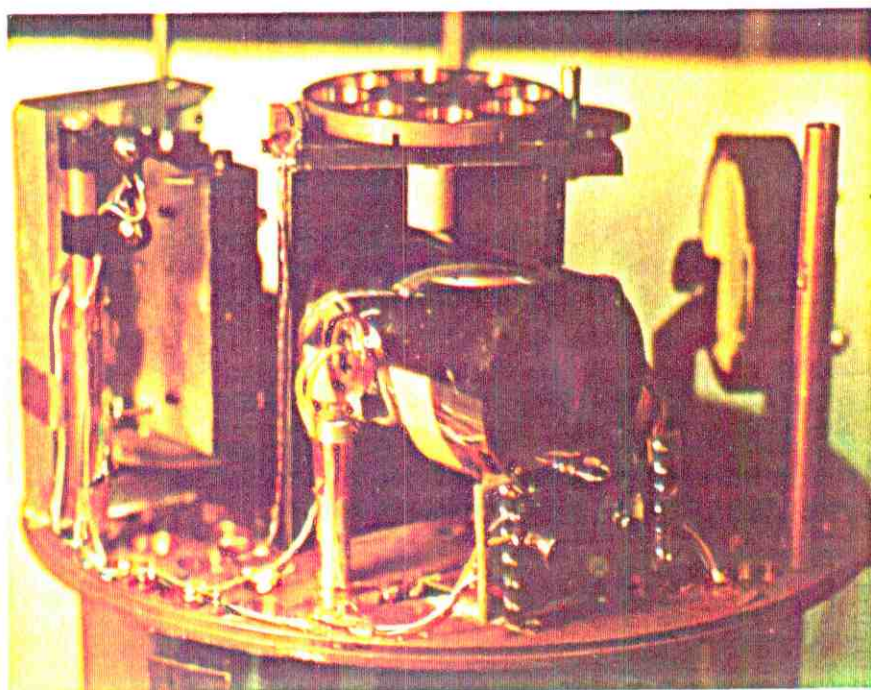
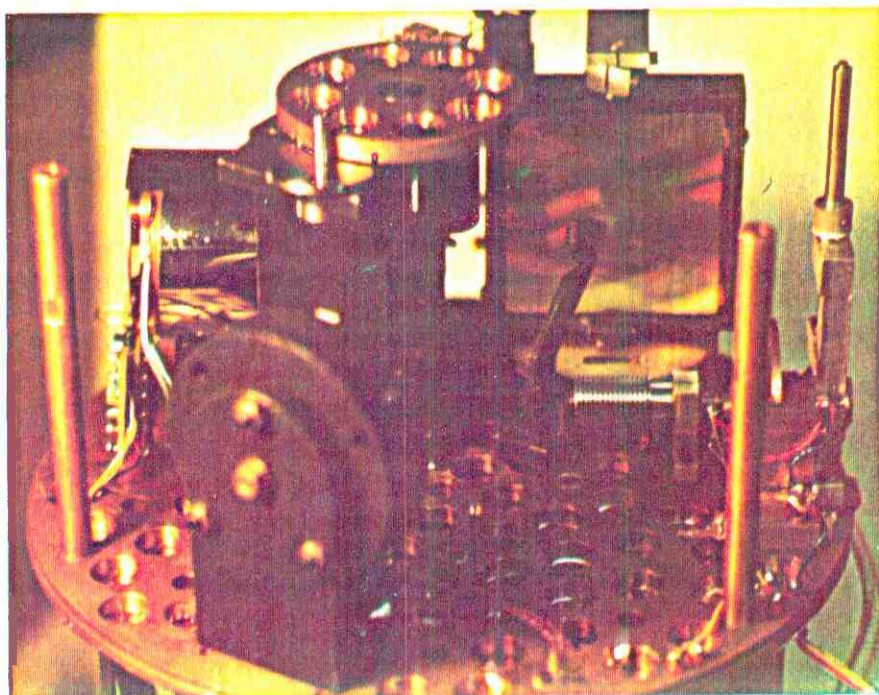


Plate 2.3 The Cooled Grating Spectrometer

CHAPTER THREE

"Although there have been great advances in the application of infrared techniques to astrophysics, a direct calibration of infrared stellar flux, i.e. one in which the flux from a star is compared with that from a standard source, does not exist".

Selby et al (1980)

3.1 Introduction

The calibration of the infrared photometric system is based solely on indirect calibrations. Johnson (1964, 1966), who originally proposed the J, H, K, L, M photometric system, based its calibration on photometry of stars of similar spectral type as the sun. With knowledge of the solar constant and by doing relative photometry of Vega, he was able to define absolute fluxes for all the infrared colours with respect to this standard calibration star. Gerhz, Hackwell and Jones (1974) have devised a system based on extrapolating the UBVRIJK photometric system using fluxes predicted from a black-body. A more sophisticated technique has recently been used by Strecker et al (1979) by doing airborne spectrophotometry of 13 bright stars. These were placed on an absolute scale using a model atmosphere for Vega, from Schild, Petersen and Oke (1971), which has an absolute calibration in the visible.

Table 3.1 shows the results of these calibrations.

TABLE 3.1

	2.2 μm	3.78 μm
	(Units are $\text{W m}^{-2} \mu\text{m}^{-1} \times 10^{10}$)	
Johnson	3.83	.538
Gerhz <u>et al</u>	4.03	.546
Strecker	3.93	

For many astrophysical problems, an accurate absolute calibration is not needed. This is not the case for accurate determination of stellar angular diameters and effective temperatures using the Infrared Flux Method (Blackwell et al 1979). The angular diameter θ of a star can be related to the stellar surface flux F_{s, λ_0} and the absolute flux at the Earth, F_{E, λ_0} by equation (3.1)

$$\theta = 2 \sqrt{\frac{F_{E, \lambda_0}}{F_{s, \lambda_0}}}, \quad \dots (3.1)$$

By measuring in addition the total integrated flux from the star at the earth, $F_E = \int_0^\infty F_{E, \lambda} d\lambda$, two equations (3.2) and (3.3) can be formed with the variables θ and effective temperature T_e .

$$F_E = \int_0^\infty F_{E, \lambda} d\lambda = \frac{\theta^2}{4} \sigma T_e^4 \quad \dots (3.2)$$

$$F_{E, \lambda_0} = \frac{\theta^2}{4} \times F_{s, \lambda_0} = \frac{\theta^2}{4} \times \phi(T_e, g, \lambda_0) \quad \dots (3.3)$$

where $\phi(T_e, g, \lambda_0)$ is the stellar surface flux as calculated from a stellar model of effective temperature T_e , surface gravity g at a wavelength λ_0 .

Figure 3.1 shows the solution of equations (3.2) and (3.3) prepared for the star γ Ser (F6 IV) at the infrared wavelength $\lambda_0 = 3.45 \mu\text{m}$. The figure shows that the two curves intersect quite sharply, so giving a well defined solution for θ and T_e . The shallow gradient of curve 3.3, and hence the sharpness of the intersection is due to weak dependence of stellar surface flux on temperature in the near-infrared. It is by choosing to use infrared wavelengths that makes this method successful. It would be possible to determine stellar angular diameters

to an accuracy of 2% and effective temperatures (T_e) to 1% *provided the absolute flux is known to 2%.*

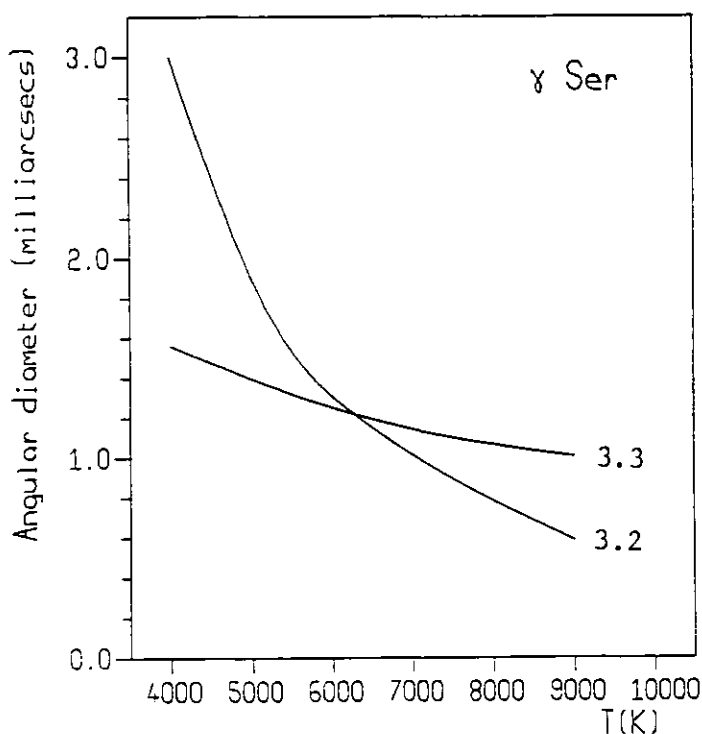


Figure 3.1 Application of the I.R. flux method to γ Ser
(Blackwell et al 1979)

An example of the consequence of the present inaccuracies in θ and T_e is that the mass of Acturus (α Boo) is uncertain to within a factor of 30.

More worrying is that by applying the IR Flux Method to a series of bright stars and determining θ as a function of photometric colour, Blackwell et al (1979) has suggested there may be a wavelength dependent error in the Johnson calibration of about 11% between 3 μ m and 5 μ m.

For the last three years Dr. M. J. Selby and I have been collaborating with the Department of Astrophysics, University of Oxford, in attempting a direct infrared measurement of the absolute flux from Vega.

3.2 The Method

For a direct measurement of absolute flux it is necessary to compare the star with a furnace of known flux. The essential elements for such a direct calibration are:

- 1) in the comparison of stellar flux with a source of known flux, the detector should "see" the star and source optically indistinguishable.
- 2) a stable, well calibrated source such as a standard furnace or blackbody cavity where both the emissivity and temperature of the cavity are known.
- 3) a linear and stable detector.
- 4) the ability to eliminate or measure atmospheric extinction so as to successfully extrapolate the measured flux to zero airmass.

3.2.1. Previous Calibrations

Before the start of our project, the absolute flux from Vega had only been measured by direct or semi-direct methods up to $1.08 \mu\text{m}$. Oke and Schild (1970) and Hayes et al (1975) have made direct measurement of absolute flux from $6800\text{\AA}$ to $10800\text{\AA}$ by comparison with standard sources. These have been either tungsten strip lamps, platinum blackbodies or copper blackbodies placed on towers some distance from the telescope. Vertical extinction could be eliminated by following the star through the Zenith and extrapolating to zero airmass. However the major source of error was in the uncertainty of the horizontal extinction to the black-body, which in some cases was up to 2.6 km from the telescope.

To date, the only other attempt to extend this measurement to the near-infrared (other than our own) is that begun again by Hayes et al (1981) at KPNO. To eliminate the horizontal extinction they use a grating spectrometer to avoid terrestrial water bands and any continuous extinction process "will be calculated semi-theoretically from measurements of vertical extinction" (Hayes et al 1981).

3.2.2 Our Method

In our method we attach a calibrated furnace, as source, directly to the I.R. photometer cage of the 1.5 m I.R.F.C. in Tenerife. The focal plane at the cassegrain focus of the telescope is reimaged, using a BaF lens, onto the detector field stop inside the cryostat. (Fig. 3.2). The detector can see either a star or a signal from the furnace, viewed through an aperture (matched to the seeing angle of the star) placed in the focal plane of the telescope. Using a limiting field stop at the focal distance of the BaF lens, where an image of the primary mirror is formed, ensures that the geometry "seen" by the detector is identical for both the furnace and star. (The limiting stop not being the telescope primary).

The advantages of this arrangement are:

- 1) Furnace, reimaging optics and detector can be firmly clamped to the photometer so making the geometry very mechanically stable.
- 2) problems of horizontal extinction are eliminated by the short distance between detector and furnace (~ 1 m)

However there are consequential disadvantages:

1) The typical seeing angle is 3 arcseconds, this means the matched aperture from the furnace is 0.3 mm in diameter. The flux through this aperture, from a 1250 K blackbody, is far larger than that from Vega ($T \sim 10^4$ K) which has an angular diameter of only 3.4 milliarcseconds. At 3.8 μ m for example, the flux ratio "seen" by the detector:

$$\frac{\text{Furnace}}{\text{Vega}} \sim \frac{(\text{blackbody flux } T = 1250 \text{ K})}{(\text{blackbody flux } T = 10^4)} \times \left(\frac{3}{3.4 \times 10^{-3}} \right)^2$$

~ 20000

If the measurement was made in space, with a furnace aperture comparable to the stellar disc, the signal from Vega would be far larger.

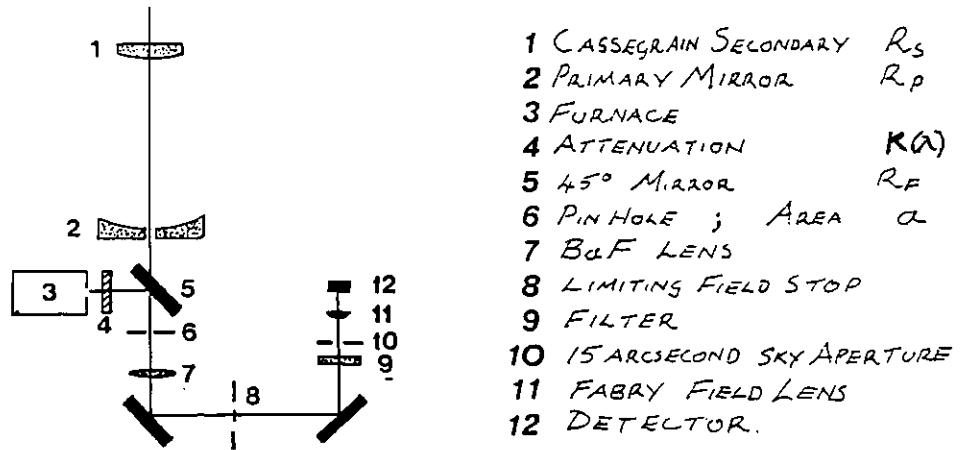
The signals from Vega and the furnace must be reasonably comparable, to keep within the dynamic range of our detector system. With our photometer Vega gives a signal of about 1 mV at 3.8 μ m which would give an equivalent signal from the furnace of 20 V, well above our saturation limit of 9 V. The flux from the furnace must therefore be attenuated in some way.

2) As seen from equation (3.4), Figure 3.2, the reflectivities of both telescope mirrors enter directly into the calculation of stellar flux.

3) Using conventional I.R. photometry chopping techniques for background cancellation are not possible with this reimaging system. The detector system must be sufficiently stable to work at D.C.

But these potential drawbacks can be and have been, overcome, or accounted for. Horizontal extinction effects, on the other hand,

Figure 3.2 Infrared reimaging system for Absolute Calibration experiment



Furnace Flux. $I_F = B_F(\lambda) R_F a \Omega \text{ watts } \mu\text{m}^{-1}$

$B_F(\lambda) \text{ watts cm}^{-1} \text{ sr}^{-1} \mu\text{m}^{-1}$

Vega Flux: $I_V = F_V(\lambda) R_s R_p A' \text{ watts } \mu\text{m}^{-1}$

$F_V(\lambda) \text{ in watts cm}^{-2} \mu\text{m}^{-1}$

$$\frac{I_F}{I_V} = \frac{B_F(\lambda) R_F a \Omega}{F_V(\lambda) R_s R_p A'} = \frac{B_F(\lambda) R_F a}{F_V(\lambda) R_s R_p f^2}$$

where $\Omega = \frac{A'}{f^2}$, f = telescope focal length

Experiment measures,

$$\frac{I_{\text{furnace}}}{I_{\text{Vega}}} = \frac{K(\lambda) B_F(\lambda) R_F a}{F(\lambda) R_s R_p f^2} \quad \dots (3.4)$$

where $K(\lambda)$ = furnace attenuation factor

$$F_V(\lambda) = \frac{K(\lambda) B_F(\lambda) R_F a}{R_s R_p f^2 10^{0.4 \Delta m}} \quad \text{watts cm}^{-2} \mu\text{m}^{-1}$$

Δm = measured magnitude difference

could always be largely unknown and at very best, variable.

3.3 Experimental Procedure

The target accuracy of the experiment was $\pm 2\%$ in the final flux determination; great effort was expended to keep the errors on the many individual measurements well below 1%.

An 'overview' of the elements in the Absolute calibration system is shown in figure 3.3. The experimental procedure has steadily evolved over the last three years, especially in respect of furnace attenuation and wavelength definition. The following discussion is made in the hindsight of the three attempts at Tenerife in July 1979 (Selby et al 1980); July 1980 (Selby et al 1982) and August 1981 (in preparation).

3.3.1. Detector Stability and Linearity

The flux comparison was made using the standard near-infrared Imperial College photometer (Jordan, 1977). It uses a 0.5 mm InSb detector, with field optics, filters and entrance apertures cooled to 77° K.

The detector is used in a Hall type transimpedance preamplifier. By using a Victoreen feedback resistor ($R = 10^8 \Omega$) gives the detector-preamplifier combination a linearity of better than 0.5% over the useful dynamic range 0 V - 9 V (MacGregor 1977).

The signal from the preamp. was fed to a variable gain, battery operated, D.C. amplifier; the gains were calibrated to 0.1%. Electronic and sky background drifts were removed by 'nodding' the telescope on and off the star after each integration (typically 10 samples in 10 seconds). There was sufficient flux from Vega at most wavelengths,

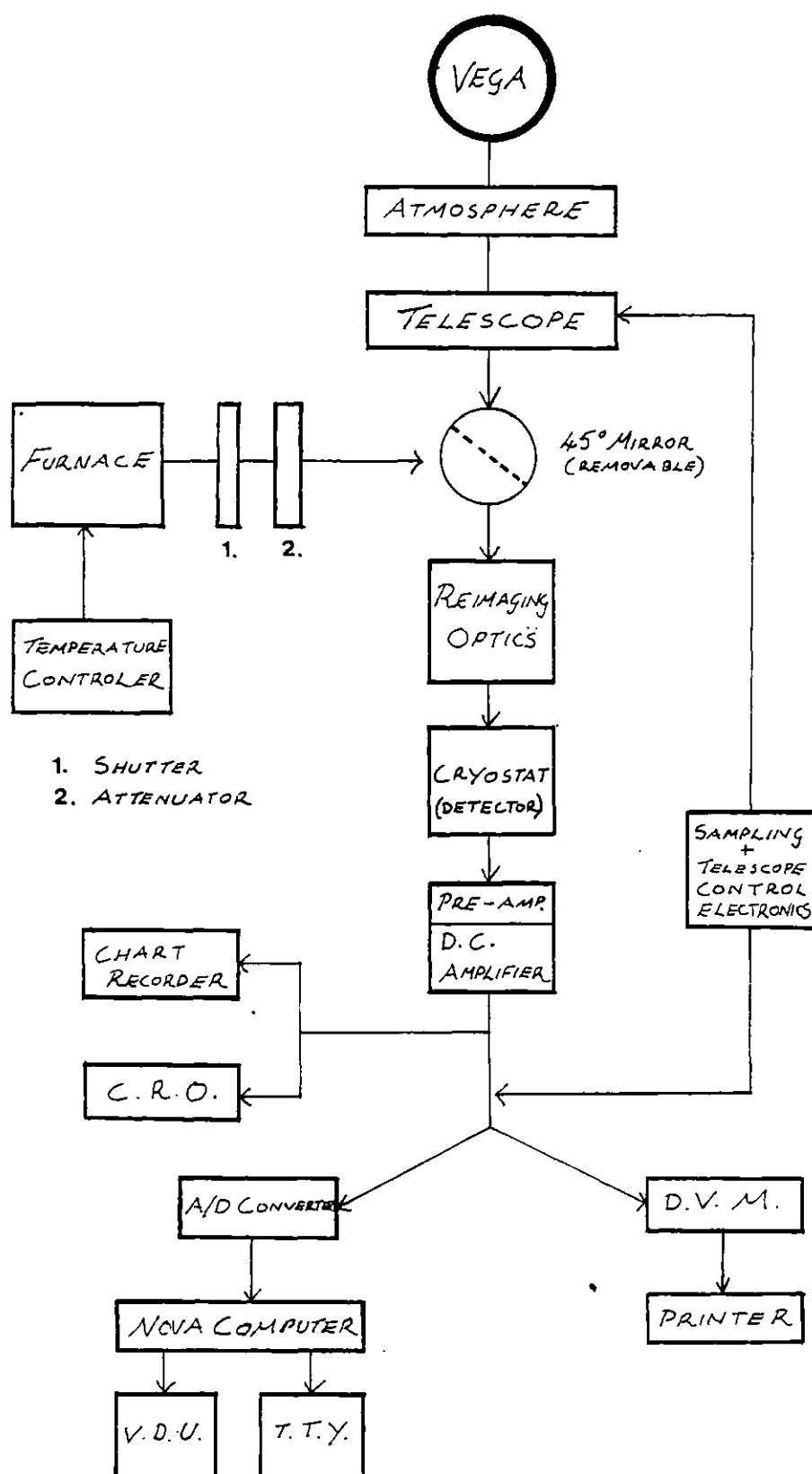


Figure 3.3 The Absolute Calibration System

except 4.6 μm . The flux from Vega at this wavelength is comparatively small compared to the large background radiation from sky/telescope and is not readily measurable by our DC technique. Our procedure to avoid this difficulty was to compare the star αHer (which has a larger flux at this wavelength) with the furnace and later compare αHer with Vega by the more conventional AC method of sky chopping.

When looking at the Furnace, these drifts were eliminated by sequentially opening and closing a shutter in front of the furnace exit aperture. This is not strictly equivalent to "nodding" the telescope on and off the star where the measured difference signal is:

$$\begin{array}{ccc} \boxed{\text{Star + Background}} & \text{upper} & - \quad \boxed{\text{Background}} \\ & \text{Beam} & \text{lower} \\ & & \text{Beam} \end{array}$$

= stellar flux

but for the furnace this difference equals:

$$\begin{array}{ccc} \boxed{\text{Furnace + Background}} & \text{shutter} & - \quad \boxed{\text{Background + Shutter emission}} \\ & \text{open} & \text{shutter} \\ & & \text{closed} \end{array}$$

= Furnace Flux - Shutter emission

the furnace would appear fainter.

However, the shutter never got noticeably warm ($T < 300\text{ K}$) and calculating the shutter emission as a percentage of furnace flux through both the 3.78 μm and 4.6 μm filters gives:

	3.78 μm	4.6 μm
T = 300 K	0.006%	0.03%
T = 400 K	0.14 %	0.44 %

Even if the shutter got "hot" ($T \sim 400$ K) the contribution to measured flux for $\lambda < 5 \mu\text{m}$ can be safely ignored.

If these measurements were extended to $10 \mu\text{m}$, the emission from a ~ 300 K shutter would be $\sim 2\%$ of the equivalent furnace flux. At $10 \mu\text{m}$ the background radiation is substantial. The only way to subtract these backgrounds and make any meaningful furnace measurement is to chop between two calibrated furnaces at different temperatures. The flux measurement would then be:

$$\begin{aligned} & \boxed{\text{Furnace } (T_1, \lambda_o) + \text{Background}}_{\text{Furnace 1}} - \boxed{\text{Furnace } (T_2, \lambda_o) + \text{Background}}_{\text{Furnace 2}} \\ &= \text{Difference in Flux between} \\ & \quad \text{the two furnaces,} \\ & \quad (F_1(T_1, \lambda_o) - F_2(T_2, \lambda_o)) \end{aligned}$$

The success of our data reduction software IRPHOT5, (Jordan 1977) and the stability of the detector-furnace combination used in the DC mode, was demonstrated by the reproducibility of the furnace measurements. These would normally remain constant to better than 0.25% throughout the night and also reproduced from one night to another remarkably well.

3.3.2 Seeing fluctuations

To avoid photometric errors from variable seeing or poor guiding, a sky aperture of $15''$ was used in the cryostat. A fabry field lens was used to give a reasonably flat field across this aperture. See Fig. 3.4.

During observing runs when seeing occasionally flared to $10''$,

there was little or no degradation in the signal stability and associated signal/noise.

3.3.3. Mirror Reflectivities

Equation (3.4, Fig. 3.2) shows that the reflectivity of both telescope mirrors and the 45° mirror must be accurately measured. The measurement of Primary and Secondary mirrors was made using a reflectometer, housing a Golay cell, source, chopper and set of filters. The reflectivity was compared, over a grid of points on each mirror, with that of a 'standard' mirror. The absolute reflectivities of this 'standard' and the small 45° flat were later measured accurately in the laboratory.

3.3.4. Pin hole area

The area of the pin hole, which was typically .3 mm in diameter has to be measured to better than 0.5%. Initially this was done with a projection microscope. Later the measurements were repeated by measuring the area photoelectrically and ratioing with larger diameter (1 mm - 2 mm) apertures of known area. (Leggett, 1983).

3.3.5 Telescope Focus

The focal length of the telescope appears in equation (3.4) as f^2 . It is also wavelength dependent because of the dispersion in the BaF reimaging lens. A precision measurement of the focus was made by timing the transit of a star across two slits in the focal plane, with the Telescope drive switched off. (Fig. 3.5). A timing precision of .1 mS in 30 s was achieved using photoelectric detection and the clock of an AIM65 microprocessor. The slit separation was measured with a travelling microscope, giving a focal length at 2.2 μm of;

$$1.812 \times 10^3 \text{ cm} \pm 0.05\%$$

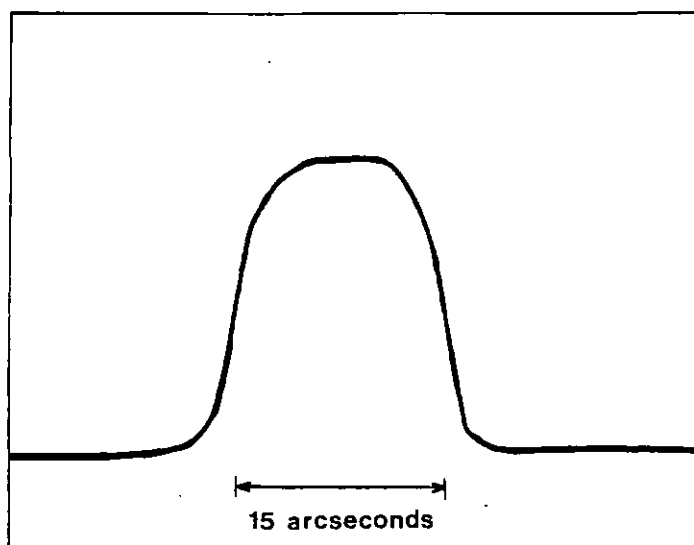
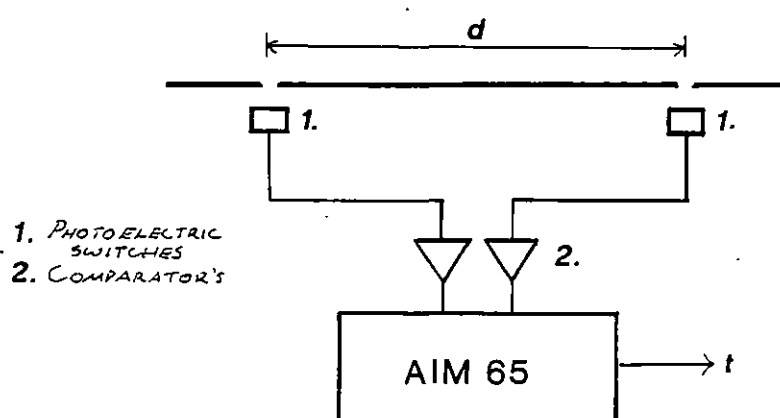


Figure 3.4 Beam profile of the Infrared photometer



$$\text{Plate scale: arcseconds mm}^{-1} = \frac{t(s) \times 15.041066 \times \cos \delta}{10 \times d(\text{cm})}$$

$$\Rightarrow \text{focal length (m)} = 137.13442 \times \frac{d(\text{cm})}{t(s) \times \cos \delta}$$

where δ is the Stellar declination angle

Figure 3.5 Method for measuring the telescope focal length using stellar transit time

3.3.6. Furnace Flux and Attenuation

The furnace used is a standard Electro Optical commercial Black-Body. The flux calibration was done at Oxford using a specially constructed black-body cavity designed at the National Physical Laboratory (Selby et al 1982). The temperature of this was measured to an accuracy of 1 K (Leggett 1983). Having an operating temperature of $\sim 1000^{\circ}$ K, in the $2\ \mu\text{m} - 5\ \mu\text{m}$ region the flux is roughly Rayleigh-Jeans and proportional to T. ($B_{\lambda}(T) \sim \frac{2ckT}{\lambda^4}$) so implying an uncertainty in flux $\sim 0.1\%$. Our commercial furnace was also used at its highest temperature (1250° K) to keep it on the Rayleigh-Jeans tail over the $2\ \mu\text{m} - 5\ \mu\text{m}$ range. At these temperatures it is imperative to attenuate the furnace flux, and this attenuation must be stable and reproducible to better than 0.5% over the period of an observing run. Over the last three years, three different attenuation schemes have been used.

3.3.6.1 MgO diffuser

In the first calibration attempt (Selby et al 1980), an MgO diffuser was used in place of the 45° mirror. (Fig. 3.2). However, when the scattering properties of MgO were investigated in the laboratory, the uncertainty in its behaviour limited the $2.2\ \mu\text{m}$ calibration accuracy to $\pm 8\%$ and $3.8\ \mu\text{m}$ measurement had to be discarded completely.

3.3.6.2 Low Temperature Furnace

In an attempt to measure the $3.8\ \mu\text{m}$ flux and get a more reliable value for $K(2.2\ \mu\text{m})$ during August 1980, the furnace flux was attenuated by lowering the furnace temperature to $\sim 750^{\circ}\text{K}$.

The detector could then view the furnace directly in the K and L bands.

If A is the area of the entrance aperture at the telescope focus, $B_{\lambda_0}^{HF}$ the monochromatic flux from the hot (~ 1250 K) furnace at λ_0 , F the effective focal length of the telescope, $R(CF, ST)$ the ratio of the signal from the cool furnace to the signal from the star, $R(HF, CF)$ the ratio of the signal from the hot furnace to the signal from the cool furnace and T_{λ} the transmission profile of the filter, it may readily be shown that after allowance has been made for reflection losses, the monochromatic flux from the star, $B_{\lambda_0}^{ST}$ is given by,

$$B_{\lambda_0}^{ST} = \frac{A \cdot B_{\lambda_0}^{HF}}{F^2 \cdot R(CF, ST) \cdot R(HF, CF)} \times \frac{\int_0^{\infty} \left(\frac{B_{\lambda}}{B_{\lambda_0}}\right)^{HF} T_{\lambda} d\lambda}{\int_0^{\infty} \left(\frac{B_{\lambda}}{B_{\lambda_0}}\right)^{ST} T_{\lambda} d\lambda} \dots (3.5)$$

The ratio $R(HF, CF)$ was measured separately by placing the furnace a long distance (~ 5 m) from the detector. It can be seen from equation 3.5, the final flux value does not require knowledge of either the high or low furnace temperatures. The flux distribution B_{λ}^{HF} was determined directly, using a monochromator, by comparison with the calibrated NPL Blackbody cavity (Leggett 1983). (The only reason in maintaining the high furnace setting was at the time it was assumed the furnace was indeed a 'good' blackbody. Only with hindsight was it realized this that this was not the case, Selby et al 1982).

For $3.8 \mu\text{m}$ this scheme proved successful. However at $2.2 \mu\text{m}$, and at this low temperature setting $T \sim 750^{\circ}$ K, the $2.2 \mu\text{m}$ flux is given by the Wien approximation, $B_{\lambda}(T) \propto \exp(-hc/\lambda kT)$. The flux is far more sensitive to changes in temperature and subsequent fluctuations in flux were as high as 2%. To get good flux stability at short

wavelengths, $\lambda < 2 \mu\text{m}$, it is necessary to operate the furnace at as hot a temperature as possible to approach the Rayleigh-Jeans part of the blackbody curve where flux $B_{\lambda}(T) \propto T$.

3.3.6.3 Attenuators

From equation 3.5, $R(\text{HF}, \text{LF})$ can be replaced by an attenuation factor AF . To measure AF , that is the ratio of flux the detector sees through the Filter pass-band with attenuator in and attenuator out, the Furnace flux must be further reduced (to avoid detector saturation when the attenuator is removed). Doing this geometrically by limiting the radiation passing through the field stop using a mask, the spectral transmission properties of the attenuators do not enter into the attenuation measurement. This has meant, in our last calibration run of August 1981, a series of glass and plastic slides could be used to attenuate the furnace. These were held in a jig in front of the furnace aperture. The furnace was used in its 'high' setting, for stability, and the attenuation could be accurately measured in situ. The attenuator transmissions of each wavelength were

	J (1.2 μm)	K(2.2 μm)	L'(3.7 μm)	M (4.6 μm)
Trans- mission	100%	32.9%	1.69%	1.56%
(no attenuator)				

3.3.7. Atmospheric Extinction and Wavelength Definition

The monochromatic flux from Vega is always quoted as the flux falling on the earth outside the atmosphere. To try and determine what this is, the stellar flux is measured at several zenith angles and an extrapolation to zero airmass is made. (Fig. 3.6). The greater

the atmospheric extinction the greater is the correction required to zero airmass, and so greater is the uncertainty of this extrapolation.

Furthermore, to extract the monochromatic flux (equation 3.5) the integral:

$$\int_0^{\infty} V(\lambda) T(\lambda) d\lambda$$

$V(\lambda) = \text{Vega Flux}$
 $T(\lambda) = \text{Filter Transmission}$

must be evaluated.

$T(\lambda)$, the cooled profile is measured in the laboratory, but in reality the detector 'sees',

$$\int_0^{\infty} V(\lambda) T'(\lambda) d\lambda$$

where $T'(\lambda) = T(\lambda) \times A(\lambda)$ and $A(\lambda) = \text{atmospheric transmission}$. The greater the extinction, the greater the weight of $A(\lambda)$, (which can be a highly structured function, Fig.(2.13), so greater the uncertainty of $T'(\lambda)$.

In 1979 a standard K band photometry filter ($\lambda_0 = 2.2 \mu\text{m}$ $\Delta\lambda = 0.4 \mu\text{m}$) was used in the absolute calibration. The measured extinction was 0.1 mag/airmass. This compared with the subsequent experiments which used narrow filters, and gave typically:

	J	K	L'
$\lambda_0 (\mu\text{m})$	1.243	2.206	3.766
$\Delta\lambda (\mu\text{m})$	0.034	0.054	0.145
Extinction (magnitudes/ airmass)	0.08	0.03	0.03

(Two extinction curves for 2.2 μm and 3.7 μm are shown in figure (3.6a, b.). If the filters are sufficiently narrow and the extinction low it is assumed $T'(\lambda) = T(\lambda)$.

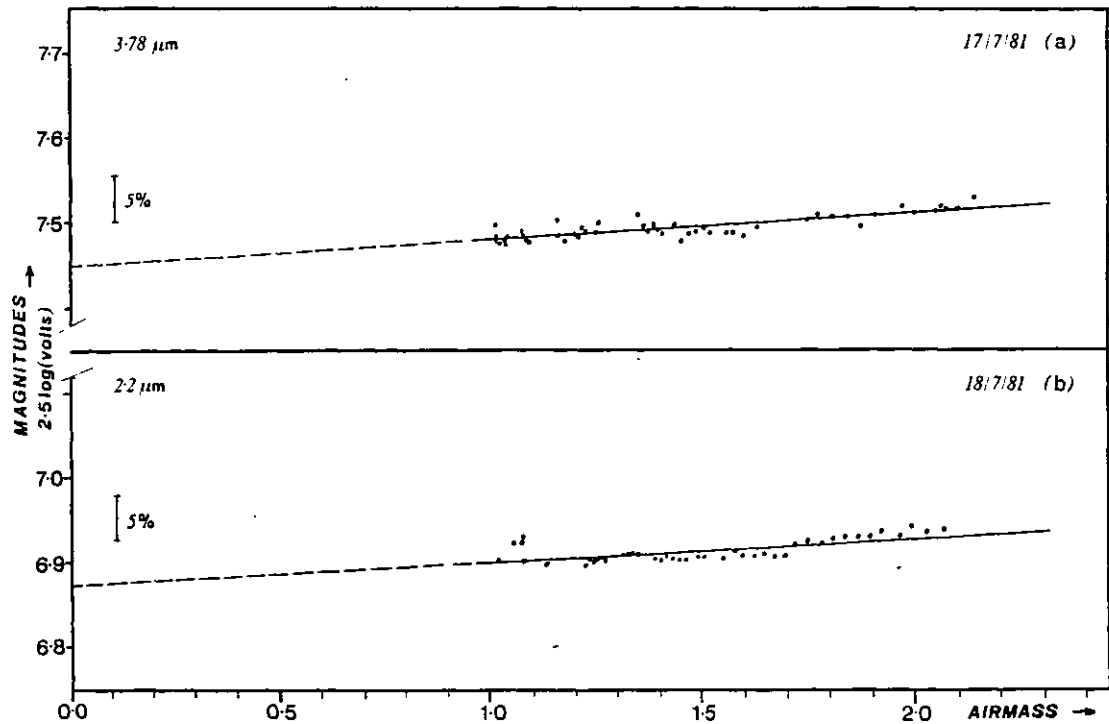


Figure 3.6 Extinction curves measured with:

- a) 2.2 μm filter
- b) 3.76 μm filter

*Note: Unfortunately the Brackett γ absorption line of hydrogen in Vega fell into the narrow K filter band pass and had to be corrected for in $\int_0^\infty V(\lambda) T(\lambda) d\lambda$ giving a 0.6% correction (Selby *et al*, 1982).*

This was not the case for the 4.6 μm filter used in 1981. Attempts to assess $A(\lambda)$ in this case are complicated and are discussed fully in Chapter Four. In the August 1981 trip as an added precaution to ensure an accurate definition of the flux $\int_0^\infty V(\lambda) T(\lambda) d\lambda$, each filter was further blocked using wide photometry filters.

If any of the filters had a shortwave leak, even as low as 0.05%, this can significantly affect the measured flux as so great a proportion of Vega's energy lies in the shortwavelengths. For example, a continuous leak from 1 μm to 4.6 μm of only 0.05% in transmission can give a systematic error in the photon flux ratio of $\frac{\text{Vega}}{\text{Furnace}} \sim 4\%$.

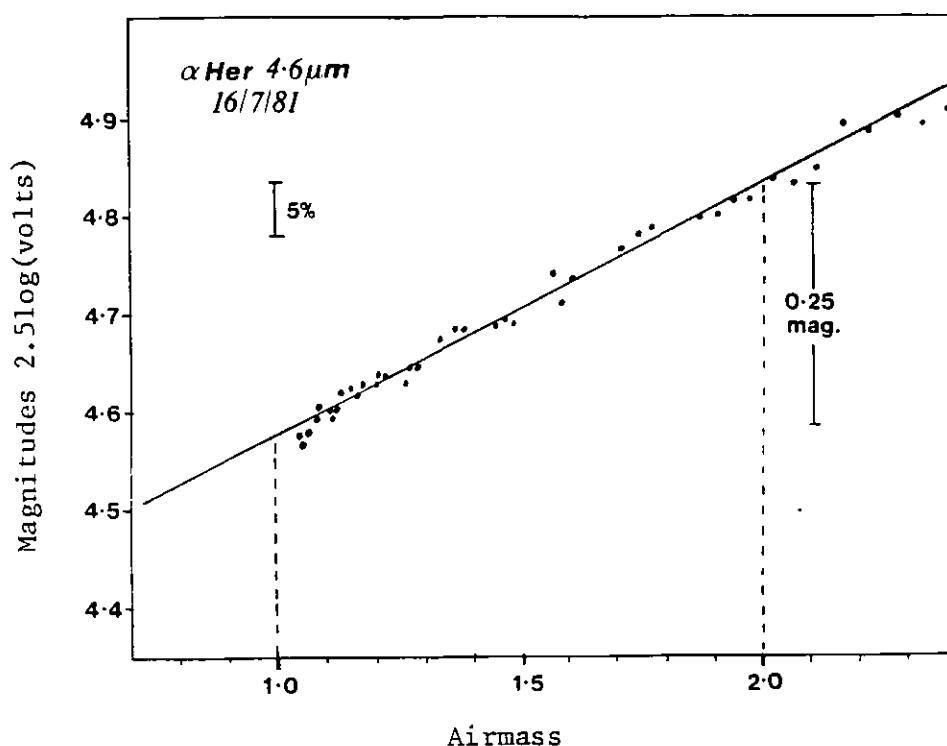


Figure 3.7 Extinction curve measured using 4.6 μm filter

The results from the three separate experiments in 1979, 1980 and 1981 are presented in Table 3.2.

TABLE 3.2

λ (μm)	1979		1980		1981	
	Flux $\times 10^{10}$ $\text{W cm}^{-2} \mu\text{m}^{-1}$	Observation Model	Flux $\times 10^{10}$ $\text{W cm}^{-2} \mu\text{m}^{-1}$	Observation model	Flux $\times 10^{10}$ $\text{W cm}^{-2} \mu\text{m}^{-1}$	Observation model
1.24					30.6 $\pm 3\%$	1.00
2.20	3.71 $\pm 8\%$	.94	3.92 4%	.99	4.19 $\pm 3\%$	1.06
3.76					.544 $\pm 3\%$	1.06
3.78			.539 4%	1.08		
4.6					.143 $\pm ?$ (.244 $\pm 12\%$)	.61 1.04 *

* see text

These results are taken from:

- (1) Selby et al (1980) (2) Selby et al (1982) (3) Blackwell et al
(in preparation)

A comparison of the measured fluxes with those calculated using the stellar model for Vega by Dreiling and Bell (1980) is given by the ratio Observation/Model.

Most of the results are near or in close agreement with the stellar calculations of Dreiling and Bell (1980); the 1.24 μm point showing excellent agreement. The 3.76 μm and 3.78 μm points give close agreement with each other indicating an excess over the model between 6%-8%. At 2.2 μm , the 1979 value is relatively less inaccurate due to

uncertainty in the scattering properties of the MgO diffuser and because of the wide K-band photometry filter used to make this measurement. (Compare Fig. 4.2(b) with Fig. 4.1(b)). However, the systematic disagreement between the two following 2.2 μm measurements (1980 and 1981) is disappointing. The improved furnace attenuation and taking the additional precaution of blocking the filter makes it probable the 1981 2.2 μm measurement is the more reliable, again being in excess of the model.

It is the 4.6 μm result which shows the largest discrepancy. The close agreement at the other wavelengths, showing a possible excess at longer wavelengths, makes it improbable that the 4.6 μm flux is 40% below that predicted by the model. The experimental errors on this point are approximately 5% so there must be some additional systematic effect causing this large disagreement. At 4.6 μm the largest correction made is the extrapolation of flux to zero airmass ($\sim .25$ magnitudes), but the extinction curve (Figure 3.7) is linear between 1.0 and 2.0 airmasses to better than 5% giving reasonable confidence in this extrapolation. Unfortunately Manduca and Bell (1979) have shown that in these structured infrared windows, where many of the molecular lines are saturated, the inclusion of so many lines within the filter pass band (indicative of high extinction), can give substantial non-linear extinction effects near zero-airmass. (See Fig. 4.3).

The problem of quantitatively assessing the extinction to zero airmass is complicated and discussed fully in Chapter Four. A tentative value for the 4.6 μm flux is given, in brackets, in table 3.2. The uncertainty of this substantial atmospheric correction is reflected in the large errors at this point.

What is demonstrated by the 4.6 μm measurement (and to a lesser extent by the disagreement of the 2.2 μm measurements) is that the major problem with the Absolute Calibration experiment is not in keeping the individual experimental errors below 1% but in the *elimination of systematic errors*. It is only if this experiment is repeated using other techniques and/or other groups will sufficient data be gathered to identify these effects and give greater statistical weight to the measurements so giving greater confidence in the final result.

CHAPTER FOUR

The correction to zero airmass ultimately determined the accuracy of the absolute flux measurement at 4.6 μm . In general the quantitative assessment of atmospheric extinction in the infrared can be a difficult and complicated problem.

4.1 Program IRTANS

The main reason for these difficulties in assessing extinction is that the atmospheric windows contain molecular absorption bands (mainly H_2O and CO_2) which are usually highly saturated so that extinction is not linear with air mass. This has been demonstrated by Manduca and Bell (1979) for photometry in the J, H, K, and L infrared windows and I have used a similar procedure for the M window where the extinction is considerably higher. These non-linear effects can be demonstrated using a theoretical atmospheric transmission model for the site on Tenerife (or La Palma), at 2.38 kilometres above sea level. I have used the program IRTANS written by W. Traub and M. Stier (1976). The program uses a single layer Curtis-Godson approximation in which the column abundance, effective temperature and pressure for each molecular species are required. The wave number, line strength, pressure broadening coefficient and energy level for over 100,000 known transitions of H_2O , CO_2 , O_3 , O_2 , CH_4 , CO and N_2O covering the infrared are obtained within the program using the Air Force Cambridge Research Laboratory's atmospheric absorption line data (McClatchey et al, 1973). For all molecular species, apart from H_2O , the variations of pressure, temperature and density with height were taken from the Standard Midlatitude Winter and Summer atmospheres

(McClatchey et al 1972). The column density of H₂O which is concentrated near the ground was used as a free parameter.

4.1.1. Atmospheric Parameters

The Curtis-Gordan approximation (Goody 1964) assumes the atmosphere is a single isothermal layer in static equilibrium where the majority of the molecular species (all except H₂O and O₃) are well mixed. According to Goody (1964) this can give remarkably accurate line profiles for strong and weak lines and perhaps errors of only ~ 2%-3% for intermediate lines. To calculate the atmospheric transmission it is necessary to integrate the intensity change $\frac{dI}{I}$ of a light beam traversing dh throughout the layer

$$\int \frac{dI}{I} = \int SF(\sigma)ndh = \int -d\tau$$

n = local number density, S = line strength and $F(\sigma)$ = line shape function.

The simplest form of $F(\sigma)$ is the pressure broadened Lorentzian line shape,

$$F_L(\alpha) = \frac{\alpha\pi}{\alpha^2 + (\sigma - \sigma_0)^2} \quad \dots (4.1)$$

where σ_0 is the wavenumber at line centre and α is the pressure broadened width (HHW). It is assumed α scales with both pressure (P) and temperature (T) as,

$$\alpha = \alpha_0 (P/P_0) (T_0/T)^{\frac{1}{2}} \quad \dots (4.2)$$

For the case of an isothermal exponential atmosphere
with,

$$\frac{n(h)}{n(o)} = \frac{p(h)}{p(o)} = \exp(-h/H) , \quad H = \text{scale height}$$

integrating over (h_1, ∞) gives:

$$\tau(\sigma) = \frac{S n_1 H}{2\pi\sigma_1} \ln \left| 1 + \left(\frac{\alpha_1}{\sigma - \sigma_o} \right)^2 \right| \quad \dots (4.3)$$

For a simple homogenous layer of thickness H the integration gives,

$$\sigma(\sigma) = \frac{S n H \alpha}{\pi} \cdot \frac{1}{\alpha^2 + (\sigma - \sigma_o)^2} \quad \dots (4.4)$$

Traub and Stier (1976) have numerically compared equation 4.3 with 4.4 and find the profiles agree to within 1% for:

$$(\sigma - \sigma_o)/\alpha_1 > 5.0 \quad \dots (4.5)$$

$$\text{if } n = n_1 \quad \text{and } \alpha = \alpha_{1/2}$$

Making the assumption in IRTANS that the atmosphere is a homogeneous layer leaves the column densities (nH) unchanged but the effective broadening pressure P_{eff} has to be half that found at $h = h_1$ for the more realistic exponential atmosphere. For the well mixed molecular species, O_2 , CO_2 , CO , H_2O and CH_4 , the effective pressure P_{eff} is taken to be half that found at the site altitude (765.7 mb at 2.38 km for Tenerife). The effective temperature T_{eff} , needed for the pressure broadening coefficient (equation 4.2), is taken as the temperature at this pressure P_{eff} as interpolated from the AFCRL

Mid-Latitude Atmospheric Model (McClatchey et al 1972). Radio Sonde data taken on Tenerife up to a height of 20 kms agreed to better than 2% with the AFCRL Mid-Latitude Summer Model.

Both H_2O and O_3 cannot be considered as well mixed species as water tends to be concentrated near the ground and Ozone is largely a component of the upper atmosphere. For these two molecules, starting at the Observatory altitude (2.38 km) I have numerically integrated the respective tabulations of density with height given in the Mid-Latitude Model. The effective pressures, $P_{eff}(H_2O)$ and $P_{eff}(O_3)$, and effective temperatures, $T_{eff}(H_2O)$ and $T_{eff}(O_3)$, are taken at the height at which the column abundances drop by half (3.64 km for H_2O and 22.35 km for O_3).

The atmospheric parameters used in IRTANS for Tenerife are given in Appendix E. The column abundances for each molecular species are taken from Traub and Stier (1976) and McClatchey et al (1972). As previously mentioned, the column abundance of H_2O is used as a free parameter and usually set to 4 mm precipitable H_2O , (1 mm precipitable mm H_2O 3.35×10^{21} molecules cm^{-2}) the annual mean found during some site tests at millimeter wavelengths.

4.1.2. Transmission Spectra

Having assumed the atmosphere is a single homogenous layer, the monochromatic transmission can be simply calculated by,

$$I(\sigma)/I_0(\sigma) = \exp(-\tau(\sigma)).$$
The actual line shape function $F(\sigma)$ used in the program is a Voigt profile. This is a more realistic line shape profile than the Lorentzian pressure broadened profile, taking into account doppler line broadening. $F_{Voigt}(\sigma)$ is given by the convolution of the Lorentzian profile with the pure Doppler

broadened profile,

$$F_V(\sigma) = F_L(\sigma) * F_D(\sigma)$$

and this is calculated using a subroutine by Rybicki (1967). However to save computer time the Voigt profile is only used if the line profile differs from the Lorentzian by more than 0.1% otherwise the simpler Lorentzian is automatically used.

Figure 4.1 a, b, c, d shows the theoretical atmospheric transmission spectra for 1 μm - 5 μm calculated for Tenerife using the parameters given in Appendix E. The monochromatic transmission was calculated with a grid spacing of 0.05 cm^{-1} , comparable to the pressure-broadened half width $\sim 0.03 \text{ cm}^{-1}$, which has been shown by Traub and Stier (1976) to be sufficiently small to give accurate results. These spectra have then been smoothed with an instrumental profile simulating a spectrometer of wavelength resolution ~ 1000 . The position and profiles of the filters used in the Absolute Calibration experiment are also plotted. Figure 4.2 a, b, c, d give similar plots computed for Mauna Kea (4.2 km, with 1.2 mm H_2O) using parameters given in Appendix D. The positions of the standard J, H, K, L' and M photometry filters is also plotted with these spectra.

4.2 Absolute Calibration Revised

In an attempt to model the atmospheric extinction, especially to determine the behaviour near zero airmass, I have used a similar procedure to Manduca and Bell (1979), with a program ATMOS.FOR.

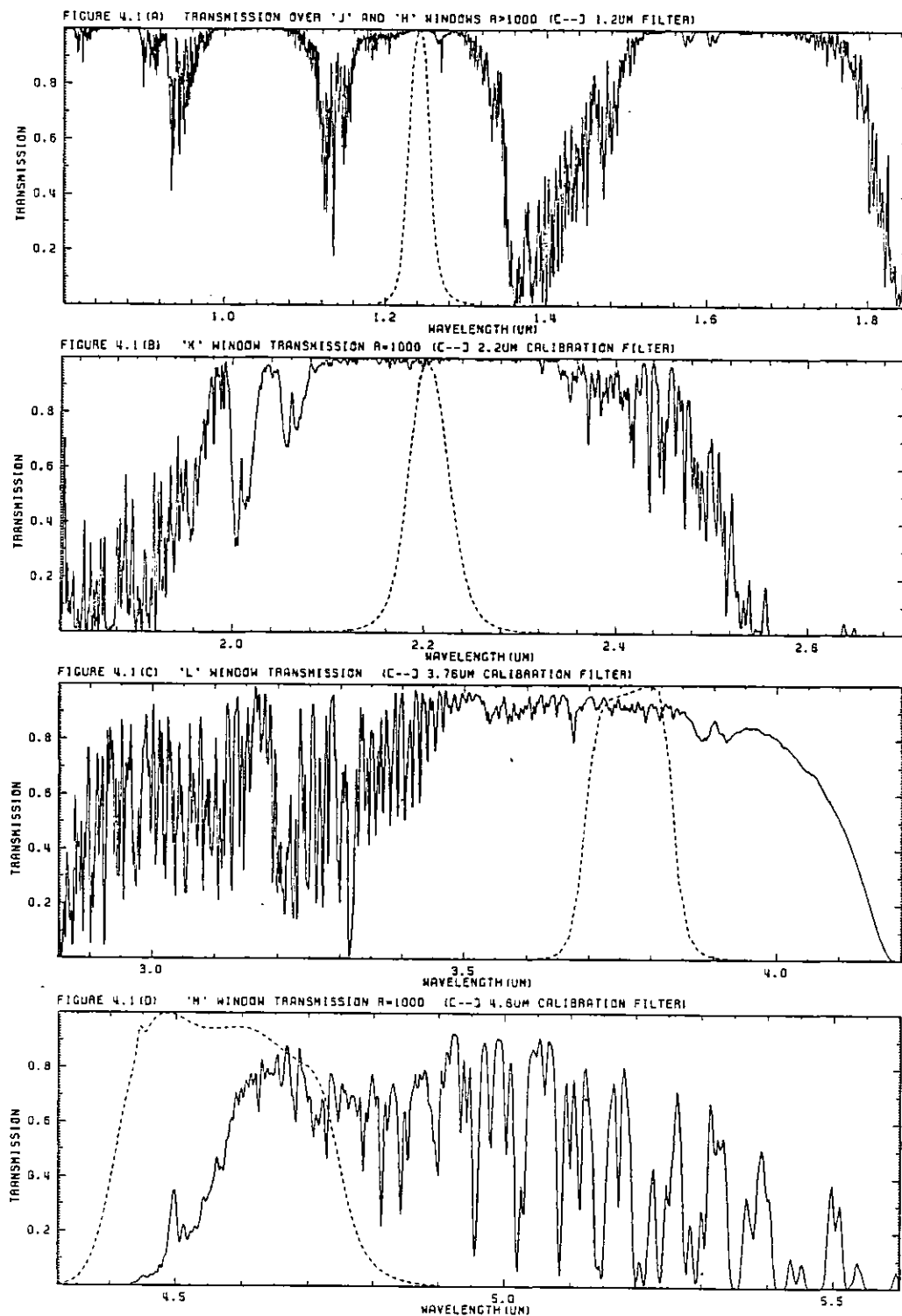


Figure 4.1 Calculated atmospheric transmission for Tenerife
(2.38 kilometres with 4 mm H₂O)

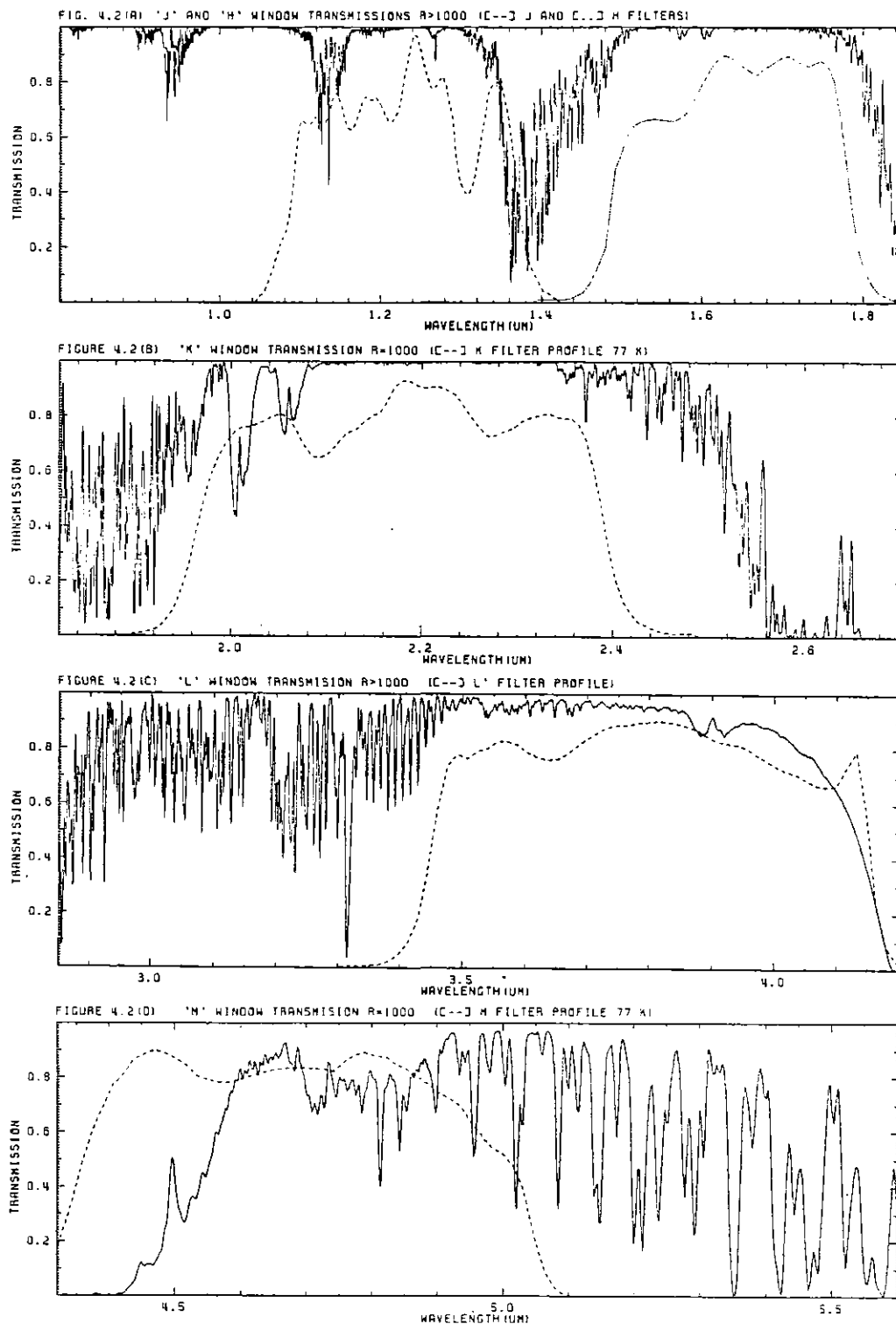


Figure 4.2 Calculated atmospheric transmission for U.K.I.R.T.
(4.2 kilometres with 1.2 mm H_2O)

4.2.1 AMOS.FOR

The program calculates the actual atmospheric extinction through a given filter profile at a specified airmass. A listing is given in Appendix B. The procedure is as follows:

- 1) The cooled filter profile for a specific wave band is read in and interpolated to unit cm^{-1} . Each spectral element is then multiplied by:
 - a) The Kurcz stellar model atmosphere for Vega, spaced in unit cm^{-1} .
 - b) the smoothed theoretical atmospheric transmission spectra produced by IRTRANS calculated for a specific airmass
 - c) the InSb detector response ($\propto 1/\nu$)
- 2) This product is then integrated, using a Simpson integration routine, across the filter band width to give a total flux at the detector.
- 3) This is converted to extinction by normalizing the result with the 'zero airmass point', the total integrated flux through the filter outside the atmosphere.

Figure 4.3 shows the calculated extinction curve using a broad band filter (4.5 μm - 5.4 μm); the measured extinction at Tenerife between one and two air masses is typically 0.3 magnitudes per air mass which is consistent with 4 mm of precipitable water vapour. The largest deviation from a linear extinction law takes place close to zero air mass; a linear extrapolation down to zero gives an error of $\Delta\text{Vega} = .268$ magnitudes ($\text{H}_2\text{O} = 4 \text{ mm}$) which creates a serious problem for absolute calibration measurements using

filters in the M window.

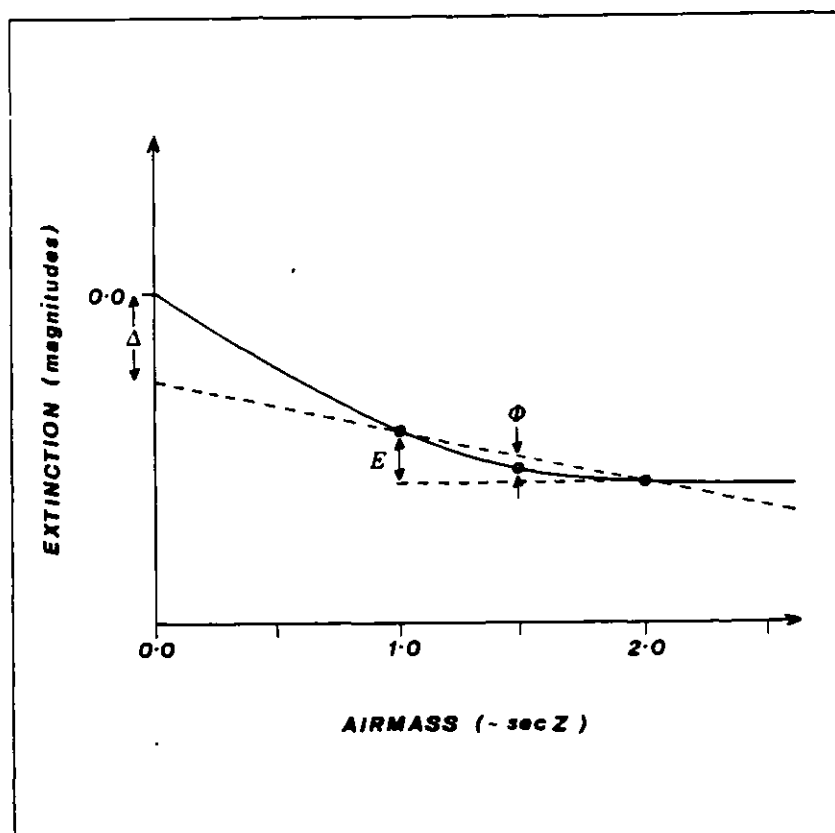


Figure 4.3 Calculated extinction curve using a broad band filter ($4.5 \mu\text{m} - 5.4 \mu\text{m}$) in magnitudes, as a function of airmass. If the extinction/unit airmass E is taken as the difference between extinctions at 1.0 and 2.0 airmasses, this gives an extinction at 1.5 airmasses which differs from the actual value by ϕ . Assuming a linear extrapolation of E gives a systematic error at zero airmass of Δ magnitudes.

4.2.2. Results for Absolute Calibration Filters

Values for E , Δ and ϕ have been calculated for each of the $1.2 \mu\text{m}$, $2.2 \mu\text{m}$, $3.78 \mu\text{m}$ and $4.6 \mu\text{m}$ calibrator filters for 2 mm, 4 mm and 8 mm of precipitable water. The results are shown in Table 4.1.

Comparing the predicted extinction values E and the actual measured values between 1 and 2 airmas Table 4.2, gives a disappointing lack of agreement.

TABLE 4.1

Values of E , Δ and ϕ , calculated for the filters
used in the absolute calibration

		E (mag./airmass)	Δ (magnitudes)	ϕ (magnitudes)
1.2 μm				
H_2O	4 mm	0.005	0.001	< 0.01
	8 mm	0.006	0.003	< 0.01
2.2 μm				
H_2O	4 mm	0.009	0.000	< 0.01
	8 mm	0.014	0.004	$\sim$ 0.01
3.76 μm				
H_2O	2 mm	0.08	0.00	< 0.01
	4 mm	0.09	0.00	< 0.01
	8 mm	0.11	0.01	< 0.01
4.6 μm				
H_2O	2 mm	0.39	0.56	0.02
	4 mm	0.412	0.57	0.02

TABLE 4.2

Extinction measured in the absolute calibration
experiment

1.2 μm	2.2 μm	3.76 μm	4.6 μm
0.087	0.036	0.029	0.25
Magnitude airmass ⁻¹			

4.2.3. 1.2 μm and 2.2 μm Corrections

For the 1.2 μm and 2.2 μm values one has to ask what additional processes are contributing to the measured extinction. For the homogeneous single layer atmosphere, the monochromatic transmission $T(\lambda)$ can be given generally by,

$$T(\lambda) = \exp(-\gamma\Delta L)$$

where ΔL is the path length and γ is the total attenuation coefficient. Here, $\gamma = k_m + \sigma_m + k_a + \sigma_a$ where, k_m is the molecular absorption coefficient calculated by IRTANS but the program takes no account of:

- 1) σ_m , the scattering from molecules (usually taken as Rayleigh scattering with a $\sim \lambda^{-4}$ dependence)
- 2) k_a and σ_a , the absorption and scattering by aerosols; that is ice and dust particles in the atmosphere.

McClatchey et al (1972) have made theoretical prediction of these aerosol effects with respect to the molecular contribution and these are shown in Table 4.3.

TABLE 4.3

$\lambda(\mu\text{m})$	Molecular Contribution		Aerosol			
			CLEAR		HAZY	
	$k_m(\text{km}^{-1})$	$\sigma_m(\text{km}^{-1})$	$k_a(\text{km}^{-1})$	$\sigma_a(\text{km}^{-1})$	$k_a(\text{km}^{-1})$	$\sigma_a(\text{km}^{-1})$
.5145	E-06	1.16E-02	E-06	2.7E-02	E-06	6.63E-02
1.06	E-06	6.38E-04	2.43E-03	8.36E-03	7.78E-03	2.67E-02
1.536	9.24E-05	1.41E-04	2.90E-03	5.03E-03	9.27E-03	1.61E-02
3.392	1.65E+00	6.18E-06	1.95E-03	2.03E-03	6.24E-03	6.58E-03
10.591	1.52E-01	E-06	6.75E-04	5.73E-04	2.16E-03	1.83E-03

(k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

Theoretical values for absorption and scattering coefficients (attenuation km^{-1}) as a function of Laser wavelength at a representative height of 2.5 km (McClatchey et al 1972). The molecular contribution is calculated from the Summer Mid-Latitude Model and σ_m assumes Rayleigh scattering. Two aerosol models are used, CLEAR (23 km visibility) and HAZY (5 km visibility).

At short wavelengths, $\lambda < 2 \mu\text{m}$, aerosol scattering and absorption can be the dominant contributor to atmospheric extinction. However in the troposphere ($h > 2 \text{ km}$) the aerosol number density is thought to scale as $\sim \exp(-h)$, (Hayes and Latham 1975). Therefore aerosol extinction should give negligible error when extrapolating measured magnitudes ($\propto \log I$) to zero airmass. The predicted extinctions may not agree with those measured but the errors Δ are realistic as it is just a measure of the number of saturated lines within the

filter passbands.

4.2.4 Correction at 3.76 μm

Unlike the shorter wavelengths, the predicted extinction here is higher than measured. The atmospheric transmission across this filter is dominated by the 'wings' of the exceptionally strong CO_2 band centred near 4.3 μm (Figure 4.1c). (The dependence of the predicted extinction on the amount of H_2O is weak Table 4.2). The accurate calculation of such strong molecular bands can be complicated (Signal, 1970)* the perhaps the simplification of assuming the atmosphere is a single homogeneous slab is breaking down (equation 4.5); the 4.3 μm band being so broad. This has yet to be looked into in more detail. However, accepting there may be an error in calculating the extent of these 'wings' from this band, the extrapolation error at zero airmass is still small; $\Delta < 0.007$ magnitudes. This can be assumed as an upper limit on the systematic error introduced in linearly extrapolating the measured extinction (in magnitudes) to zero airmass and so safely ignored.

4.2.5. 4.6 μm correction

As with the 3.76 μm filter, the extinction measured for the 4.6 μm filter is lower than predicted by ATMOS.FOR. A quick examination of Figure 4.1d will confirm this problem is dwarfed by a serious

* Signal, 1970 has looked at the behaviour of the atmospheric CO_2 band near 15 μm and found the contribution to the atmospheric absorption in the wings far less than predicted from the calculation of Voigt profiles.

error in the choice of position for the $4.6\ \mu\text{m}$ filter.* The correction at zero airmass is enormous (~ 0.6 magnitudes) simply because at best only one third of the filter is being used at Tenerife altitudes; the $4.3\ \mu\text{m}$ CO_2 band "blocking" the rest of the filter is one of the most opaque in the $1\ \mu\text{m} - 5\ \mu\text{m}$ region. The wings from this band are still visible for a path length of only 2 metres calculated at the Observatory altitude. (Figure 4.4).

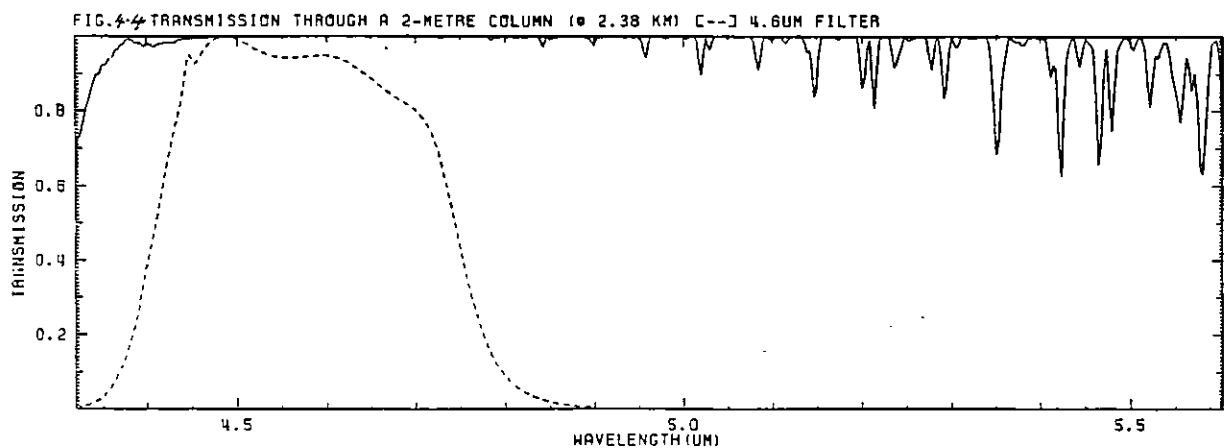
I have attempted to make some correction for the $4.6\ \mu\text{m}$ filter (Table 4.2). The computed values for Δ over this filter is critically dependent on the accuracy with which the band shape is calculated and this is already in doubt due to the $3.78\ \mu\text{m}$ result (error $\sim 7\%$). The inclusion of so much of this CO_2 band over a filter bandwidth of $0.33\ \mu\text{m}$ makes accurate assessment of the zero airmass flux difficult and is the cause of the large error of the $4.6\ \mu\text{m}$ point. (Figure 4.5).

4.3 Conclusions

The absolute calibration experiment, particularly at $4.6\ \mu\text{m}$, has demonstrated the dangers of making simplistic assumptions about the behaviour of atmospheric extinction in the near-infrared. (See also Appendix E). The use of a theoretical model to try and

* It should be noted that this error is faithfully reproduced in the choice of the standard $M(5\ \mu\text{m})$ band photometry filter used at both Tenerife and UKIRT (Figure 4.2d).

quantitatively assess the behaviour of this extinction, especially in the case of saturated lines near zero airmass, can at least give upper limits on the systematic error introduced. This procedure has been successful for the narrow 1.2 μm , 2.2 μm and 3.76 μm filter. In the highly structured M(5 μm) window, these corrections are the major source of error for any absolute calibration. But it is at 5 μm where the systematic disagreement between measured absolute flux and current stellar models could be as high as 10% (Figure 4.5). It is very important to try and find ways to make this measurement with greater precision.



Observed Flux
Calculated Flux

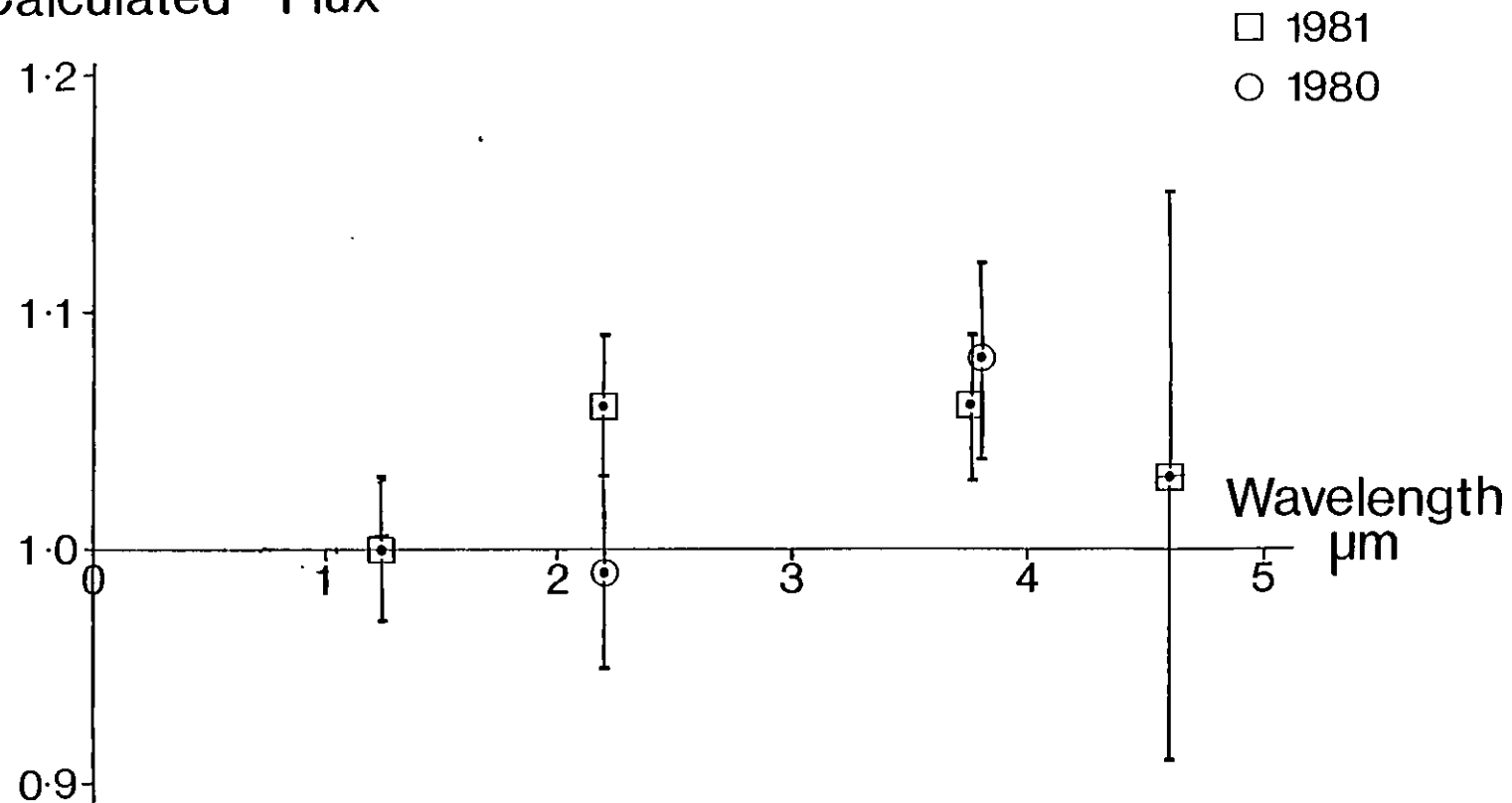


Figure 4.5 Results from the absolute calibration experiment (1980, 1981) compared to the stellar model of Dreiling and Bell (Blackwell et al (in preparation))

CHAPTER FIVE

To get a better understanding of the behaviour of atmospheric extinction in the near-infrared it would be interesting to look at the spectral structure of the extinction across an infrared window. It is essential to understand the nature of this extinction if it is hoped to do any accurate spectrophotometry. This may also lead to the possibility of setting up an absolute spectrophotometric standard for future spectrometry in the near-infrared.

5.1 INTRODUCTION

A simple program EXTINCT.FOR calculates the atmospheric extinction as a function of wavelength at a resolution comparable to that of the cooled grating spectrometer ($\lambda/\delta\lambda \sim 1000$). For a specific I.R. window three IRTANS transmission spectra are calculated at 1.0, 1.5 and 2.0 airmasses which are smoothed with an appropriate instrumental profile normally simulating a resolution $R \sim 1000$. The extinction E , the zero airmass extrapolation error Δ and the 1.5 airmass extinction error ϕ (the difference between the extrapolated and actual extinction error at 1.5 airmasses, Figure 4.3) are calculated for each spectral element σ_i (SIGMA(I)) by:

```
RM10(I)      = 2.5*ALOG10(TRANS10(I))
RM15(I)      = 2.5*ALOG10(TRAN15(I))
RM20(I)      = 2.5*ALOG20(TRANS20(I))
EXTINCT      = RM20-RM10
E( $\sigma_i$ ); EXTINCT(I) = EXTINCT
 $\Delta(\sigma_i)$ ; DELTA(I) = RM10-EXTINC
 $\phi(\sigma_i)$ ; DEV(I) = -(RM20-(EXTINC/2))
```

where TRANS10(I), TRANS15(I) and TRANS20(I) are the atmospheric transmission as a function of wavenumber σ_i (SIGMA(I)) for 1.0, 1.5 and 2.0 airmasses respectively. (Full listing given in appendix C).

An application of this technique to the 5 μm window appropriate for Tenerife (2.38 km with 4 mm H₂O) is shown in Appendix E. What is immediately clear is that the extinction E and extrapolation error Δ is highly structured. But what is also shown is that at points such as 4.93 μm , and 5.05 μm (in the wings of features) though the extinction is ~ 0.3 magnitudes/airmass, the extrapolation error to zero airmass is very small (see also Figure 5.1 a, b). It is therefore apparent, if the absolute calibration could be done using sufficiently narrow bandwidths (such as are available with a cooled grating spectrometer) a linear extrapolation of measured extinction through these narrow bands would lead to accurate predictions of flux at zero airmass.

5.2 ABSOLUTE CALIBRATION USING THE COOLED GRATING SPECTROMETER

The advantages in using the cooled grating spectrometer are twofold.

- 1) The narrow spectral bandwidths make it possible to isolate portions of the window showing low extinctions and/or low extrapolation errors Δ .
- 2) As the bandwidths are much narrower than those of filters, the need to use attenuators to prevent the Furnace from saturating the detector system (a major problem throughout the project) is circumvented. With the 4.6 μm filter ($\Delta\lambda = .33 \mu\text{m}$) an attenuation of 1.56% transmission was used, giving ~ 1.5 volts from the detector preamplifier.

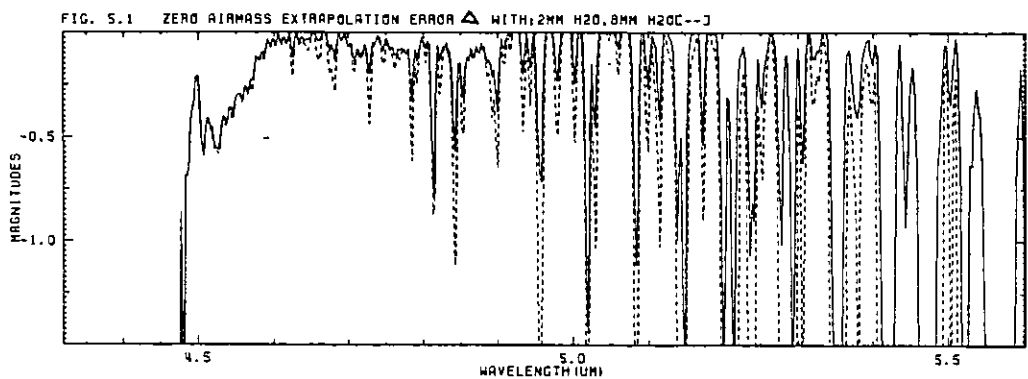
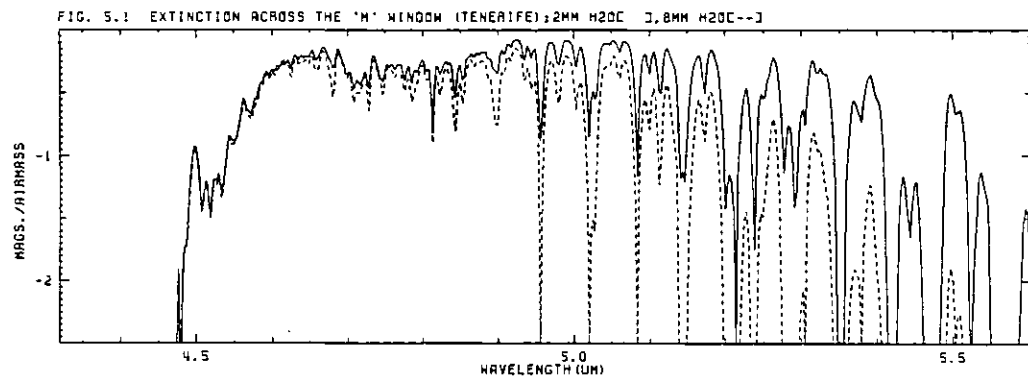


Figure 5.1 a) The dependance of extinction upon water vapour
 b) The corresponding dependance of extrapolation error Δ on water vapour

Looking at the furnace directly with the spectrometer (throughput $\sim 30\%$ and $\Delta\lambda = 0.006 \mu\text{m}$ at $5 \mu\text{m}$) produces only ~ 0.7 volts from the preamplifier.

This eliminates two sources of error which in both cases (especially the atmospheric correction) are systematic errors. In addition, the absolute flux is given as a monochromatic flux. Using the spectrometer defines this wavelength far more accurately than the comparatively broad filters previously used. It is now probable that we could achieve our target accuracy of 4% (or better) in determining the absolute flux at $5 \mu\text{m}$

A preliminary attempt at a spectrophotometric calibration was tried in Tenerife in November 1981. This used the original Absolute Calibration apparatus (Figure 3.2), simply substituting the photometer with the spectrometer (Figure 5.3). Hoping to test the technique and to try and check the accuracy of the program IRTANS the calibration tried initially by scanning the $2 \mu\text{m}$ window using the F5 star Procyon as source. Vega, with a temperature $\sim 10^4 \text{ K}$ (A0), is not an ideal spectral standard in the near-infrared as it has comparatively deep hydrogen absorption lines at these wavelengths. In cooler stars, such as Procyon (F5 IV-V) these absorption lines are far weaker. However it is desirable to choose standard stars no later than K as these would show considerable molecular absorption lines. As the backgrounds are low at $2 \mu\text{m}$ and Procyon bright ($K_{\text{mag}} = -0.65$) we hoped to produce a spectrally continuous comparison with the furnace over the K window, so creating an absolute spectrophotometric standard. The weather however prevented any accurate or even complete measurements, and only preliminary scans are shown in Figure 5.2 a,b. A similar procedure was tried over the M($5 \mu\text{m}$) window (in again poor photometric conditions), but the large changes in emission across this window

Figure 5.2 (a) - 2 μ m scan
of Procyon (D.C. scan)
with a resolution of ~ 6000
-blocked with a standard
2 μ m photometry filter.

(arbitrary flux scale)

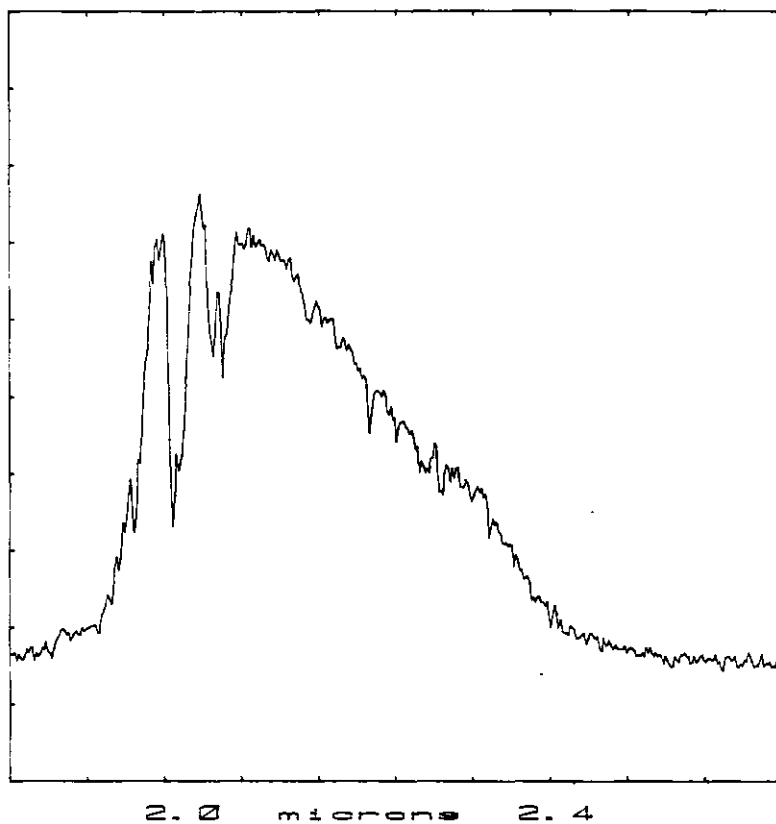
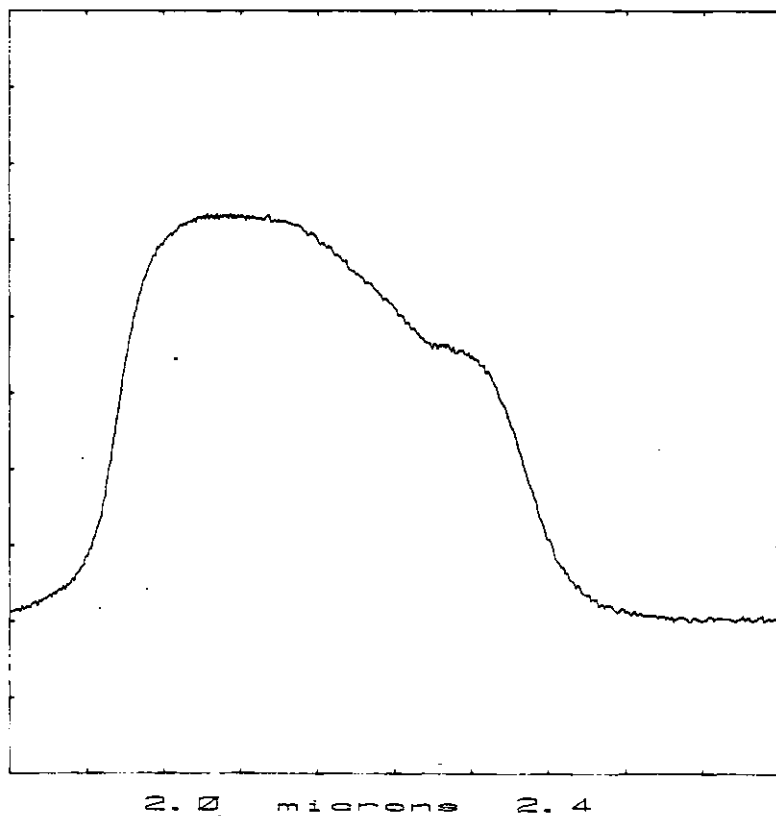


Figure 5.2 (b) - equivalent
D.C. 2 μ m scan of 1253 K
Calibration Furnace,
-blocked with a standard
2 μ m photometry filter.

(arbitrary flux scale)



allowed insufficient dynamic range to make any meaningful measurements. It is planned to repeat these measurements on Vega (especially important at 5 μm) simply using the spectrometer as a narrow bandwidth monochromator and offsetting the backgrounds with a stable D.C. amplifier.

5.3 EXTENDING THE ABSOLUTE CALIBRATION BEYOND 3 μm

It is clear there is a need for accurate absolute infrared fluxes beyond 3.8 μm . In addition a continuous absolute spectrophotometric standard is needed for accurate spectrophotometry. It is especially important to try and confirm the present systematic disagreement with current stellar models (which could be as high as 10% at 5 μm) by possibly extending the measurement to the 8 μm - 13 μm window. The problem of making any D.C. measurements beyond 3 μm is the large infrared backgrounds at these wavelengths. Ideally the comparison between star and standard furnace should be made using the conventional sky chopping techniques; automatically subtracting backgrounds and drifts. It would also be extremely advantageous to measure several wavelengths in one night. Not only would this speed the experiment up and produce a spectrally continuous comparison, but also give greater confidence in correcting for atmospheric extinction. Measuring the extinction in several parts of the infrared windows would tightly constrain and check the consistency of theoretical synthesis programs such as IRTANS. Measuring the widths of specific H_2O bands, as suggested by Goody (1964) (see also appendix E) would give a measure of the water vapour and give greater confidence when establishing upper limits on the systematic errors induced by extrapolating fluxes to zero airmass.

A proposed absolute calibration scheme which retains the advantages of our present system (listed in Section 3.2.3) but allows for the improvements mentioned above is shown in Figure 5.4

This reimaging system uses only reflecting optics (so avoiding chromatic BaF₂ lens and allows measurement of several wavelengths to be made quickly). The chopping mirror M serves two purposes.

- 1) Sky/telescope background correlation is achieved by chopping the mirror in a square wave (at a frequency ~ 20 Hz) so the detector 'sees' alternatively star + sky/telescope background or just sky/telescope background. Subsequent phase sensitive detection (rectification) extracts just the stellar signal. On this mirror an image of the Telescope primary is formed by the reimaging mirror I, so effectively "freezing" the chopping beam on the primary mirror.
- 2) This mirror (M) can therefore also be used as a reflecting limiting stop for the system (c.f. the limiting stop in Fig. 5.3).

The furnace is equivalently chopped by a sector chopper (the background from which has already been shown to be small for $\lambda < 5 \mu\text{m}$. (Section 3.3.6.3.)

If this system is to be extended to $10 \mu\text{m}$ (as already mentioned in Chapter 3) it is desirable if not essential to arrange to chop between two furnaces at different temperatures. This would be possible by using two 45° mirrors (fixed in a 'V') shown in figure 5.4. Using two pin holes in the telescope focal plane (both

matched to the stellar seeing disc), spaced at a distance equivalent to the 'chop' amplitude on the sky, would allow mirror 'M' to chop between the two furnaces. A theoretical transmission spectra for the $8\text{ }\mu\text{m} - 13\text{ }\mu\text{m}$ window at UKIRT has been calculated, Fig. 5.5 a) and the associated plots of E , Δ and ϕ as a function of wavelength are also shown (Fig. 5.5 b, c, d). Certain parts of this window appear exceptionally transparent (at UKIRT) and the associated errors Δ are also small. With good AC background cancellation, an absolute calibration through this window should be possible.

The proposed scheme has been designed for a $1\text{ }\mu\text{m} - 5\text{ }\mu\text{m}$ side entry spectrometer. Such an instrument is already in the design stage jointly at the Royal Greenwich Observatory and Imperial College. This instrument will take 7-element array, so allowing several spectral elements to be measured simultaneously and so giving an excellent check on the internal consistency of the method.

It should also be noted that this instrument uses only reflecting optics so could be fitted with a $10\text{ }\mu\text{m}$ detector. It is only the detector that has to be cooled to 4°K . (The facility to cool the InSb array to these temperatures is already incorporated) as the background from 77 K surfaces is still negligible at $10\text{ }\mu\text{m}$.

5.4 CONCLUSIONS

The Absolute Calibration project has demonstrated the dangers in making simplistic assumptions about the behaviour of atmospheric extinction in the near-infrared. Using the theoretical atmospheric transmission program IRTANS to look at the detailed spectral structure of atmospheric extinction has shown that even over the far narrower bandwidths of our spectrometer ($\lambda/\delta\lambda \sim 10^3$) these

simplistic assumptions are still precarious. The inclusion of saturated atmospheric lines still produce non-linear extinction curves; especially near zero airmass. To get any photometric accuracy on weak astrophysical lines in these highly structured windows it is necessary to accurately assess the atmospheric extinction. A significant amount of time may be saved by using such theoretical models if the water vapour concentration at the time of observation can also be measured. At the very least, the use of these models gives a measure of the error that must be placed on the photometric accuracy of any line or continuum measurement made in both spectrometry and photometry. Finally, the study of these structured infrared 'windows' shows that it should be possible to measure accurate absolute fluxes if the narrow band-widths of a cooled grating spectrometer are used. Using a totally reflecting reimaging scheme, and sky chopping, a continuous absolute standard for accurate spectrophotometry can be established. It may even be possible to extend these measurements to the $8\text{ }\mu\text{m} - 13\text{ }\mu\text{m}$ window; confirming finally if there is indeed an infrared excess in the standard calibration star Vega.

Figure 5.3 Original Absolute Calibration apparatus using the spectrometer

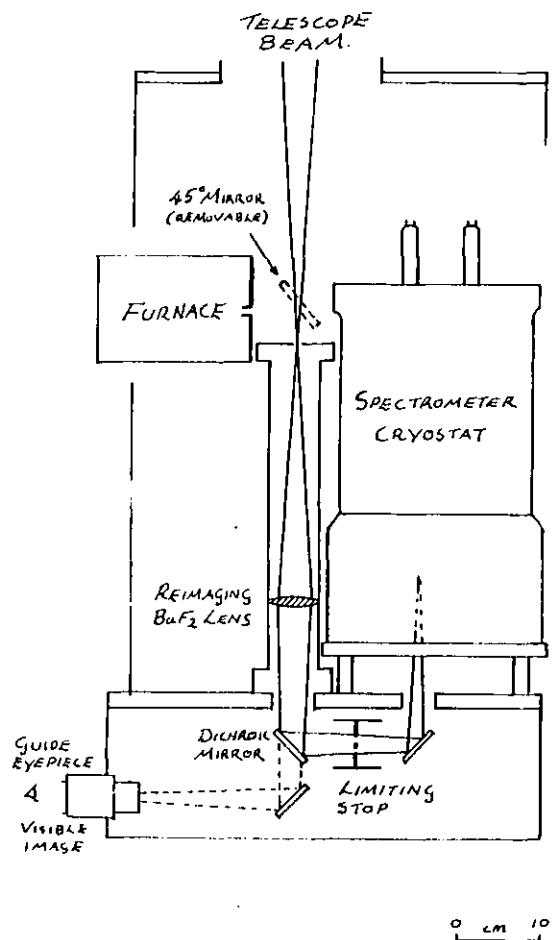
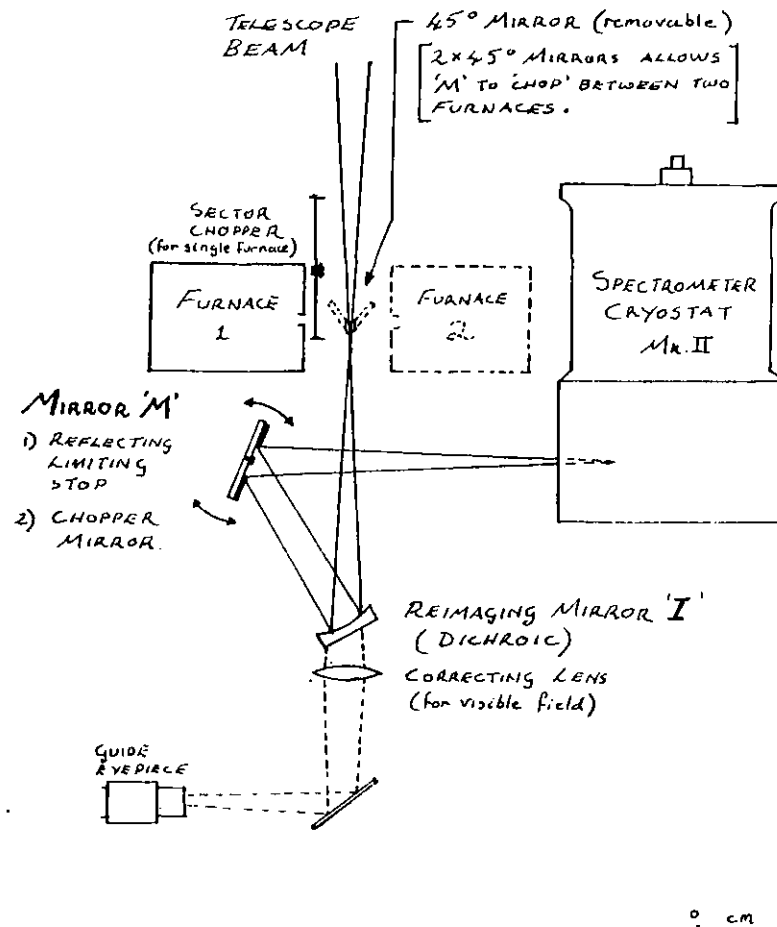


Figure 5.4 Proposed scheme for Absolute spectrophotometric calibration (all reflecting and incorporating sky 'chopping')



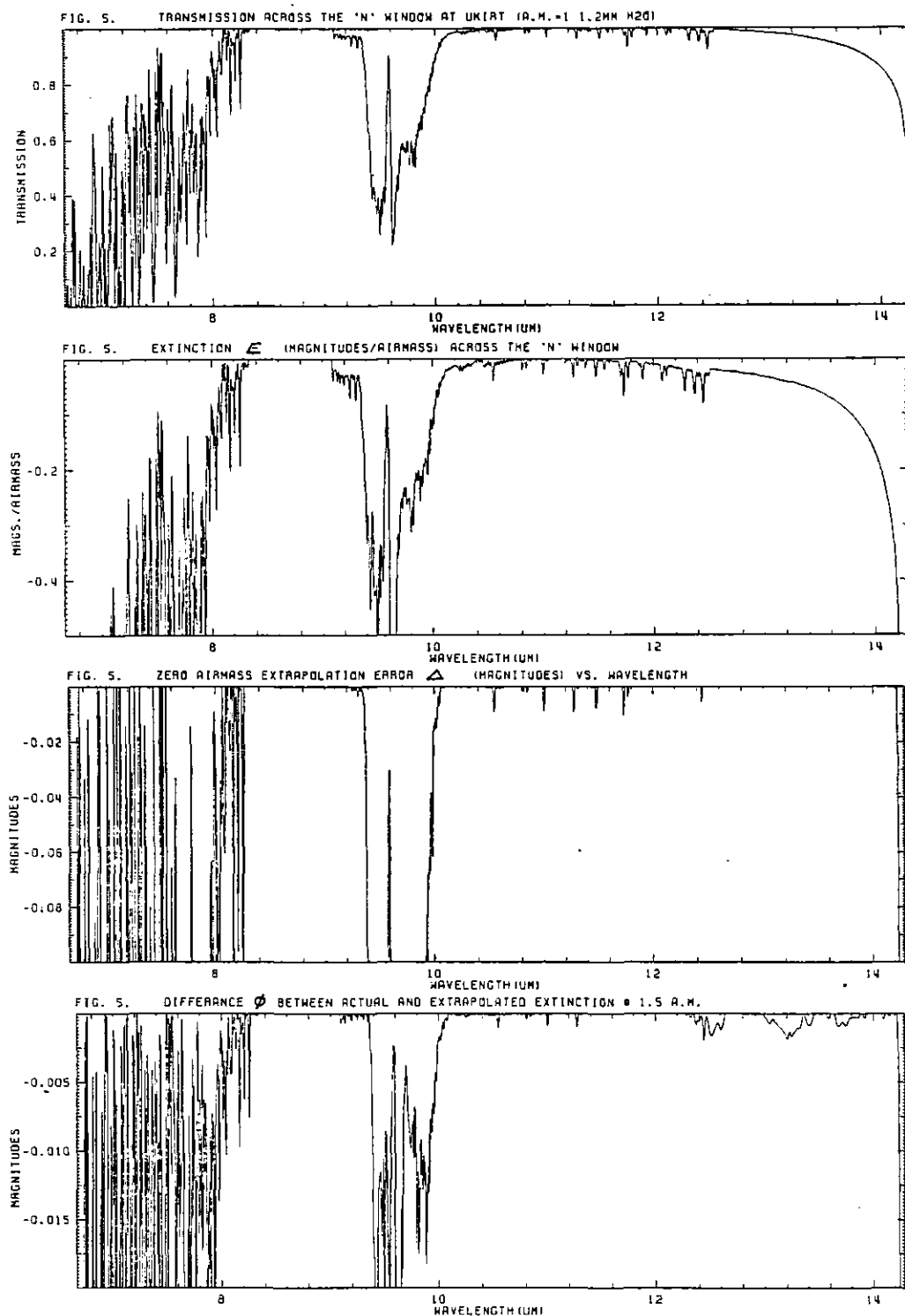


Figure 5.5 Transmission and corresponding extinction calculated for the 10 μ m window (U.K.I.R.T. 4.2 km 1.2 mm H₂O)

APPENDIX A

'NOVA' Data Logging PROGRAM

```

0100 PRINT "=== SPEC3(R03/P)AUJ/CMM 15:8:81 ==="
0102 REM SPECTROMETER PROGRAM
0106 PRINT
0110 REM N2=PSC. N3=A/D. N4=PUNCH
0120 LET N2=20
0130 LET N3=4
0140 LET N4=5
0150 REM INITIALISE CAMAC VARIABLES
0160 LET N=0
0170 LET K=0
0180 LET M=0
0190 REM INITIALISE CAMAC MODULES
0200 CALL 1.0
0210 CALL 1.3
0220 CALL 2.N3.0.26
0225 REM SET AIM HOLD (PA0=1)
0226 CALL 3.N2.2.17.1
0227 PRINT "AIM ON HOLD"
0230 DIM SC1000
0235 LET R=0
0240 REM RESTART HERE: INPUT SUB.
0250 GOSUB 1000
0260 REM ZERO SCAN ARRAY
0270 FOR I=1 TO N
0280 LET SC1I=0
0290 NEXT I
0300 REM DISPLAY CONTENTS OF SC200
0310 CALL 101.SC1I.N.1.0
0320 REM START OF SCAN
0325 INPUT "START? ".A
0326 IF A=0 THEN GOTO 0240
0330 LET R=R+1
0340 LET SC0I=R
0355 PRINT "SCAN ":R
0360 REM SAMPLE LOOP BEGINS
0370 FOR I=1 TO N
0372 REM ARM A/D TRIGGER
0373 CALL 2.N3.0.26
0374 REM RELEASE HOLD (PA0=0) AND WAIT FOR AIM
0375 CALL 3.N2.2.17.2
0376 CALL 2.N3.0.8
0377 CALL 5.0.X
0378 IF Q>K1 THEN GOTO 0376
0379 REM READ A/D: CHECK SATURATION
0380 CALL 4.N3.0.0.D
0390 IF D=1023 THEN PRINT "I:OVER"
0395 IF D=0 THEN PRINT "I:UNDER"
0398 LET SC1I=0
0400 REM SET HOLD (PA0=1)
0410 CALL 3.N2.2.17.1
0450 NEXT I
0480 INPUT "PUNCH? ".A
0490 IF A=0 THEN GOTO 0570
0500 REM PUNCH CONTENTS OF SC200
0510 OPEN FILEC2.1I."$PTP"
0520 FOR I=0 TO N
0530 PRINT FILEC2I.SC1I
0540 NEXT I
0550 CLOSE FILEC2I
0560 PRINT "SCAN":R:" PUNCHED"
0570 INPUT "CONTINUE? ".A
0580 IF A=1 THEN GOTO 0320
0590 GOTO 0240
0600 END
1000 REM SETTING UP SUBROUTINE
1030 INPUT "ENTER STARTING POINT AND FINAL SAMPLE POINT ".P1.P2
1040 LET N=P2-P1
1050 IF N<1001 THEN GOTO 1080
1060 PRINT "MORE THAN 1000 SAMPLE POINTS..."
1070 GOTO 1030
1080 PRINT N:"SAMPLE POINTS:FIRST POINT IS":P1+1:"OKAY?"
1090 PRINT
1100 PRINT
1110 INPUT A
1120 IF A=0 THEN GOTO 1030
1150 PRINT "ENTER SAMPLE POINTS INTO AIM:N=":N
1160 PRINT
1170 PRINT
1180 RETURN

```

* RUN

APPENDIX B Program ATMOS.FOR

```

      PROGRAM ATMOS

c
c   This program calculates the theoretical ATMOSPHERIC extinction
c   through a filter profile, FILTER(I), using the Kurucz Vega model
c   as source (or a 'flat' spectrum) and IRTANS transmission
c   spectra previously calculated for the appropriate region and airmass.
c   The filter profile is interpolated to 1 CM-1 spacing (SUBROUTINE
c   LINEAR) and the integration under the filter profile uses Simpsons
c   rule (SUBROUTINE SIMPSON).
c   The detector response, DETECTOR(I), is calculated for an InSb;
c   proportional to No. of photons (DETECTOR(I)=PHOTON/SIGMA(I)).
c   To calculate the extinction all results MUST be normalized to the
c   ZERO AIRMASS point SOURCE(VEGA)*FILTER*DETECTOR (i.e TRANS=1.0)
c   LINK ATMOS, LINEAR, SIMPSON
c   ATMOS.COM will assign the appropriate filter file.
c
      CHARACTER*30 FILE
      CHARACTER*80 TEXT1, TEXT2
      INTEGER INFO(10), IDATA(10), WHEN(3), CLTIM(2)
      integer info2(10), idata2(10), when2(3), cltim2(2)
      REAL SIGMA1, SIGMA2
      REAL DETECTOR(3000)
      DIMENSION SIGMA(3000), TRANS(3000), FLAM(500), TLAM(500)
      DIMENSION FILTER(3000), transd(3000), sigmad(3000)
      DIMENSION IFNU(12500), VEGA(3000)
c   Data statement to 'set' units for detector response.
      DATA PHOTON/1.0/
      CALL DATE(WHEN)
      CALL TIME(CLTIM)
c   Enter wavenumber working range (cm-1) /used though out program.
c
10      TYPE *, 'Lower and Upper waveno. (SIGMA1, SIGMA2)?'
      ACCEPT 1020, SIGMA1
      TYPE *, 'and SIGMA2...'
      ACCEPT 1020, SIGMA2
      N=IFIX(SIGMA2-SIGMA1+1.)

c
c   check array limits (3000) not exceeded.....
c
      if(N.le.3000) go to 15
      type *, 'arrays must not exceed 3000 !!! '
      go to 10
c
c   .....
c   now check no. of elements is ODD for Simpson intergration..
15      if(MOD(N,2).NE.0) GO TO 20
      TYPE *, 'Intergration needs odd No. elements...'
      GO TO 10
c   Read in filter profile (assigned unit 1)
20      READ(1,*,END=30)(FLAM(I), DUMB, TLAM(I), I=1, 500)
      TYPE *, 'Filter file too lang!!'
      go to 10
30      J=I-1
      TYPE *, 'Filter file read..'
c   Interpolate filter profile into correct range.....
c   (interpolated to unit spaced cm-1)
c
      DO 100 I=1,N
          COUNT=FLDAT(I-1)
          SIGMAI=SIGMA1+COUNT
          WAVEI=10000./SIGMAI
          CALL LINEAR(FLAM, TLAM, WAVEI, TRANI, J)
          FILTER(I)=TRANI
          SIGMA(I)=SIGMAI
    
```

```

100      CONTINUE
c
c  Write FILTER(I) to FILTER.DAT (assigned unit 2).....
      TYPE *, 'File Header? :2*40 character lines'
      READ(*,1010) INFO
      READ(*,1010) IDATA
1000      FORMAT(1X,F10.4,1X,F10.3,E10.4)
1010      FORMAT(1X,10A4)
1020      FORMAT(F10.3)
      OPEN(UNIT=2,NAME='FILTER.DAT',TYPE='NEW',FORM='UNFORMATTED')
      WRITE(2) INFO, IDATA, WHEN, CLTIM
      WRITE(2) N
      WRITE(2) (SIGMA(I), FILTER(I), I=1, N)
c Section to read in Vega Fluxes (Kurucz Model).....
c   on scratch disk , format 13I6 in 1cm-1;12500-100
c   model in VEGA.DAT on Scratch disk (attached in ATMOS.COM)
c
      II=12501
      READ(3,1040) TEXT1
      READ(3,1040) TEXT2
      WRITE(*,1040) TEXT1
      WRITE(*,1040) TEXT2
      READ(3,1030,END=40) (IFNU(II-I), IFNU(II-I-1), IFNU(II-I-2),
1 IFNU(II-I-3), IFNU(II-I-4), IFNU(II-I-5),
1 IFNU(II-I-6), IFNU(II-I-7), IFNU(II-I-8), IFNU(II-I-9),
1 IFNU(II-I-10), IFNU(II-I-11), IFNU(II-I-12), I=1, 12401, 13)
c hopefully IFNU(I) filled in correct order.....
c Now convert Fluxes and fill VEGA(I)
c
40      DO 200 I=1, N
          ISIGMA=SIGMA(I)
          VEGA(I)=10.**(FLOAT(IFNU(ISIGMA))*1.E-5)
200      CONTINUE
c write to file 'SOURCE.DAT'.....
      OPEN(UNIT=40,NAME='SOURCE.DAT',TYPE='NEW',FORM='UNFORMATTED')
      WRITE(40) INFO, IDATA, WHEN, CLTIM
      WRITE(40) N
      WRITE(40) (SIGMA(I), VEGA(I), I=1, N)
      TYPE *, 'Source.dat written..'
1030      FORMAT(2X,13I6)
1040      FORMAT(A80)
c
c Enter transmission file if necessary.....
c
75      TYPE *, ' an ITRANS2 file (1) or zero airmass point(0)..?'
      ACCEPT 1050, IR
1050      FORMAT(I1)
c If no file needed (zero airmass point) set all TRANS(I)=1.0
c
      IF(IR.EQ.1) GO TO 80
          DO 400 I=1, N
              TRANS(I)=1.0
400      CONTINUE
          FILE='zero.dat'
          GO TO 90
c
c ..... otherwise read in required ITRANS2 file.
c
80      TYPE *, ' ITRANS2 file name ?'
      ACCEPT 1060, FILE
1060      FORMAT(A30)
      OPEN(UNIT=41,NAME=FILE,TYPE='OLD',FORM='UNFORMATTED')

```

```

      READ(41) INFO2, IDATA2, WHEN2, CLTIM2
      READ(41) JJ
      read(41)(sigmad(i), transd(i), i=1, JJ)
      II=1
C   Only read in file within SIGMA1 and SIGMA2.....
C
      DO 500 I=1, JJ
          SIGMAI=sigmad(i)
          ATRAN=transd(i)
          IF(SIGMAI.LT.SIGMA1) GO TO 500
          IF(SIGMAI.GT.SIGMA2) GO TO 95
          TRANS(II)=ATRAM
          II=II+1
500    CONTINUE
      CLOSE(UNIT=41)
      TYPE *, ' something wrong with range of IRTRANS2 file.... '
      go to 75
95     TYPE *, ' Transmission file read.... '
      CLOSE(UNIT=41)
      WRITE(*,1070) INFO2, IDATA2, WHEN2, CLTIM2
1070    format(1x,10a4, /1x, 10a4, /1x, 'When, CLTIM =', 3a4, 2a4)
C
C   write file to 'TRANS.DAT'.....
C
90     OPEN(UNIT=42, NAME='TRANS.DAT', TYPE='NEW', FORM='UNFORMATTED')
      WRITE(42) INFO, IDATA2, WHEN, CLTIM
      WRITE(42) N
      WRITE(42)(SIGMA(I), TRANS(I), I=1, N)
      CLOSE(UNIT=42)
C
C   Now form product VEGA(I)*FILTER(I)*TRANS(I)*DETECTOR(I) .....
C   DETECTOR(I) is the detector response (for InSb = PHOTON/SIGMA(I) )
C
      DO I=1, N
          DETECTOR(I)=PHOTON/SIGMA(I)
      ENDDO
      type*, ' flat spectrum(1) or Vega(0)...?'
      accept *, iflat
C   ... this gives the option to use a 'flat spectrum'.....
C
      DO 600 I=1, N
          IF(IFLAT.EQ.1) THEN
              TRANS(I)=FILTER(I)*TRANS(I)*DETECTOR(I)
          ELSE
              TRANS(I)=VEGA(I)*FILTER(I)*TRANS(I)*DETECTOR(I)
          ENDIF
600    CONTINUE
C   ... and write this to PRODUCT.DAT ...
C
      OPEN(UNIT=43, NAME='PRODUCT.DAT', TYPE='NEW', FORM='UNFORMATTED')
      WRITE(43) INFO, IDATA2, WHEN, CLTIM
      WRITE(43) N
      WRITE(43)(SIGMA(I), TRANS(I), I=1, N)
      TYPE *, ' PRODUCT.DAT file written...'
      CLOSE(UNIT=43)
C
C   Finally integrate over SIGMA1 to SIGMA2.....
C   ... this uses subroutine SIMPSON..
C
      A=0.0
      CALL SIMPSON(SIGMA, TRANS, N, A)
      WRITE(*,1080) A, FILE
1080    FORMAT(1X, E13.6, ' = Final integrated flux, using: ', A30)

      type *, ' new IRTRANS2 file ? (1/0).. '
      accept 1050, IR
          if(ir.eq.1) go to 75
      STOP
      END

```

APPENDIX C Program EXTINC.FOR

```

      PROGRAM EXTINCT
C
C  Program EXTINCT uses three ITRANS transmission spectra , calculated
C  over identical regions at 1.0 , 1.5 and 2.0 airmasses , to give as a
C  function of wavenumber (SIGMA(I) ) ;
C    1) The extinction/airmass calculated using the 1.0 and 2.0
C       airmass points [ written to EXTINCT.DAT ],
C    2) The error at zero airmass assuming a linear extrapolation
C       (on an magnitude airmass plot) of this extinction.
C       [ written to DELTA.DAT ]
C    3) the difference at 1.5 airmasses between the interpolated
C       extinction ( between 1.0 and 2.0 airmasses ) and the actual
C       value. [ written to DEV.DAT ]
C
C  To avoid dividing by zeroes a lower transmission limit must be set,
C  default value = 0.01 (all EXTINCT, DELTA and DEV correspondingly set)
C  Files can be written with MAGNITUDES or PERCENT as Y-axis (X-axis given
C  in wavenumber). All output files formatted for IRGRAPH (i.e. UNFORMATTED)
C
C
      INTEGER INFO(10), IDATA(10)
      INTEGER WHEN(3), CLTIM(2)
      CHARACTER*30 FILE1, FILE2, FILE3
      DIMENSION SIGMA(2000), TRANS10(2000), TRANS15(2000), TRANS20(2000)
      DIMENSION EXTINCT(2000), DELTA(2000), DEV(2000)
C  ENTER  FILE NAMES. . . .
      TYPE *, 'SECZ=1 FILE?'
      ACCEPT 1000, FILE1
      TYPE *, 'SECZ=1.5 FILE?'
      ACCEPT 1000, FILE2
      TYPE *, 'SECZ=2.0 FILE?'
      ACCEPT 1000, FILE3
1000  FORMAT(A30)
      OPEN(UNIT=40, NAME=FILE1, TYPE='OLD', FORM='UNFORMATTED')
      OPEN(UNIT=41, NAME=FILE2, TYPE='OLD', FORM='UNFORMATTED')
      OPEN(UNIT=42, NAME=FILE3, TYPE='OLD', FORM='UNFORMATTED')
      READ(40) INFO, IDATA, WHEN, CLTIM
      READ(40) INUM
      READ(40) (SIGMA(I), TRANS10(I), I=1, INUM)
      WRITE(*, 1010) INFO, IDATA, WHEN, CLTIM
      READ(41) INFO, IDATA, WHEN, CLTIM
      READ(41) INUM
      READ(41) (SIGMA(I), TRANS15(I), I=1, INUM)
      WRITE(*, 1010) INFO, IDATA, WHEN, CLTIM
      READ(42) INFO, IDATA, WHEN, CLTIM
      READ(42) INUM
      READ(42) (SIGMA(I), TRANS20(I), I=1, INUM)
      WRITE(*, 1010) INFO, IDATA, WHEN, CLTIM
1010  FORMAT(1X, 10A4, /1X, 10A4, /1X, 'WHEN, CLTIM = ', 3A4, 2A4)
C  CALCULATE EXTINCTION, DELTA AND DEVIATION (MAGS). . . .
C
C
C  Default: if any TRANS(I).le.0.01 then set
C          EXTINCT(I), DELTA(I), DEV(I) to -5.0 mags or -99 pc.
C
55    type*, ' what is lower transmission cutoff. . ?'
      tcut=0.01
      accept *, tcut
      cutmag=2.5*log10(tcut)
      cutpc=((10.**(cutmag/2.5))-1.)*100.
      write(*, 1090) tcut
      write(*, 1100) cutmag, cutpc
1090  format(1x, ' lower cutoff is ', f8.4)

```

```

1100    format(3x, 'giving cutmag. =', f8.3, 2x, 'and cutpc. =', f8.3
1      , 2x, 'okay(1/0)')
      accept *, ir
      if(ir.eq.0) go to 55
c
c
c  EXTINCT, DELTA, DEV loop.....
c
      do i=1, inum
        if(trans20(i).le.0.01.or.
1      trans15(i).le.0.01.or.
1      trans10(i).le.0.01) then
          EXTINCT(I)=CUTMAG
          DELTA(I)=CUTMAG
          DEV(I)=CUTMAG
        else
          RM10=2.5*ALOG10(TRANS10(I))
          RM15=2.5*ALOG10(TRANS15(I))
          RM20=2.5*ALOG10(TRANS20(I))
          EXTINC=RM20-RM10
          EXTINCT(I)=EXTINC
          DELTA(I)=RM10-EXTINC
          DEV(I)=RM15-(RM20-(EXTINC/2.))
        endif
      enddo
c
      type *, ' magnitude(1) or percent(0) scale ?'
      accept *, ir
      if(ir.eq.0) then
        do i=1, inum
          EXTINCT(I)=((10.**((EXTINCT(I)/2.5))-1.)*100.
          DELTA(I)=((10.**((DELTA(I)/2.5))-1.)*100.
          DEV(I)=((10.**((DEV(I)/2.5))-1.)*100.
        enddo
      endif
      OPEN(UNIT=50, NAME='EXTINCT. DAT', TYPE='NEW', FORM='UNFORMATTED')
      OPEN(UNIT=51, NAME='DELTA. DAT', TYPE='NEW', FORM='UNFORMATTED')
      OPEN(UNIT=52, NAME='DEV. DAT', TYPE='NEW', FORM='UNFORMATTED')
      CALL DATE(WHEN)
      CALL TIME(CLTIM)
      WRITE(50) INFO, IDATA, WHEN, CLTIM
      WRITE(50) INUM
      WRITE(50) (SIGMA(I), EXTINCT(I), I=1, INUM)
      WRITE(51) INFO, IDATA, WHEN, CLTIM
      WRITE(51) INUM
      WRITE(51) (SIGMA(I), DELTA(I), I=1, INUM)
      WRITE(52) INFO, IDATA, WHEN, CLTIM
      WRITE(52) INUM
      WRITE(52) (SIGMA(I), DEV(I), I=1, INUM)
      WRITE(*,*) 'Files: EXTINCT. DAT, DELTA. DAT, DEV. DAT written..'
      STOP
      END

```

APPENDIX D

IRTRANS PARAMETERS; UKIRT (4.2 km 1.2 mm H₂O)

	4.2km (mixing ratios)	Column abundances (cm ⁻²)
O ₂	2099460.0 x 10 ⁻⁶	2.663 E24
CO ₂	325.0 "	4.132 E21
CH ₄	1.5 "	1.907 E18
N ₂ O	0.25 "	3.179 E18
CO	0.07 "	8.90 E17
H ₂ O	1200 μm	4.02 E21
O ₃		7.28 E18

P	600.0 mb
p(eff)	300.0 mb
p(H ₂ O)	506.0 mb
p(O ₃)	36.4 mb
T(eff)	228.0 K
T(H ₂ O)	252.0 K
T(O ₃)	219.0 K

$$N_{\text{TOTAL}} \text{ (cm}^{-2}\text{)} = p/\overline{mg} = 2.119 \times 10^{22} p(\text{m bar})$$

$$(\text{g} = 973.8 \text{ cm sec}^{-2} \text{ @ } 22 \text{ km})$$

$$1 \text{ pptu} = 3.35 \times 10^{18} \text{ cm}^{-2}$$

APPENDIX E Paper for the XVth ESLAB Symposium

EXTINCTION CORRECTIONS IN GROUND-BASED INFRARED SPECTROMETRY

C. M. Mountain

M. J. Selby

C. Sanchez-Magro

Department of Physics,
Imperial College, London

Instituto Astrofisica de
Canarias, Tenerife

ABSTRACT

Calculations of atmospheric transmission through the M (5 μ m) atmospheric window, at a resolution of 10^3 are presented for sites at the Observatorio del Teide, Tenerife and the NHO, La Palma in the Canary Islands. We use a standard midlatitude atmospheric model and absorption line strengths for the known molecular species calculated at a height of 2.38 kms. It is demonstrated how the normal procedure for calibration of extinction can give systematic errors in the assessment of infrared flux both for photometry, using broad band filters, and for spectrometry.

Keywords: Atmospheric Extinction, Infrared Spectrophotometry

Also the non-linearity changes across the windows because the bandwidth can contain various blends of lines with widely differing strengths.

We demonstrate the non-linear effects using a theoretical atmospheric transmission model for a site on Tenerife or La Palma, in the Canary Islands, at 2.38 kilometres above sea level. We use the program IRTANS written by M. Stier and W. Traub (ref. 2). The program uses a single layer Curtis-Godson approximation in which the column abundance, effective temperature and pressure for each molecular species are required. The wave number, line strength, pressure broadening coefficient and energy level for over 100,000 known transitions of H_2O , CO_2 , O_3 , O_2 , CH_4 , CO and N_2O covering the infrared are obtained within the program using the Air Force Cambridge Research Laboratory's atmospheric absorption line data (ref. 3). For all molecular species, apart from H_2O , the variations of pressure, temperature and density with height were taken from the Standard Midlatitude Winter and Summer atmospheres (ref. 4). The column density of H_2O which is concentrated near the ground was used as a free parameter.

1. INTRODUCTION

It is normal practice to spend a substantial fraction of the total time spent in infrared ground-based observations to determine atmospheric extinction. This can be a difficult and complicated problem and usually determines the ultimate accuracy for flux measurements of strong sources, both for photometry and spectrophotometry. In addition to the errors caused by changing atmospheric conditions, the simple and normally used method of calibration can lead to serious systematic errors. This has been demonstrated by Manduca and Bell (ref. 1) with photometry in the J, H, K and L near infrared windows; in this paper we use a similar procedure to theirs and apply it to the 5 μ m(M) window for photometry and spectrometry. The extinction in the M window is considerably higher than in the other windows mentioned.

The main reason for these difficulties in assessing extinction is that the atmospheric windows contain molecular absorption bands (mainly H_2O and CO_2) which are usually highly saturated so that even for typically used bandwidths in spectrometry ($R = 10^3$) extinction is not linear with air mass.

2. PHOTOMETRY AT 5 μ m

The calculated atmospheric transmission for Tenerife in the M window is shown in Figure 2.1 where the spectrum has been smoothed corresponding to a resolving power of $R = 10^3$. Table 1 lists the atmospheric parameters used in the program. Radio sonde data taken on Tenerife up to a height of 20 kms agreed to better than 2% with the model of the Standard Summer Midlatitude atmosphere. Figure 1 shows the calculated extinction curve using a broad band filter (4.5 - 5.4 μ m); the measured extinction at Tenerife between one and two air masses is typically 0.3 magnitudes per air mass which is consistent with 4 mm of precipitable water vapour. This is also the annual mean found during some site tests at mm wavelengths. Table 2 lists the relevant parameters defined in Figure 1 for α Lyr ($T_e = 10^4 K$) the principal calibration star and for a source with a flat spectrum ($F(\lambda) = \text{constant}$). The largest deviation from a linear extinction law takes place close to zero air mass; a linear extrapolation down to zero gives an error of $\Delta V_{\text{ega}} = .268$ magnitudes ($H_2O = 4$ mm) which

creates a serious problem for absolute calibration measurements using broad filters in the M window (ref 5, ref 6). For the determination of the source flux relative to Vega there will be a systematic error due to their differing colours; however this is less than 2% (see $\Delta_{\text{Flat}} - \Delta_{\text{Vega}}$ in table 2) which is considerably less than the uncertainty in the knowledge of the absolute flux of Vega at 5 μm .

SPECTROMETRY IN THE M WINDOW

Similar problems of calibration arise with spectrometry in the M window as those with photometry. Figures 2.1, 2.2, 2.3, 2.4 are plots of the transmission, E , Δ and Φ , (the parameters defined in Figure 1), across the window. For calibration of the extinction one would normally attempt to ratio the source's spectrum with a similar one from the calibration star taken at the same air mass. However if this is not convenient or possible then systematic errors can result. The residual error Φ (plotted in Figure 2.4) arises if a linear extrapolation is used between two measurements at one and two air masses to determine the extinction at 1.5 air masses. Even in the better parts of the window these residual errors are $\sim 2\%$. More seriously this error Φ is highly structured across the window which makes the detection of weak spectral lines on a large continuum difficult.

We suggest that atmospheric transmission models are used to make first order corrections and they may also save time in performing calibrations at a large number of air masses. For this application to succeed the question of the accuracy of the models arises and the method used to select the column density of H_2O and effective temperature. The ground temperature and the midlatitude atmospheric model can provide an accurate temperature. Two methods for the accurate determination of the column density of H_2O are worthy of mention. First the column density in the model calculation giving the best fit for selected H_2O bands within the windows. Alternatively the integrated band absorption of some selected H_2O bands have known functional relationships with pressure and column density. If bands involving ground-state transitions are selected, then to a good approximation, the absorption is independent of temperature, whereas with upper-state bands variations of absorption can be more affected by changes in temperature than density (even though the water vapour density can vary greatly). Details of the determination of column density using effective band absorption area is given in ref. 7.

We have compared the measured spectra of bright calibration stars with the predicted atmospheric transmission at a resolving power $R \approx 10^2 - 10^3$ in the windows between 2 μm and 5 μm at Tenerife. We found good agreement particularly as regards general shape and structure, however we see a deviation from the model in the wings of the very strong CO_2 bands near 4.3 μm . For example on the long wavelength side of this band (dominating the short wave side of the M window, see Figure 2.1) we estimate, from extinction measurements, a deviation from the model of the order of $\sim 10\%$ in absolute transmission at 4.6 μm but only $\sim 3\%$ at 4.7 μm .

We would like to thank W. Traub and M. Stier for

sending us a copy of the ITRANS programme and Sid Wright, Jack Giddings of the UCL Starlink node for help with the computing.

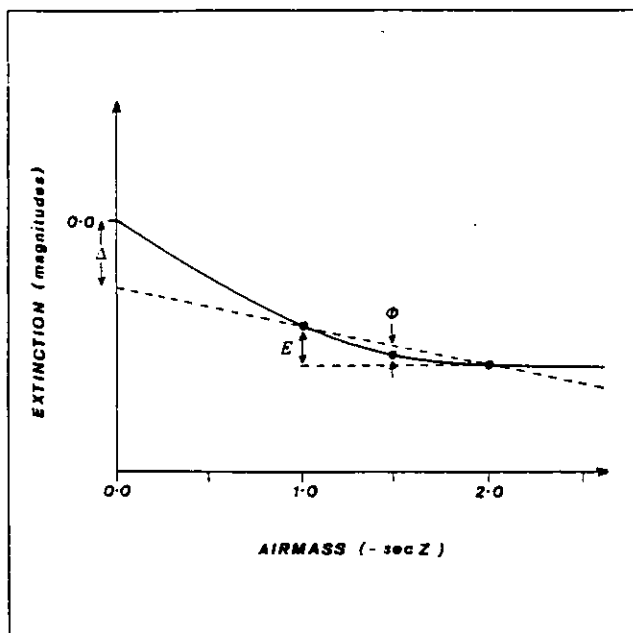


Figure 1. The calculated extinction, in magnitudes, as a function of airmass. If the extinction/unit airmass E is taken as the difference between extinctions at 1.0 and 2.0 airmasses, this gives an extinction at 1.5 airmasses which differs from the actual value by Φ . Assuming a linear extrapolation of E gives a systematic error at zero airmass of Δ magnitudes.

TABLE 1

ITRANS atmospheric parameters
for TENERIFE/NHO LA PALMA 2.38 km
(AFCRL Mid-Latitude Summer Model)

	Column Densities (cm^{-2})	T_{eff} ($^{\circ}\text{K}$)	P_{eff} (mb)
H_2O	1.34E22*	275.1	651.1
O_2	3.40E24	249.4	382.9
CO_2	5.27E21	249.4	382.9
N_2O	4.06E18	249.4	382.9
CH_4	2.43E19	249.4	382.9
CO	1.14E18	249.4	382.9
O_3	8.54E18	220.7	41.5

*(1.34E22 cm^{-2} $\text{H}_2\text{O} \equiv 4 \text{ mm}$ precipitable H_2O)

FIG. 2.1 TRANSMISSION ACROSS 'M' WINDOW AT 2.38 KM (4MM H2O SECZ=1.0)

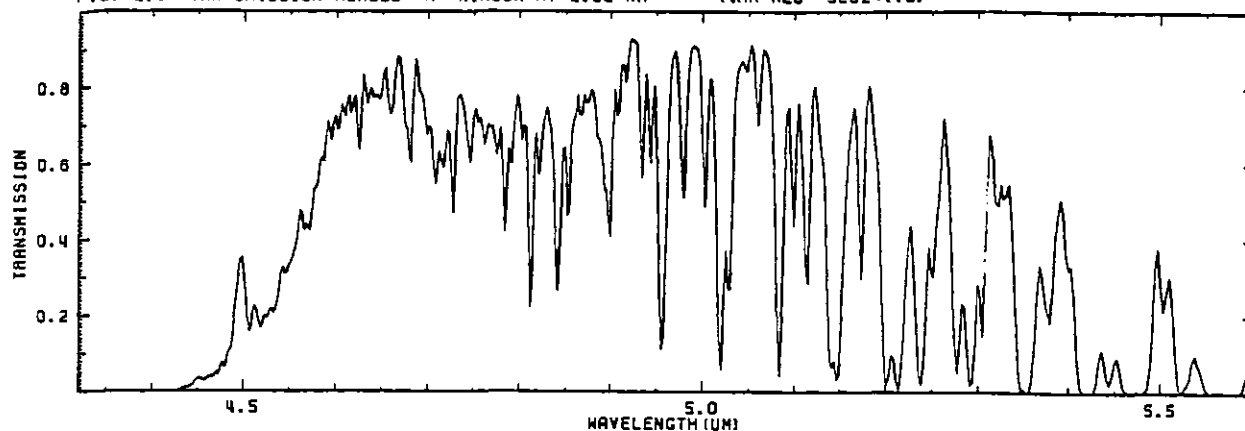


FIG. 2.2 EXTINCTION VS. WAVELENGTH FOR 'M' WINDOW (4MM H2O)

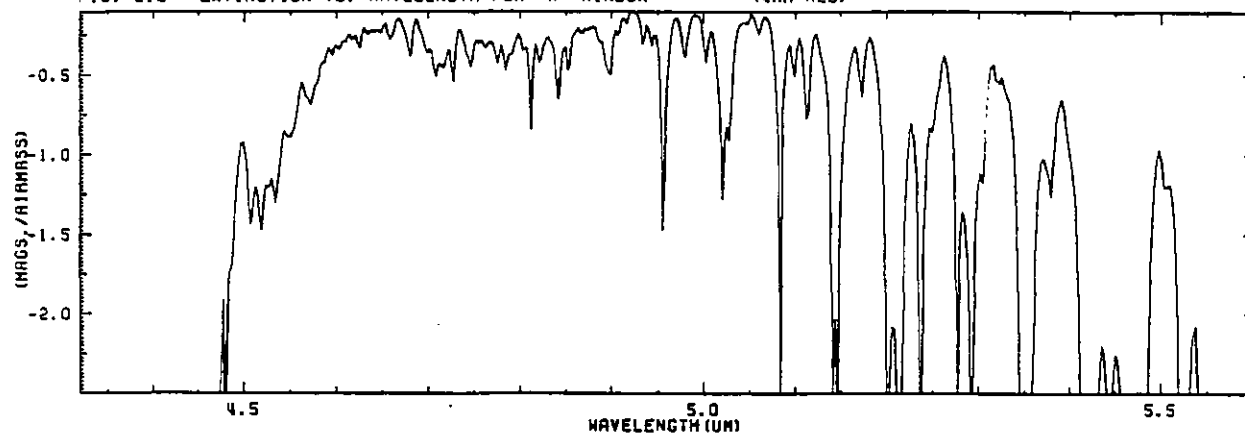


FIG. 2.3 ZERO AIRMASS EXTRAPOLATION ERROR Δ VS. WAVELENGTH (4MM H2O)

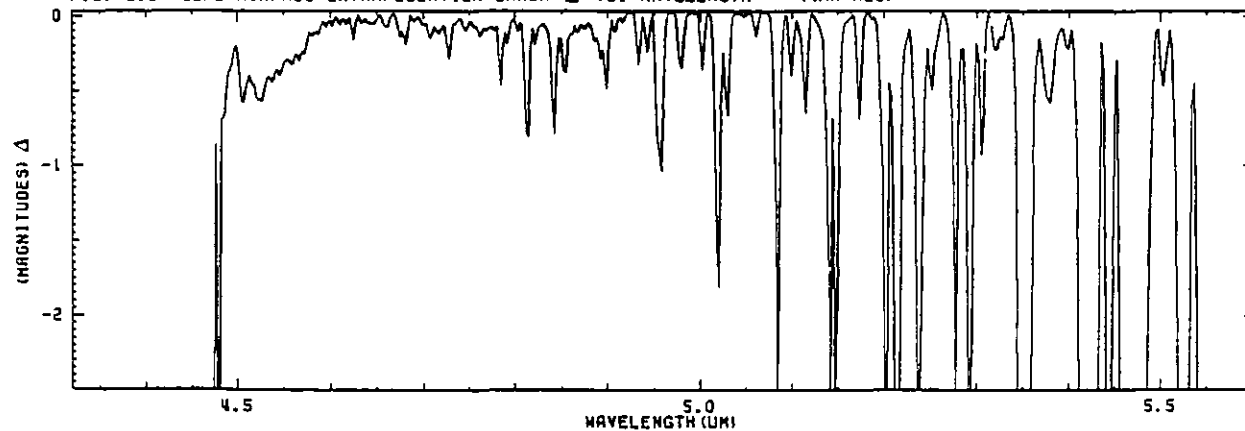


FIG. 2.4 DIFFERENCE BETWEEN EXTRAPOLATED AND ACTUAL EXTINCTION AT 1.5 A.M. (Φ)

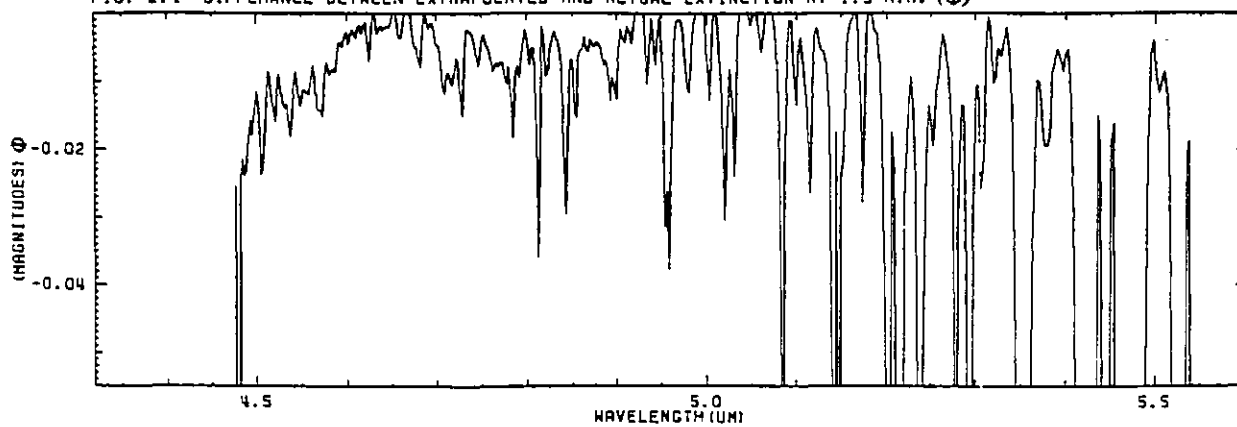


TABLE 2

E , Δ and Φ calculated for Vega
(Kurucz Model) and a flat $F(\lambda)$
source using IRTANS transmission
spectra for 2, 4 and 8 μm H_2O
with a M photometry filter

Vega		E	Δ	Φ
		(magnitudes)		
	2	.279	.205	.009
μm H_2O	4	.335	.268	.011
	8	.402	.364	.013
Flat Spectrum				
	2	.280	.213	.009
μm H_2O	4	.339	.282	.011
	8	.409	.387	.014
		$\Delta_{\text{flat}} - \Delta_{\text{Vega}}$ (magnitudes)		
	2	.008		
μm H_2O	4	.014		
	8	.023		

Measurement of the Absolute flux from Vega
in the J, K, L and M bands. In progress.

7. Goody, R.M., 1964,
Absorption by Atmospheric gases,
Atmospheric Radiation, 1. Theoretical
Basis Ch.5. O.U.P.

4. REFERENCES

1. Manduca, A. and Bell, R.A., 1979
Atmospheric Extinction in the Near-
Infrared, P.A.S.B., 91, 848
2. Traub, W.A., and Stier, M.T. 1976
Theoretical Atmospheric Transmission in
the Mid- and Far-Infrared at Four
Altitudes, Appl. Optics, 15, 364
3. McClatchey, R.A., Benedict, W.S.,
Slough, S.A., Burch, D.E., Calfee, R.F.,
Fox, K., Rothman, L.S., and Garing, J.S. 1973,
AFCRL Atmospheric Absorption Line Parameter
Compilation, AFCRL-TR-73-0096, Bedford, Mass.
4. McClatchey, R.A., Fenn, R.W., Selby, J.E.A.,
Volz, F.E., and Garing, J.S. 1972,
Optical Properties of the Atmosphere,
AFCRL-72-0497, Bedford, Mass.
5. Selby, M.J., Blackwell, D.E., Petford, A.D.
and Shallis, M.J. 1980,
Measurement of the Absolute flux from
Vega in the K band (2.2 μm), M.N.R.A.S.
193, 111.
6. Selby, M.J., Mountain, C.M., Blackwell, D.E.,
Legget, S.K., and Petford, A.D. 1982,

THE STRENGTH OF HD INFRARED EMISSION IN ORION

T. W. Hartquist

C. M. Mountain

M. J. Selby

E. Roueff

Department of Physics
and Astronomy
University College London

Department of Physics,
Imperial College, London

Département de Astrophysique
Fondamentale,
Observatoire de Meudon

ABSTRACT

If rotational-vibrational levels of HD are excited primarily by collisions the HD line emission from vibrationally excited levels is approximately 10^{-4} - 10^{-3} as strong as the observed H_2 line radiation. The ratio is more likely to be 10^{-3} - 10^{-2} when comparing emission from levels in the ground vibrational states. However, ultraviolet pumping of HD is probably very important and the HD infrared emissivity is roughly 10^{-2} - 10^{-1} that of H_2 . With the lines from the R and P branches of the rotational-vibrational bands falling in the 2 μm and 3 μm atmospheric windows, the observation of HD emission is well within the range of present ground based instruments.

Keywords: Molecular Clouds, Interstellar Shocks, Ultraviolet Pumping, Deuterium, Orion Nebula.

1. INTRODUCTION

Excited rotational-vibrational levels in the ground electronic state of molecular hydrogen can be populated either by collisions occurring in hot ($T > 10^3$ K) gas or by the radiative cascade following electronic excitation by ultraviolet radiation (Refs 1, 2). The infrared line emission of H_2 in Orion (Ref 3) almost certainly occurs in a hot post-shock region (cf. Ref 4). Shull (Ref 5) has shown that the H_2 fluxes which could result from the radiative pumping mechanism are roughly an order of magnitude less than observed.

In Section 2, we estimate the strength of HD emission from Orion assuming that all excitation is collisionally induced. In Section 3 we argue that the ultraviolet pumping will lead to infrared fluxes comparable to those which would arise from radiatively pumped H_2 .

In Section 4 we discuss briefly the possibility of detecting HD emission using present instruments.

2. COLLISIONALLY INDUCED EMISSION

Assuming that the only excitation is collisionally induced, the number of photons, $p(HD)$, emitted by

HD molecules in a particular excitation state will be related approximately to the number of photons, $p(H_2)$ emitted by H_2 molecules in the same state by

$$\frac{p(HD)}{p(H_2)} = \frac{n(HD)}{n(H_2)} \times \frac{\lambda(HD)}{\lambda(H_2)} \times \frac{V(HD)}{V(H_2)} \times \frac{\tau_{H_2}(c) + \tau_{H_2}(r)}{\tau_{HD}(r)}$$

The first term is the ratio of the number densities which we take to be 3×10^{-5} , somewhat of an underestimate if collisional dissociation occurs behind the shock. The second term is the ratio of the rates at which the levels are collisionally excited; this term will differ from unity by a factor of the order $\exp(-\Delta/kT)$ where Δ is the difference in energy required to excite H_2 and HD to the same levels. Because HD levels are less energetic than their H_2 counterparts, a gas of a given temperature distribution will excite HD levels in a greater volume than for the equivalent H_2 levels; the third term accounts for this. The product of the first three terms is unlikely to exceed a few times 10^{-4} in most circumstances.

The last term is the inverse of the ratio of the radiative decay rate to the total decay rate, (due to collisional destruction and radiative decay), for H_2 . The number density of H_2 in the Orion infrared line-source is $1 \times 10^6 \text{ cm}^{-3}$ (Ref 6) which is high enough to thermalise many level populations. Hence, each collisionally induced excitation will not lead to a radiative decay. The radiative lifetimes of HD levels are much shorter (Ref 7) than those of H_2 (Ref 8) and each collisional excitation of HD leads to radiative decay. Collisional de-excitation rates for H_2 on H_2 depend on the temperature (Ref 8). However for the $v = 0, J = 8$ level collisional de-excitation could easily exceed the radiative de-excitation rate by an order of magnitude at densities of 10^6 cm^{-3} , and at the temperature in the emitting region HD $v = 0, J = 3$ emission could approach one percent that of H_2 . However, the radiative decay rates of vibrationally excited H_2 levels are typically at least an order of magnitude greater than that of the $v = 0, J = 3$ H_2 level and the total emission from vibrationally excited states of HD should be around a few 10^{-4} that of H_2 .

3. EMISSION FOLLOWING RADIATIVE PUMPING

Molecular hydrogen absorbs ultraviolet photons in transitions to excited electronic states. Photo-emission and cascade (Ref 1, 2) lead to the population of excited rotational-vibrational levels in the ground electronic state. These levels decay by emitting infrared photons; at densities of 10^6 cm^{-3} collisional de-excitation of H_2 levels must be considered but can be ignored for HD. In the limit of low ultraviolet radiation field and assuming that dust absorption is unimportant, ninety percent of all photons with wavelengths corresponding to those of the Lyman and Werner transitions lead to infrared emission while the rest lead to dissociation. In this limit it is possible to calculate the shape of the emission spectrum given the shape of the ultraviolet spectrum (Ref 2).

However, if radiative pumping is invoked to reproduce the flux of H_2 emission from Orion, the ultraviolet radiation field must be strong, and repumping occurs before the cascade takes the molecule back to a low vibrational level. Though the percentage of photoabsorptions leading to dissociation is small, repumping, occurs enough times in a strong field that the molecule dissociates before a single cascade through the low levels takes place (Ref 5). Dissociation and dust absorption prevent ultraviolet pumping models from producing more than ten percent of the observed $v = 1 \rightarrow v = 0$ H_2 emission.

The HD cascade is far faster (due to the dipole nature of the emission), and multiple pumping does not occur in the radiation field near the Orion source. The HD dissociation rate is much lower than that of H_2 and up to 90% of the photons at the HD Lyman and Werner wavelengths will lead to cascades through lowly excited rotational-vibrational levels. Detailed calculations are in progress (Ref 10) with the expectation that the HD infrared emission in ultraviolet pumped regions can be a substantial fraction of the observed H_2 emission; with emissivities of $10^{-2} - 10^{-1}$ that of H_2 .

4. PLANNED OBSERVATION

The line positions of the vibrational-rotational bands for HD have been calculated using molecular constants from Durie and Hertzberg (Ref 11) and Stoicheff (Ref 11). The R branch lines ($R(4) - R(12)$) fall near the edge of the $2 \mu\text{m}$ atmospheric window and the P branch lines ($P(8) - P(14)$) in the $3 \mu\text{m}$ window.

We assume first the most pessimistic case of collisionally excited HD with an emissivity of 5×10^{-4} that of H_2 . At Peak 1 in the Orion Molecular Cloud (Ref 8), using a cooled grating spectrometer (Ref 12), we would expect a detection in a 4 hour integration at the 3.8 m UKIRT telescope. If HD is predominantly radiatively pumped, we expect an equivalent detection within 2 minutes.

Even if no detection were made, to establish an upper limit on the line strengths would indicate the nature of the excitation.

5. REFERENCES

1. Stecher, T.P., and Williams, D.A. 1967
Photodestruction of Hydrogen Molecules in

HI regions, Ap.J. (Letters), 149, L29

2. Black, J.H., and Dalgarno, A., 1976
Interstellar H_2 : The Population of Excited Rotational States and the Infrared Response to Ultraviolet Radiation, Ap.J., 203, 132
3. Gautier III, T.N., Fink, U., Treffers, R., and Larson, H.P. 1976
Detection of Molecular Hydrogen Quadrupole Emission in the Orion Nebula. Ap.J. (Letters) 207, L129
4. Draine, B.T. and Roberge, W.G. 1982
A Model for the Intense Molecular Line Emission from OMC-1, Ap.J. (Letters) 259, L91
5. Shull, J.M. 1978,
Vibrational Excitation of H_2 in intense ultraviolet fluxes, Ap.J. 219, 877
6. Storey, J.M.V., Watson, D.M., Townes, C.H., Hallen, E.E. and Hansen, W.L. 1981
Far-Infrared Observations of shocked CO in Orion, Ap.J., 247, 136
7. Abgrall, H., Roueff, E. and Viala, Y. 1982
Vibration-Rotation Transition Probabilities for the Ground Electronic X'^Σ^+ state of HD. Astron.Astroph. Suppl., in press
8. Green, S., Ramaswamy, R. and Rabitz, R. 1978
Collisional Excitation of Interstellar Molecules: H_2^+ , Astrophys.J.Suppl. Vol 36, 483-496
9. Allison, A.C. and Dalgarno, A. 1967
The Rotational excitation of Molecular Hydrogen, Proc.Phys.Soc. (London) 90, 609
10. Hartquist, T.W. and Roueff, E. 1982
in progress
11. Durie, R.A. and Herzberg, G. 1960
Forbidden Transitions in Diatomic Molecules, Paper V. Can.J.Phys. Vol 38, 806
12. Wade, R., 1982
UKIRT Cooled Grating Spectrometer, UKIRT Users and Operators Manual

HD line positions of the Rotation-vibration bands,
using constants from Durie and Herzberg.

[Can. J. Phys. Vol. 38 (1960)]

1 - 0 band;	R(0) =	3717.5226 cm-1	2.690 microns
1 - 0 band;	R(1) =	3798.4514 cm-1	2.633 microns
1 - 0 band;	R(2) =	3874.3585 cm-1	2.581 microns
1 - 0 band;	R(3) =	3944.7292 cm-1	2.535 microns
1 - 0 band;	R(4) =	4009.1180 cm-1	2.494 microns
1 - 0 band;	R(5) =	4067.1643 cm-1	2.459 microns
1 - 0 band;	R(6) =	4118.6084 cm-1	2.428 microns
1 - 0 band;	R(7) =	4163.3071 cm-1	2.402 microns
1 - 0 band;	R(8) =	4201.2497 cm-1	2.380 microns
1 - 0 band;	R(9) =	4232.5740 cm-1	2.363 microns
1 - 0 band;	R(10) =	4257.5817 cm-1	2.349 microns
1 - 0 band;	R(11) =	4276.7547 cm-1	2.338 microns
1 - 0 band;	R(12) =	4290.7705 cm-1	2.331 microns
1 - 0 band;	R(13) =	4300.5187 cm-1	2.325 microns

1 - 0 band;	P(1) =	3542.9090 cm-1	2.823 microns
1 - 0 band;	P(2) =	3450.4566 cm-1	2.898 microns
1 - 0 band;	P(3) =	3355.4155 cm-1	2.980 microns
1 - 0 band;	P(4) =	3258.4084 cm-1	3.069 microns
1 - 0 band;	P(5) =	3160.0320 cm-1	3.165 microns
1 - 0 band;	P(6) =	3060.8413 cm-1	3.267 microns
1 - 0 band;	P(7) =	2961.3336 cm-1	3.377 microns
1 - 0 band;	P(8) =	2861.9329 cm-1	3.494 microns
1 - 0 band;	P(9) =	2762.9739 cm-1	3.619 microns
1 - 0 band;	P(10) =	2664.6860 cm-1	3.753 microns
1 - 0 band;	P(11) =	2567.1779 cm-1	3.895 microns
1 - 0 band;	P(12) =	2470.4213 cm-1	4.048 microns
1 - 0 band;	P(13) =	2374.2355 cm-1	4.212 microns
1 - 0 band;	P(14) =	2278.2709 cm-1	4.389 microns

Line frequencies only accurate to $\pm 0.1 \text{ cm}^{-1}$ (calculation
was only carried on to look for systematic errors in program;
calculated in double precision on PDP/1123)

REFERENCES

- Beckwith, S. 1981. Infrared Astronomy I.A.U. Symposium No. 96
- Bignall, K.J. 1970. Quart. J. R. Met. Soc., 96, 390.
- Blackwell, D.E., Shallis, M.J. and Selby, M.J., 1979. M.N.R.A.S.
188, 847.
- Chaball, R., 1953. J. Tech. C.N.R.S. 24, 138.
- Dalgarno, A., 1976. Frontiers of Astrophysics edited by
E.H. Avrett.
- Dreiling, L.A. and Bell, R.A., 1980. Ap.J. 241, 736.
- Eddington, A.S., 1937. Observatory, 60, 99.
- Gautier, T.M. III et al, 1976. Ap.J. (Letters) 207, L129.
- Gehrz, R.D., Hackwell, J.A. and Jones, T.W., 1974. Ap.J. 191, 675.
- Goody, R.M., 1964. Absorption by Atmospheric Gasses, O.U.P.
- Harwitt, M. and Ming Hing Tai, 1976. Applied Optics, Vol. 15, No. 11.
- Hayes, D.S., Latham, D.W. and Hayes, S.H., 1975. Ap.J. 197, 587.
- Hayes, D.S. et al, 1981. Am. Astro. Soc. 157th meeting, Albuquerque.
- Jacquinot, J. 1954. J. Opt. Soc. Amer. 44, 761.
- Johnson, H.L., 1964. Boln. Obs. Tonantzintla Tacabaya, 3, 305.
- Johnson, H.L., 1966. A. Rev. Astro. Astrophysis. 4, 193.
- Jorden, P.R., 1977. New techniques and Measurements in Ground Based
I.R. Astronomy. Ph.D. Thesis, University of London.
- Lacy, J.H., 1981. Infrared Astronomy. I.A.U. Symposium No. 96.
- Leggett, S.K., 1983. Ph.D. Thesis, University of Oxford.

- MacGregor, A.D., 1977. I.C.S.T. Detector Testing Contract:
Final Report. Royal Observatory, Edinburgh.
- Manduca, A. and Bell, R.A., 1979. P.A.S.B. 91, 84.
- McClatchey et al 1972. Optical Properties of the Atmosphere.
- McClatchey et al, 1973. Atmospheric Absorption Line Parameter
Compilation. AFCRL-TR-73-009.
- Nelson, E.D. and Fredman, M.L., 1970. J. Opt. Soc. Amer. 60,
No. 12.
- Oke, J.B. and Schild, R.E., 1970. Ap. J. 161, 1015.
- Rybicki, G., 1967. Listing Given in Smithsonian Astrophysical
Observatory Special Report 303.
- Schild, R., Peterson, D.M. and Oke, J.B., 1971. Ap.J. 166, 95.
- Selby, M.J. et al 1980. M.N.R.A.S., 193, 111.
- Selby, M.J. et al, 1982. M.N.R.A.S. (in print).
- Sloane, N.J.A. et al, 1969. Applied Optics Vol. 8, 10.
- Strecker, P.W., Erikson, E.F. and Whitteborn, F.C., 1979.
Ap.J. Suppl., 41, 501.
- Traub, W.A. and Stier, M.T., 1976. Appl. Optics. 15, 364.
- Willner, S.P. and Pipher, J.L. Preprint No. 1695. Centre for
Astrophysics, Cambridge, Mass. 02138.