Low-to-Moderate Resolution Optical Spectroscopy Manual for Kitt Peak

Phil Massey Jim DeVeny Buell Jannuzi Ed Carder

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Contents

1 Introduction

1.1 About This Manual

This manual brings together all of the "astronomer information" about low-to-moderate resolution (R< 5000) optical spectroscopy at Kitt Peak in order to (1) make it easier to write an observing proposal, and (2) to have one convenient reference for the astronomer at the telescope.

This manual covers the 4-m RC Spectrograph, the 4-m Cryogenic Camera ("Cryo-Cam"), and the 2.1-m GoldCam spectrometer. We also include some data here for the multi-object fiber positioner Hydra used with the Bench Spectrograph at the WIYN 3.5-m telescope, although complete information on this will be found in a separate manual described below. We do not discuss high dispersion optical spectroscopy in this manual, but instead refer the reader to the appropriate manuals for the 4-m Echelle spectrograph and the Coude Feed spectrograph.

1.2 Who To Contact with Further Questions

Any of the following can answers questions about the spectrographs at Kitt Peak. Once you have been assigned telescope time, it is easiest to direct your questions to the staff contact listed in your letter assigning time.

Jim DeVeny	520-318-8390	jdeveny@noao.edu
Buell Jannuzi	520-318-8353	bjannuzi@noao.edu
Ed Carder	520-318-8291	ecarder@noao.edu
Phil Massey	520-318-8271	pmassey@noao.edu

1.3 Other Manuals

Other manuals that you may find useful are listed below. They are all available in electronic form via anonymous ftp to *ftp.noao.edu* in the "kpno/manuals" subdirectory. They are all in *compressed* form and need to be transferred in binary mode, then *uncompressed* before printing. They are also available via the World Wide Web by looking under "documentation" on the Kitt Peak home page (*http://www.noao.edu/kpno/kpno.html*).

- Individual reference manuals for the RC Spectrograph (*rcspx.ps.Z*) and GoldCam (*gcam1.ps.Z*).
- *An Observer's Guide to Taking CCD Data with ICE:* This manual covers the IRAF software commands needed to take data with the CCD software. (*ice.ps.Z*).

- *Multi-Slits At Kitt Peak* This manual describes the construction and use of multi-slit aperture masks with the 4-m CryoCam and with the RC Spectrograph. (*multi-slits.ps.Z*)
- *Hydra Users Manual.* The multi-object fiber position Hydra is used on the WIYN 3.5-m telescope; this manual describes the use of the instrument, and the options for its associated spectrograph, in detail. (*hydrawiynmanual.ps.Z*)

2 The Facts

2.1 Overview

The following table gives the basic characteristics of the instruments discussed here.

General Facts About the Spectrographs

Instrument	Resolution ($R = \lambda/\Delta\lambda$)	Detector CCD	Detector Useful Area	Slit Length (arcmin)	Scale Detector $''$/pixel	Scale Slit $1'' =$	Multiplexing?
4-m RC Spect	300-5000	T2KB	300×1500-1700	5.4	0.69	150μm	single or multi-slits
4-m CryoCam	400-600	F1KA	320×1000	4.5	0.84	150μm	single or multi-slits
2.1m GoldCam	300-4500	F3KC	400×2000	5.2	0.78	79μm	single
WIYN Hydra	700-14000	T2KC	2000×2048	fibers (FOV≈1°)			≈100 fibers

In the above table the "Useful Area" refers firstly to the number of pixels of spatial extent covered by the slit, and secondly to the number of pixels which are in focus and/or not strongly vignetted, as described below.

Each spectrograph is used typically with a specific CCD. In the case of the 4-m CryoCam and the 2.1-m GoldCam, the chip is actually built into the camera. We describe the CCD characteristics below. "Linearity" refers to the number of electrons when the departure from linearity is 0.1%, but in point of fact, things deteriorate quickly above the listed values. The DQE curves can be found in Fig. 1.

Facts About the CCDs

Instrument	CCD	Pixel Size (μm)	Default Gain: Gain ($e-$/ADU)	Default Gain: Read-noise RMS ($e-$)	Default Gain: $\#e-$ @65,000 ADU	Linear(0.1%) to ($e-$)
4-m RC Spect	T2KB	24	3.1	4.0	201,500	220,000
4-m CryoCam	F1KA	15	0.8	15	52,000	150,000
2.1-m GoldCam	F3KC	15	1.4	8.5	91,000	80,000
WIYN Hydra	T2KC	24	1.7	4.3	110,500	190,000

Our CCD controllers all now contain 16-bit A/D converters, and so the maximum digitization limit is 65,634. We see from the table above that staying with the default gain assures both good sampling of the read-noise and the use of most of the linear range of the device, with the exception of CryoCam. There the default gain is kept small to significantly decrease the read-noise contribution.

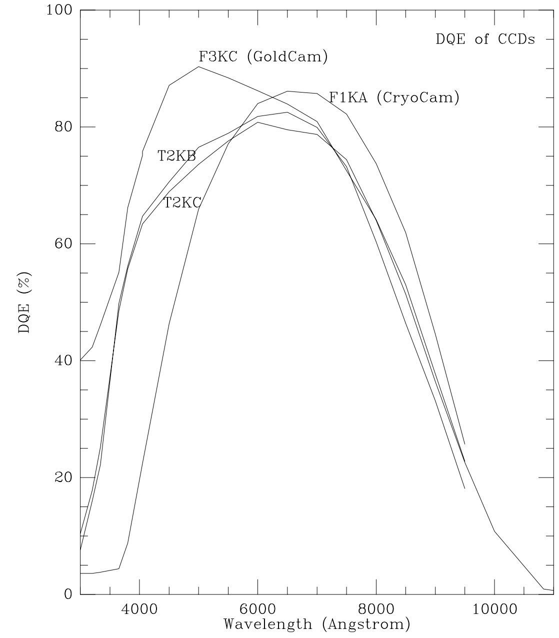

Figure 1: The relative DQEs of the four CCDs used for low-to-moderate resolution spectroscopy at Kitt Peak.

2.2 4-m RC Spectrograph

The 4-m Ritchey-Chretien Focus Spectrograph is the primary spectroscopic work-horse for optical spectroscopy at Kitt Peak. There are a dozen diffraction gratings available, which provide resolutions from 300 to 5000. It uses the "UV Fast Camera" to focus the spectrum onto a CCD detector. The CCD currently in use with the RC Spectrograph is a Tektronix 2048^2 detector with excellent cosmetics. The total system throughput (telescope + spectrograph + CCD) is 11-14% under typical seeing conditions with a nominal slit width (18% peak under excellent seeing conditions). The spectrograph is normally used in long-slit mode (slit length=$5.2'$) for either two-dimensional spectroscopy of extended sources or for spectroscopy of point sources with excellent sky subtraction. In this (normal) mode, a slit-viewing TV (field of view $2.5'$) provides the means for acquisition. However, the spectrograph can also be used with multi-slit masks. The instrument rotator at the 4-m allows remote control of the position angle of the slit on the sky, although such rotations need to be done with the telescope within 30° of zenith. Thus the spectrograph can be rotated to the parallactic angle (to keep all of the light down the slit), or, if you need to use a particular position angle, you can use the atmospheric dispersion corrector ("Risley prisms"); see Sec. 4.4.1.

The focus of the RC Spectrograph begins to degrade on the red side (large pixel numbers) past pixel 1500, with poor resolution and substantial vignetting past pixel 1700. A similar focus degradation occurs on the blue side between pixels 0 and 200.

A list of the available gratings with the resulting wavelength coverage, dispersion, and resolution, is given below. We give the wavelength coverage both for 1500 pixels, to which people doing demanding work may want to restrict themselves, and for 1700 pixels, which may be suitable for some qualitative applications. The laboratory measurements of the grating efficiences are shown in Figs. 2 and 3.

4-m RC Spectrograph Gratings

Name	l/mm	order	Blaze	Coverage(Å)		Dispersion	Resolution[a]
			(Å)	1500 pixels	1700 pixels	(Å/pixel)	(Å)
BL 250	158	1	4000	1 octave[b]		5.52	13.8
BL 400	158	1	7000	1 octave[b]		5.52	13.8
		2	3500	<4100[c]		2.76	6.9
KPC-10A	316	1	4000	4100	4700	2.75	6.9
BL 181	316	1	7500	4100	4700	2.78	7.0
		2	3750	<2000[c]		1.39	3.5
KPC-17B	527	1	5540	2500	2850	1.68	4.2
BL 420	600	1	7500	2300	2600	1.52	3.8
		2	3750	1150	1300	0.76	1.9
KPC-007	632	1	5200	2100	2350	1.39	3.5
KPC-22B	632	1	8500	2150	2450	1.44	3.6
		2	4250	1050	1200	0.72	1.8
BL 450	632	2	5500	1050	1200	0.70	1.8
		3	3666	690	780	0.46	1.2
KPC-18C	790	1	9500	1700	1900	1.14	2.9
		2	4750	850	970	0.57	1.4
KPC-24	860	1	10800	1600	1820	1.07	2.7
		2	5400	800	900	0.53	1.3
BL 380	1200	1	9000	1100	1250	0.74	1.9
		2	4500	550	630	0.37	0.9

Notes: (a) Based on 2.5 pixels FHWM corresponding to 300 μm slit (2 arcsec). Better resolution can be achieved with smaller slit widths. (b) Spectral coverage limited by overlapping orders. (c) Spectral coverage limited by grating efficiency and atmospheric cut-off.

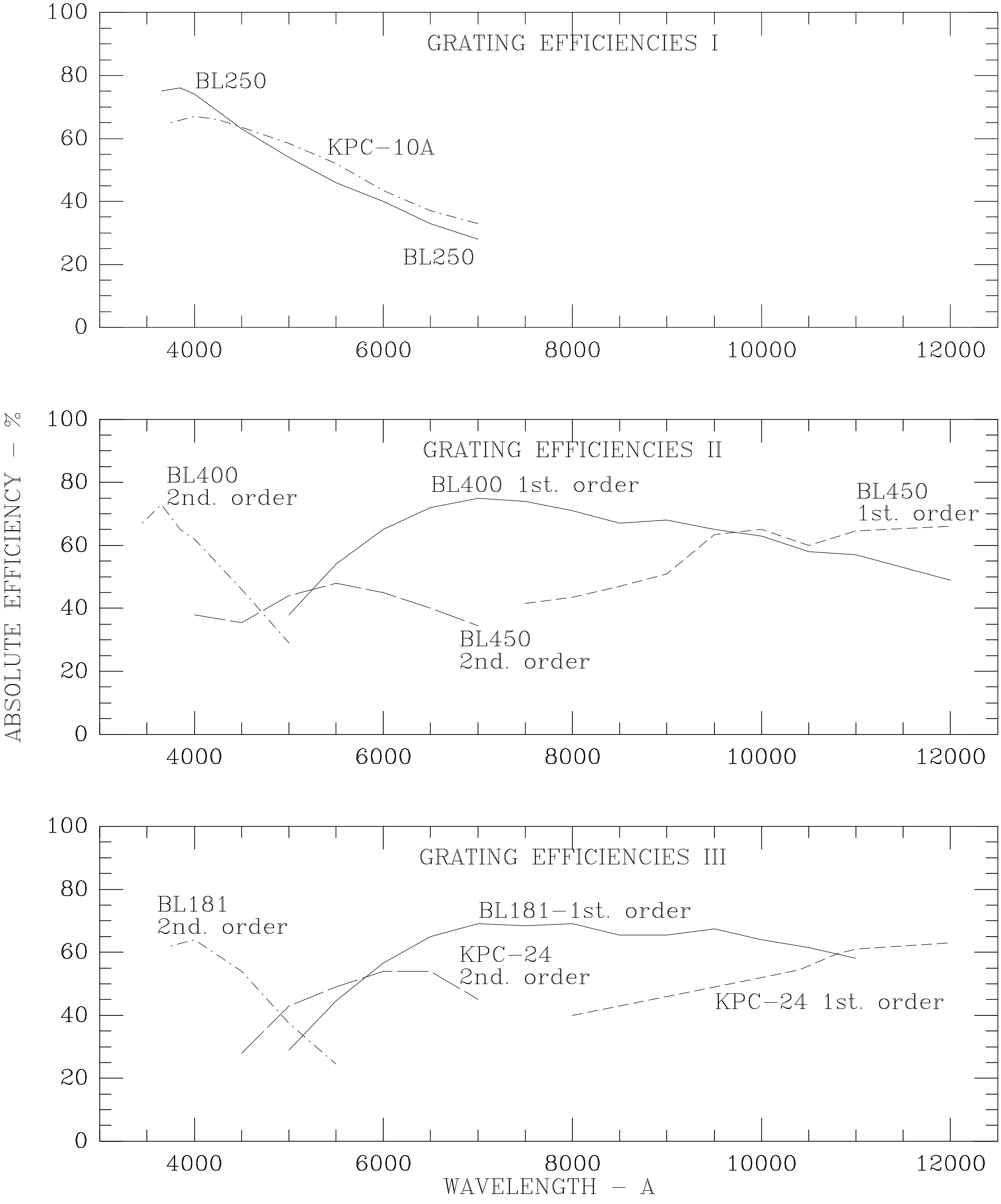

Figure 2: The efficiencies of the various RC gratings are shown here (continued on the next figure).

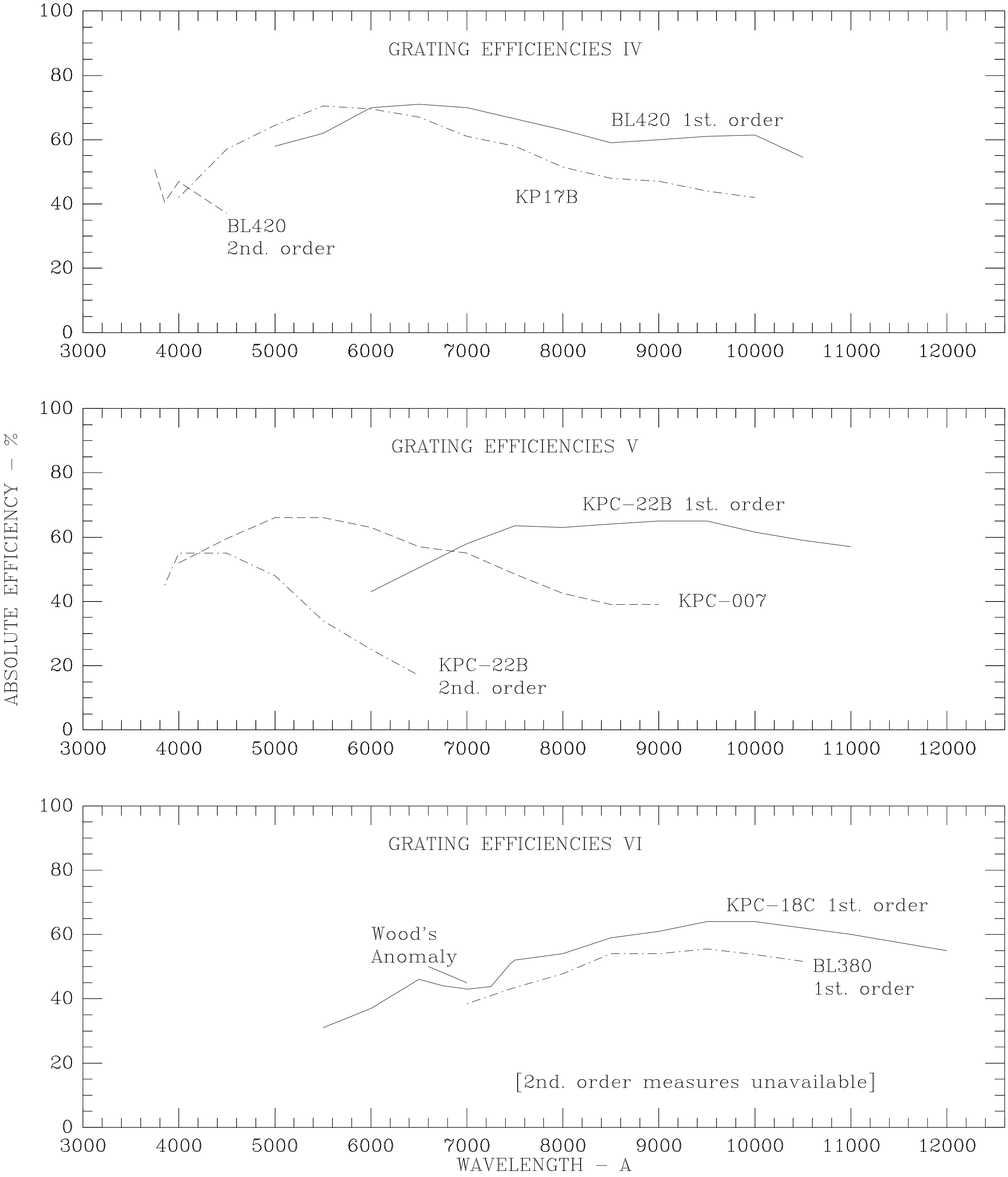

Figure 3: The efficiencies of the various RC gratings are shown here (continued from the previous figure).

2.3 4-m Cryogenic Camera

The "CryoCam" is a high-throughput analog of the RC Spectrograph. The instrument actually consists of the RC Spectrograph but with the grating replaced by any of 6 "grisms" as the dispersive elements and with the collimator mirror replaced by a collimating lens. The detector is a dedicated Loral (Ford) 800 × 1200 device with relatively good cosmetics sitting in a fast (f/1) camera-dewar combination. The result of these all-transmission optics is a total system throughput (telescope + spectrograph + CCD) that is typically 20% (29% peak under excellent seeing conditions). Glass optics curtail the throughput below 4000Å. CryoCam is often used with the multi-slit mechanism (see below); in this mode the acquisition is done by interrupting the light path with a pick-off mirror below the mask assembly. The entire 5′ field can be viewed with this camera when the masks are in their *out* position. Of course, during the actual exposure the TV pickoff mirror must be out of the beam and so one is observing "blind", but with the excellent guiding provided by the auto-guider this is, in practice, no problem. The instrument rotator at the 4-m allows remote control of the position angle of the slit on the sky, although such rotations need to be done with the telescope within 30° of zenith. Thus the spectrograph can be rotated to the parallactic angle (to keep all of the light down the slit), or, if you need to use a particular position angle, you can use the atmospheric dispersion corrector ("Risley prisms"); see Sec. 4.4.1.

The table below shows the six grisms, the resulting wavelength coverage, dispersion, and resolutions. A table of the various offset slits can be found in Sec. A.1.2.

4-m Cryogenic Camera Grisms

Name	l/mm	order	$\lambda_{central}$ (Å)	Coverage[a] (Å)	Dispersion (Å/pixel)	Resolution[b] (Å)	Blocking filter
Grism 810	150	1	6360	1 octave[c]	9.1	32	(see c)
Grism 770	300	1	5970	4300-8500	4.3	15	GG420
Grism 730	300	1	8010	5500-10000	4.3	15	OG530
Grism 650	400	1	4950	4000[d]-6800	3.2	12	—
Grism 780-1	300	1	9700	7100->10000	4.3	15	RG-610
Grism 780-1	300	2	4850	4000[d]-6100	2.2	8	BG-38 or 39
Grism 780-2	300	1	7100	4800-9500	4.3	15	GG-475

Notes: (a) The central wavelength changes by up to 7% depending upon location in the field (perpendicular to the slit). (b) Resolution is based upon a FWHM of 3.5 pixels, corresponding to a 2.5-3.0″ slit. (c) Grism 810 covers an entire octave; choice of wavelength coverage from 4300->10000Å is dictated by blocking filter (i.e., a BG-39 will provide <4000-6000Å coverage without overlapping; using an OG530 filter would allow coverage from approximately 5500Å to >10000Å. Note, however, that Grism 730 would be more appropriate in the latter case, providing the useful wavelength coverage but at higher spectral resolution. (d) Glass optics curtail the throughput below 4000Å.

2.3.1 Blocking Filters for the 4-m RCSpec and CryoCam

The RC and CryoCam spectrographs take 3.5-in square filters used for order separation (see Sec. B). The following table gives the available filters; transmission curves can be found in Fig. 4.

Blocking Filters for RCSpec & CryoCam

Long λ cut-off		Short λ cut-off			
Filter	Thickness	Filter	Thickness	Filter	Thickness
CuSO4[a]	8mm	WG-345	1mm	OG-515[b]	3mm
BG-38	2mm	WG-360	2mm	OG-530	3mm
BG-39	2mm	GG-375	1mm	OG-550[b]	3mm
4-96	5mm	GG-385	3mm	OG-570	3mm
KG-2	2mm	GG-400[b]	3mm	OG-590[b]	3mm
KG-3	2mm	GG-420	3mm	RG-610	3mm
		GG-455	3mm	RG-645	3mm
		GG-475	3mm	RG-695	3mm
		GG-495	3mm	RG-830	3mm

Notes: (a) $CuSO_4$ is too narrow for multi-slit work, but does cover the entire length of the slit. (b) New filter on-order; should be available in early 1997.

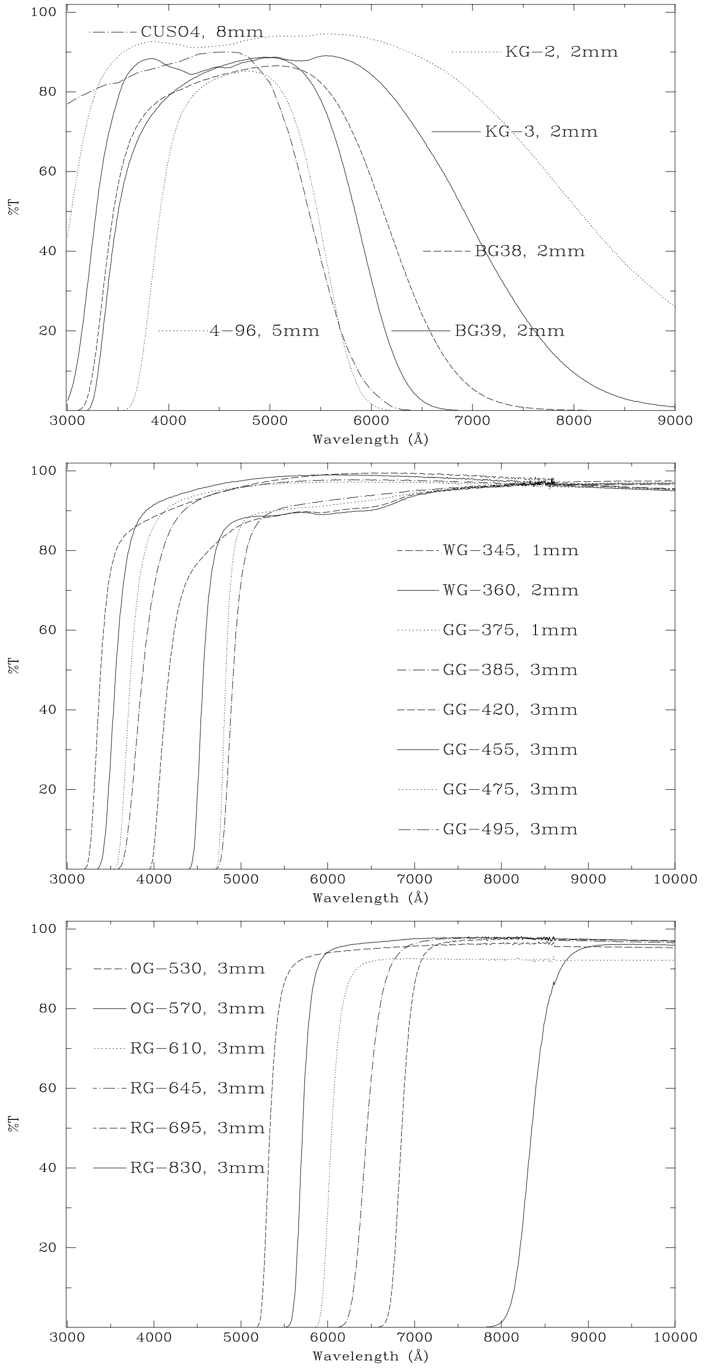

Figure 4: The transmission curves for the various RC and CryoCam blocking filters. You may examine these electronically at *http://www.noao.edu/kpno/filters/filters.html*

2.4 The 2.1-m GoldCam Spectrometer

The 2.1-m GoldCam spectrometer has proven to be one of the most popular spectroscopic instruments at Kitt Peak. While one cannot go as faint with it as one can with the 4-m on stellar sources, many programs simply need more observing time than can typically be accommodated during short 4-m runs. The total system throughput (telescope + spectrograph + CCD) is 15-18% under typical seeing conditions with a nominal slit width (24% peak throughput under excellent seeing conditions). GoldCam offers resolutions from 300 to 4500 using a variety of gratings. The detector in GoldCam is a Ford 3K x 1K CCD with 15μm pixels and fairly good cosmetics. The full $5.2'$ slit projects to $\approx$ 400 rows, and so only half of the chip is used. The camera design does not give good focus over the entire 3K length, although we find that the central 2000 pixels are in relatively good focus. A TV camera views the slit, and guiding is accomplished using a second TV which is moved around the xy axis outside of the instrument field of view.

It is possible to rotate the slit to specific position angles at the 2.1-m, but doing so requires moving the telescope to zenith and must be done manually by the telescope operator. Allow a minimum of 10 minutes of overhead for each rotation.

The following table lists the available gratings and wavelengths coverage.

2.1-m GoldCam Gratings

Name	l/mm	order	Blaze (Å)	Coverage(Å) 2000 pixels	Dispersion (Å/pixel)	Resolution[a] (Å)
201	150	1	5000	1 octave[b]	4.85	13.1
250	158	1	3800	1 octave[b]	4.60	12.4
400	158	1	6750	1 octave[b]	4.60	12.4
09	300	1	4000	<4940[c]	2.47	6.7
32	300	1	6750	<4940[c]	2.47	6.7
		2	3375	2480	1.23	3.3
58	400	1	8000	3800	1.90	5.1
		2	4000	1400	0.95	2.6
240	500	1	5500	3040	1.52	4.1
26old	600	1	4000	2480	1.24	3.3
26new	600	1	4900	2480	1.24	3.3
35	600	1	6750	2480	1.24	3.3
		2	3275	1240	0.62	1.7
56	600	1	11000	2480	1.24	3.3
		2	5500	1240	0.62	1.7
47	831	1	8000	1800	0.90	2.4
		2	4000	900	0.45	1.2

Notes: (a) Based on 2.7 pixels FHWM corresponding to 100 μm slit (1.3 arcsec). Resolution will degrade to 3 pixels at 150 μm slit (2 arcsec). (b) Spectral coverage limited by overlapping orders. (c) Spectral coverage limited by grating efficiency and atmospheric cut-off.

The grating efficiencies have been measured in the laboratory and are shown in Fig. 5

2.4.1 Blocking Filters for GoldCam

There are a variety of order-separation filters available for use in GoldCam. These filters are listed below and their transmission curves are shown in Fig. 6 and 7.

Blocking Filters for GoldCam

Long λ cut-off		Short λ cut-off			
Filter	Thickness	Filter	Thickness	Filter	Thickness
BG-1	1mm	WG-320	2mm	GG-455a	2mm
BG-38	1mm	GG-345	2mm	GG-475	2mm
BG-38	2mm	WG-375	2mm	GG-495	2mm
CuSO4	8mm	WG-1 (WG-360)	2mm	OG-530	3mm
KG-3	2mm	GG-385	2mm	OG-550	2mm
BG-1	1mm	3-75	2mm	OG-570	2mm
BG-39	2mm	GG-400	2mm	RG-610	1mm
4-96	4mm	GG-420	2mm	RG-610	2mm
		O-51	4mm	RG-695	2mm
		WG-420	3mm	RG-695	3mm
		GG-455	2mm		

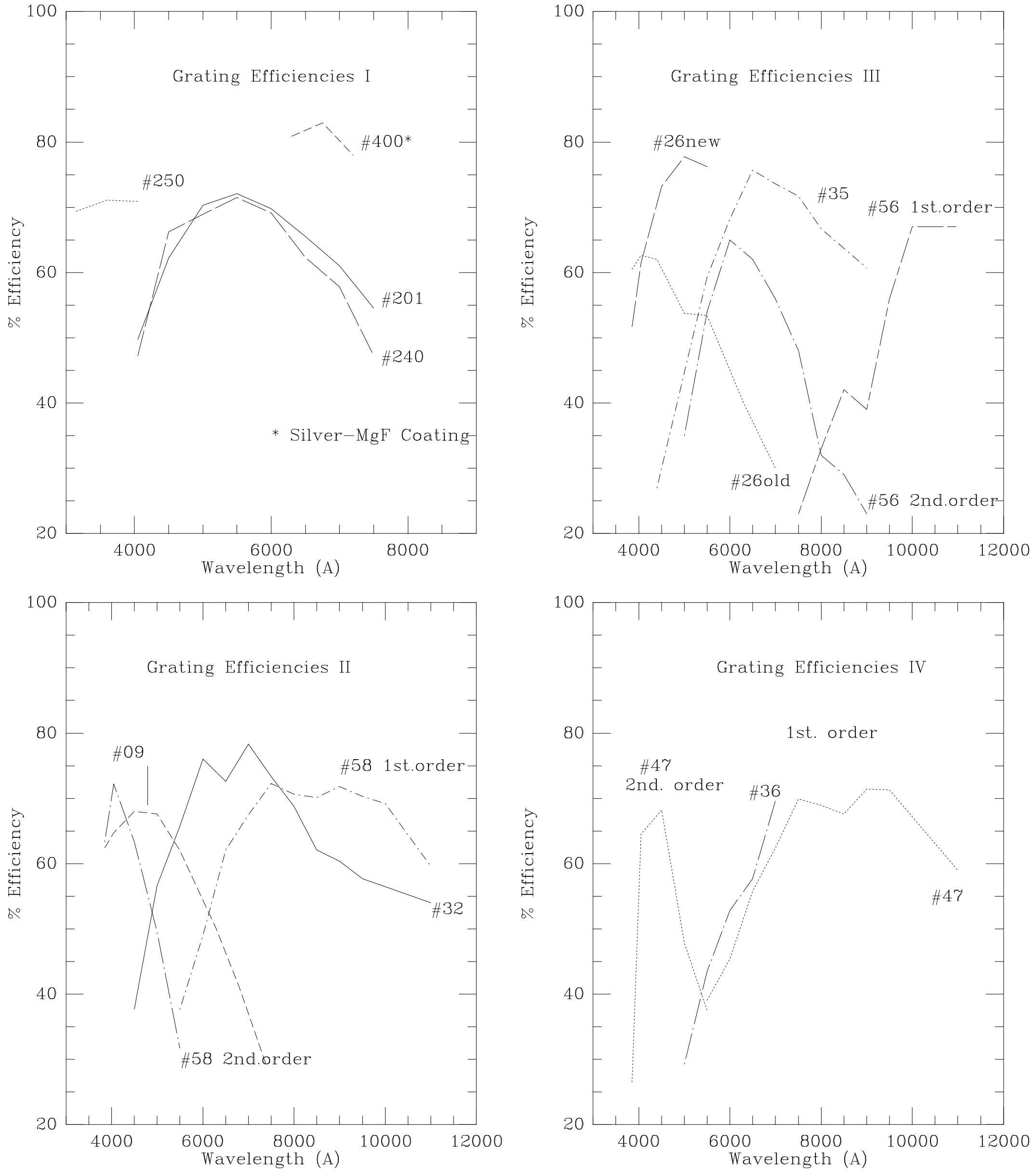

Figure 5: The efficiencies of the various GoldCam gratings are shown in this figure.

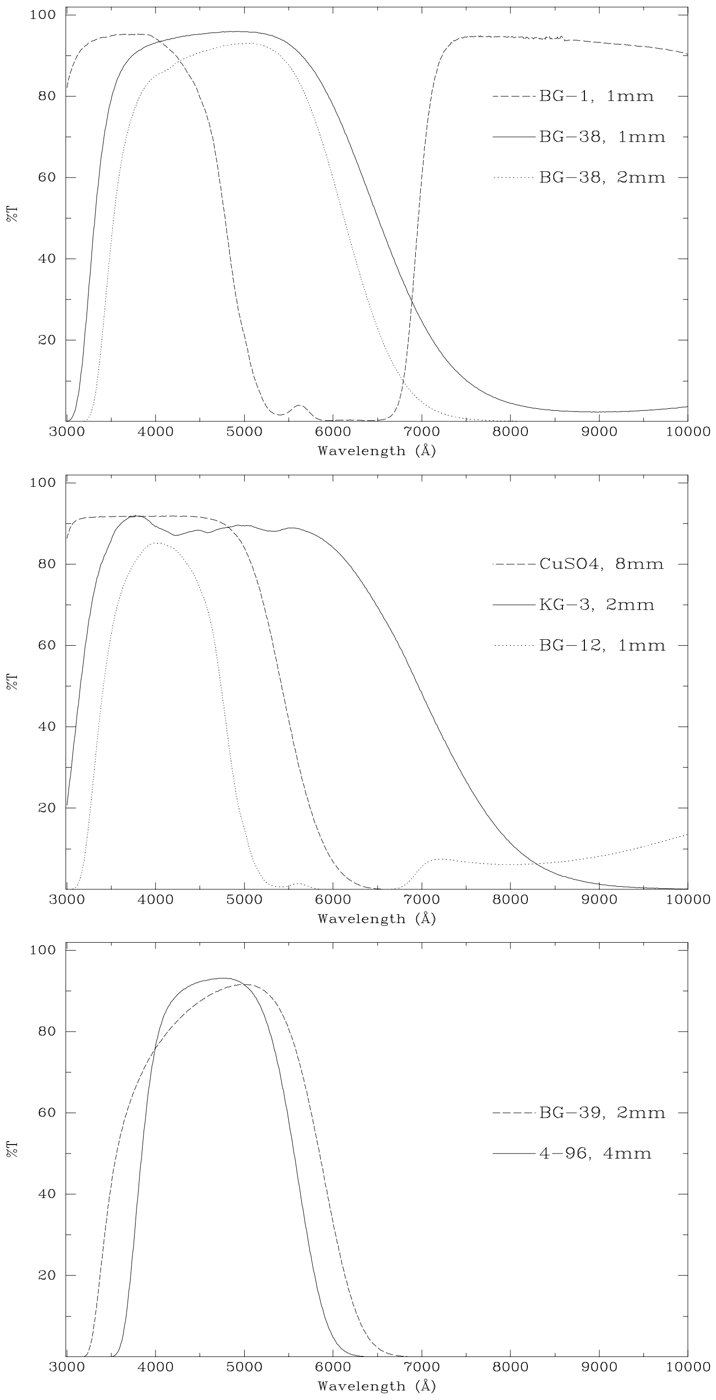

Figure 6: The transmission curves for the various GoldCam long-λ cut-off filters.

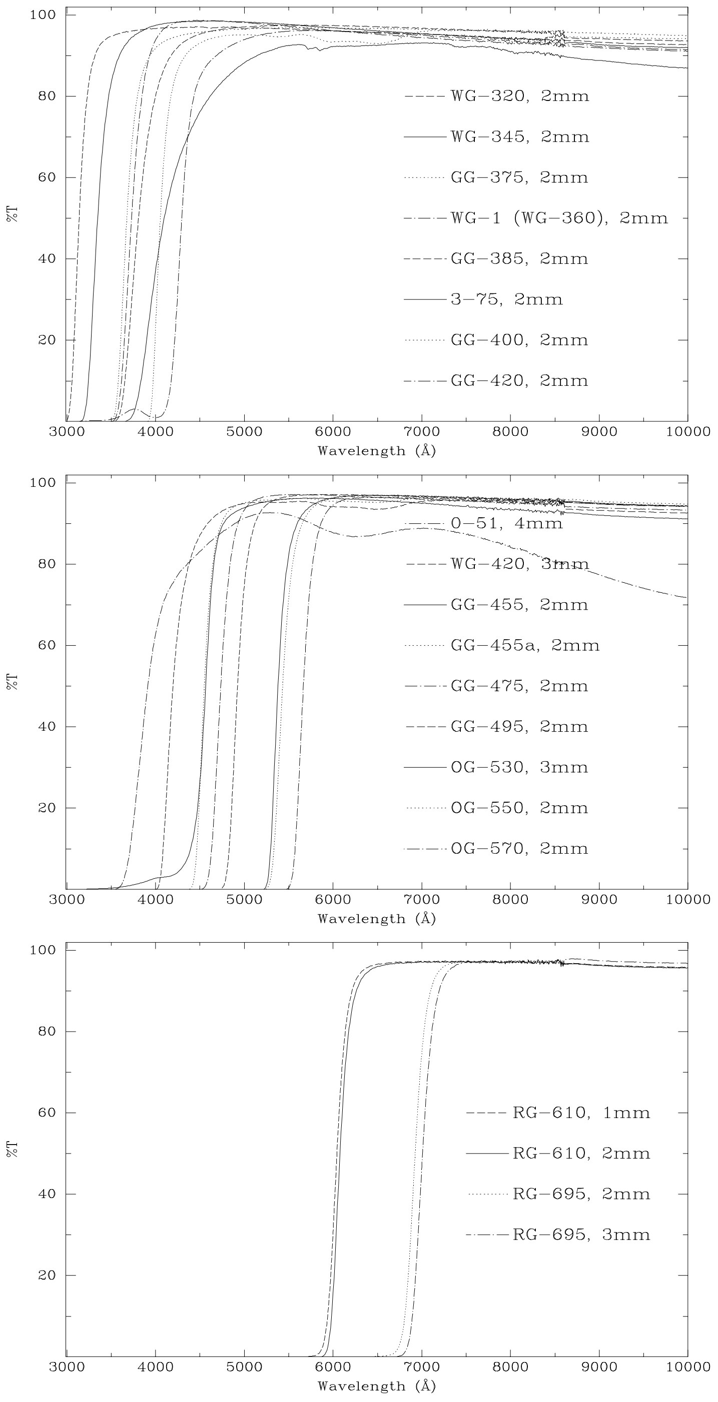

Figure 7: The transmission curves for the various GoldCam short-λ cut-off filters.

3 Estimating Exposure Times

3.1 Through-put Measurements and SNR

In order to provide an easy way of estimating exposure times, we provide in Fig. 8 the actual measured count rates (per Å, *not* per pixel) normalized to an $m_\nu = 10.0$ mag star. We show both the case where the slit is essentially wide-open ($8''$) and when the slit has a nominal size in modest seeing conditions. Although various gratings and grisms are shown, the basis for comparing different gratings should really be the grating efficiency plots in the previous section. But Fig. 8 should provide a good guide to what to expect at the telescope in terms of count rates near the grating blaze in medium and excellent seeing.

Thus, we might expect to obtain about 800 e/sec/Å at $m_\nu = $ 10th mag with the 4-m RCSpec under moderate seeing conditions. If the seeing were spectacular, it might be as much as 1000 or 1300, but let's not get too optimistic at proposal writing time—we're after a realistic number. Thus at 18th magnitude, we would expect to obtain $800 \times 10^{((10-18)/2.5)} = 0.5$ e/sec/Å. To obtain a SNR of 50 per 3Å resolution element would require 2500 e per 3Å, or 2500/1.5 ≈1700s, or about half an hour.

If you are working near the sky limit, you will have to contend not only with photon-noise from your object, but photon-noise from the sky. We assume that you can determine the sky level to infinite precision (a good enough assumption if your object is small compared to the slit length [not always true with multislits], and if you have done a good job in matching the slit-function as described in Sec. 4.1), but there will still be root-Nish fluctuations in the sky over your spectrum.

Let us imagine that we wish to observe a V=21 mag object at 5000Å with the RC Spectrograph on a good, moonless night, with $1.4''$ seeing. We are using a $2''$ slit.

We show the spectrum of the Kitt Peak dark sky in Fig. 9. At 5000Å the sky is about 22.8 mag/arcsec^2. The number of square arcseconds in this example is 4 arcsec^2, if we assume that we will extract the object spectrum using a 3 pixel extraction aperture (3 pixels = $2''$). Thus on top of our V=21 object we have a $22.8 - 2.5 \times \log 4.0 = 21.3$ mag source: the sky. We expect to obtain $1300 \times 10^{(10.0-21.3)/2.5)} = 0.039$ e/sec/Å from the sky, and, unfortunately, only $800 \times 10^{(10.0-21.0)/2.5} = 0.032$ e/sec/Å from the object. Note that we needed to use the "full throughput" number for the sky, while we must accept the "modest seeing" number for our object! To reach a SNR of 50 per 3Å resolution element, we have as "signal" $3 \times 0.032t$ from our object, but our noise sources are two-fold: the photon-noise from our object ($\sqrt{3 \times 0.032t}$) plus the photon-noise from the sky: ($\sqrt{3 \times 0.039t}$), where t is the integration time in seconds. We must add the two noise sources in quadature, and hence

$$SNR = 0.096t/\sqrt{(0.096 + 0.117)t} = 0.208\sqrt{t}$$

or 20800s (5.8 hrs), a little more than double the 2.6 hrs had there been no sky contribution.

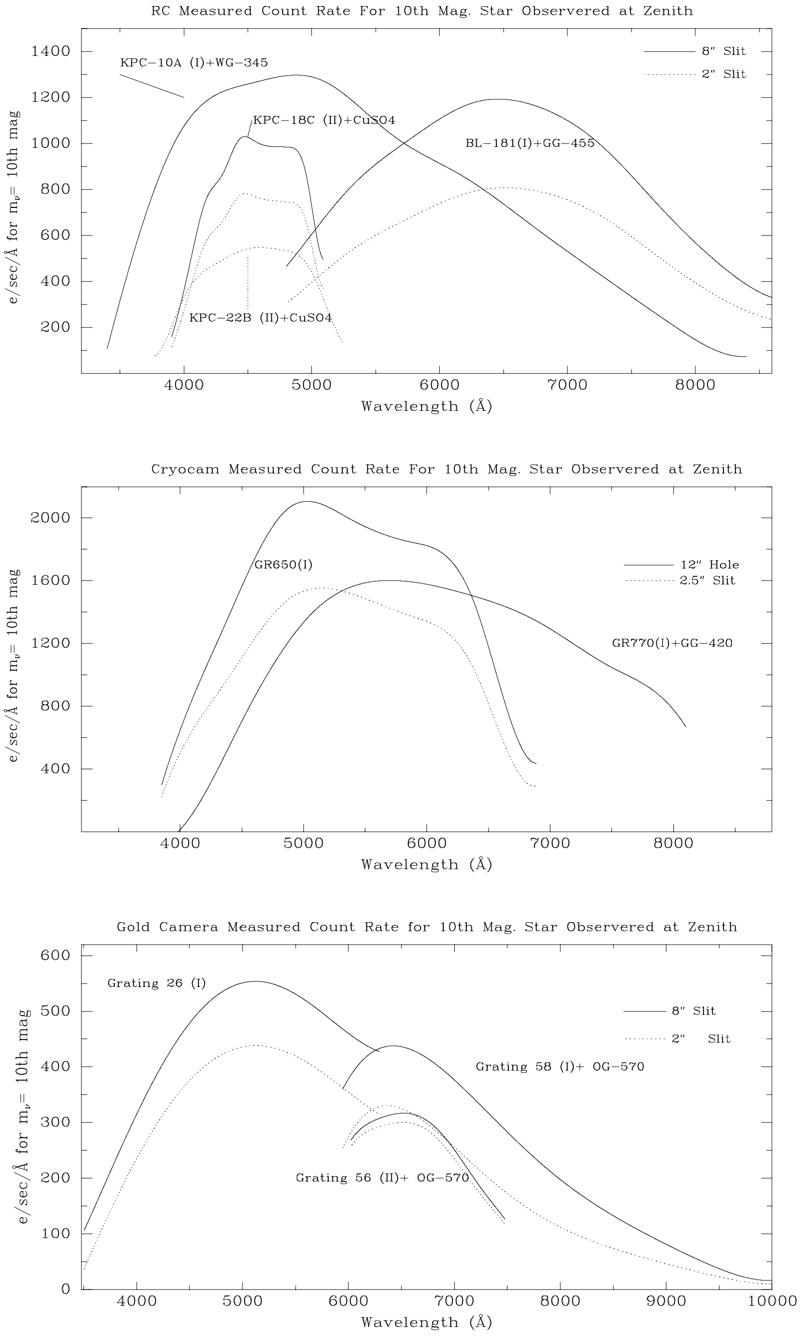

Figure 8: The measured count rates per Å for the RC Spectrograph (4-m), the CryoCam (4-m), and GoldCam (2.1-m), normalized to a 10th magnitude star observed near zenith.

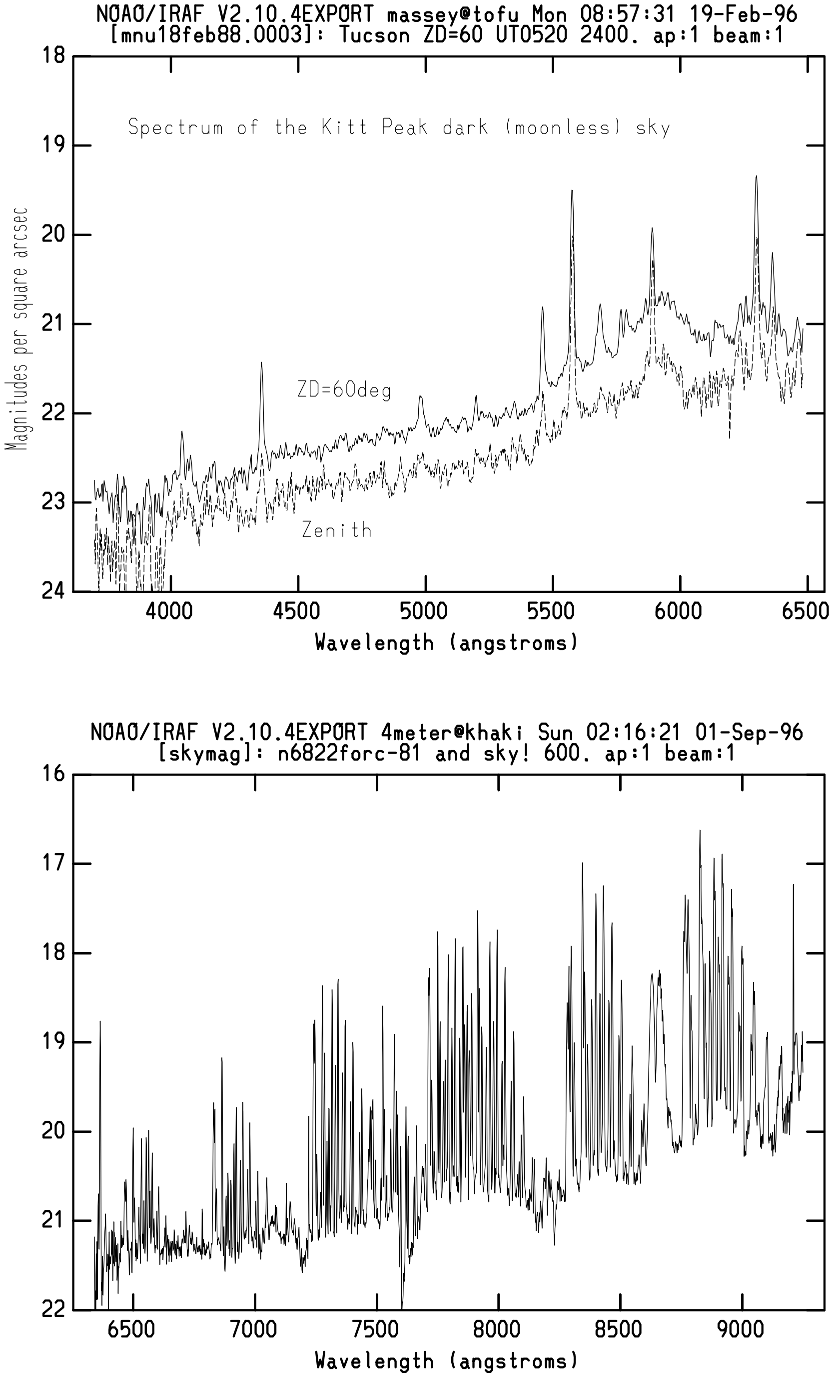

Figure 9: The spectrum of the moonless Kitt Peak sky. In the "optical" region ($\lambda\lambda 4000-6500$) the continuum rises from 23 mag/arcsec^2 to 21.5, with the major artifical source the NaD lines from street-lights (see Massey, Gronwall & Pilachowski 1990 PASP, 102, 1046). Further in the red, the sky spectrum is dominated by OH emission lines.

With some moonlight, the sky will be brighter in the blue; the following table gives a rough guide.

Sky Brightness (mag/arcsec^2)

lunar age (days)	U 3600Å	B 4300Å	V 5500Å	R 6500Å	I 8200Å
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

We have ignored a third source of noise in the above discussion, namely read-noise. The read-noise component will be $\sqrt{p} \times R$, where p is the number of pixels in a spectral resolution element and integrated over the spatial profile, and R is the read-noise. In the example above we would expect p to be roughly $2.5 \times 3 = 7$ pixels. With T2KB, the read-noise $R = 3$ e. The noise contribution from photon-noise of the object is $\sqrt{0.096 \times 20800} = 45$; the contribution from the photon-noise is $\sqrt{0.117 \times 20800} = 49$, while the read-noise contribution will be $\sqrt{7} \times 3 = 8$, and thus we were justified in ignoring it, even though in practice we'd probably break the 5.8 hr exposure down into 6 one-hour integrations, increasing the read-noise by $\sqrt{6}$. But in the case of low signal-to-noise, the read-noise may be important, particularly with the 15 e read-noise of CryoCam.

3.2 Summary

The following allows us to compute the exposure time we need as a function of signal-to-noise:

SNR=signal-to-noise ratio per spectral resolution element that you require.

t=integration time in seconds needed to achieve this SNR.

N_o is the number of e per second per spectral resolution element from your object; i.e., take something like the dashed lines in Fig. 8 and scale by the magnitude of your object ($10^{(10-mag)/2.5}$) and multiply by your spectral resolution in Å.

N_s is the number of e per second per spectral resolution element contributed by the sky. Use Fig. 9 and/or the table above to find the sky brightness in magnitudes per square arcsecond. Correct this by the number of square arcseconds by multiplying your slit width by the number of arcseconds in your extraction aperture. Determine your count rate from the solid lines in Fig. 8.

p is the number of pixels in a spectral resolution element integrated over the spatial profile.

R is the read-noise (in electrons, RMS), obtained from the table in Sec. 2.

Use when the sky contribution is negligible:

$$SNR = \sqrt{N_o \times t}$$

Use when the sky contribution is significant but read-noise is negligible:

$$SNR = \frac{N_o \times \sqrt{t}}{\sqrt{N_o + N_s}}$$

Use when the sky contribution and the read-noise are all significant.

$$SNR = \frac{N_o \times t}{\sqrt{N_o \times t + N_s \times t + p \times R^2}}$$

In practice, plan on splitting your exposures into separate integrations of 3600s or less to keep the cosmic-ray incidence finite.

4 Observing Strategies

4.1 Calibration

The amount and type of calibration data you require depends critically on what you are doing. We'll begin by briefly reviewing the type of calibration data that may be required, along with our recommendations.

- Bias frames. You may wish to take 10-15 of these at some convenient time when the dome is dark; they can be combined into a master bias frame by using *zerocombine*. In reality, none of these three chips have much bias structure (the hot columns cannot be effectively removed via biases), and so this is fairly pro forma.
- Dark frames. You may wish to take three frames of the same length of time as your longest exposure to evaluate how much dark current is contributing if you are attempting to do long-slit spectrophotometry without local sky subtraction. In practice, the dark current on all three of these chips is fairly minimal. Be sure to make these exposures with the dome dark.
- Wavelength calibration. All spectrographs have some minimal amount of flexure. If you are interested in radial velocities, then doing a new comparison exposure at each new position (and possibly bracketing) your exposures is a good idea. If you are satisfied with shifts of a pixel or two, then a single comparison exposure in the afternoon is good enough. There are a variety of comparison sources available at the 4-m, including a HeNeAr source and Th-A. The thorium-argon source should be used for higher dispersion applications. At the 2.1-m the only comparison source is a HeNeA source.
- Flat-field calibration. Flat-field calibration is needed to remove two instrumental effects:
  - Pixel-to-pixel sensitivity variations on the chip.
  - The "slit function" in the spatial direction.

  Any line-free source will do to remove the first of these: either exposures of the large white spots on the side of the dome, or exposures with the internal quartz lamps. It is a little trickier to deal with the slit function, although a line-free source is not needed (i.e., twilight skys will work in principle) and yet removing this large-scale structure is crucial for good sky subtraction. Here are your options:

  - Exposure with the internal quartz lamp (projector flat) but correct the slit illumination by a twilight exposure.

  - Use the white spot (dome flat).

  Either of these two methods will work, but you have the following logistical considerations:

  - It takes about 10-15 minutes to do dome flat exposures. If you are using a slit, and not changing anything (such as the slit width), doing dome flat exposures during the afternoon should work fine. You may still want to obtain some twilight exposures to test how well the dome flats work, but our experience from direct imaging suggests that these should work to <1% across the length of the slit. (Note that at the 2-m that very bright twilight exposures will actually not mimic the dark sky illumination very well, which we attribute to the considerable amount of scattered light within the dome during twilight.)
  - Projector flats can be run in a few minutes without moving the telescope, and so are fast and convenient. However, the large scale stucture does not match the night sky very well. In the case of multi-slit masks, though, you may be best off by obtaining projector flats but *not* using these to remove the slit function: instead, assume that the slit function is constant over the short lengths of a particular slitlet. This reduction procedure is explained in the "Multi-slits" manual (use *apflatten* rather than *apnormalize*.)

- Flux Calibration. Calibration to flux (and removal of atmospheric and instrumental wavelength effects) can be readily achieved by observing one or more spectrophotometric standards during the night. We recommend using the "Kitt Peak Spectrophotometric Standards". These are 25 mostly line-free stars calibrated at 50Å intervals from 3200Å to 8100Å (Massey et al. 1988 ApJ 328, 315); 11 of these have been calibrated out to 1μm (Massey et al. 1990, ApJ, 358, 344). Finding charts can be found in each of the domes, as well in the 1988 paper cited above. The spectrophotometric extinction for Kitt Peak is relatively well-known, and changes appear to be pretty gray. It is our experience that good results can be achieved by observing only a few standards, at airmasses comparable to your object using the same slit-width and observing technique used for your program objects. If you are using the Risley prisms at the 4-m to deal with atmospheric dispersion, you must also observe your standards through these prisms (even at zenith) in order to account for the wavelength-dependent transmission of the glass.

4.2 Focusing the Telescope

4.2.1 RC Spectrograph and GoldCam

The amount of light you actually get down the slit and onto the detector will depend not only on the seeing but also on how well the object is focused onto the slit. In the case of the RC Spectrograph and GoldCam, there is a natural tendency to focus the telescope using the slit-viewing TV as a guide. Our experience is that this is generally not adequate by itself. Instead, we strongly advise uers to take an actual focus exposure once per night, and determine the offset between the best image seen on the TV, and the results of the focus exposure. A sample procedure is:

- Focus the telescope using the slit-viewing TV.
- Move the star to one end of the slit.
- Run an ICE focus exposure specifying *shtype=telescope* and *focmode=manual* within **obspars** using the typical focus step size specified in the table below.
- Determine the smallest FWHM of the stellar profile using the "j" or "i" key within *imexamine*. (Use "j" to plot this if the dispersion axis is up and down; use "k" if the dispersion axis is left and right.)
- Compare the focus number that produced the skinniest image with the focus value of the best focus with the TV. Use this offset. If the offset is large (best focus on spectrograph slit results in poor looking images on TV), it may be worthwhile refocusing the TV camera to better match the spectrograph, if this has not previously been done. You should still determine a new offset.

Note: The focus of the TV cameras will be considerably different if the TV's internal neutral density (ND) filter is in place! You should make certain that the above procedure is carried out on a sufficiently faint star that the ND filter is not needed, or at least compare the spectrograph focus on a bright star to the TV focus on a nearby faint star. Refocus the telescope during the night only with the ND out.

4.2.2 CryoCam and the RC Spectrograph with Multi-slits

With the aperture plate mechanism in place (normal operating mode with CryoCam, and used when the RC Spectrograph is being used with multi-slit masks), focusing is slightly different as there is no slit-viewing TV. Instead, the following procedure should be used:

- At the beginning of the night, ask the LTO to run a knife-edge focus on a bright star. This involves placing an aperture plate containing a large hole in place, and inserting a negative lens into the post-slit viewer.

- Once a good knife-edge focus has been established, run a focus sequence with your first slitlet mask or aperture slit to determine any offset between the two.
- Refocus once or twice a night using the knife-edge method, but then applying the offset you've determined.

Our experience is that the offset between the knife-edge focus, and the actual focus on the slitlet mask, may be significant.

Typical Focus Values and Step Sizes

Telescope	Focus	Step Size
4-m RC Spec slit	10750	50
4-m RC Spec slit w/ Risleys	12300	50
4-m CryoCam	11400	50
4-m CryoCam w/ Risleys	13000	50
2-1-m GoldCam	????	30

Note: The 4-m RC with the multi-slit mechanism will be the same as the 4-m CryoCam values listed above.

4.3 How Wide You Can Really Open the Slit: Anamorphic Demagnification

Most of us are aware that the demagnification of a spectrograph (conversion from mm at the focal plane to mm at the detector) is dependent upon the relative f ratios of the camera and collimator. However, when there are significant collimator-to-camera angles there can be additional demagnification in the spectral direction due to the tilt of the grating. (This is nicely reviewed by François Schweizer in 1979 PASP **91**, 149). The effect of this works in the astronomer's favor; at large grating tilts the slit can be opened wider (letting in more light) without degrading the resolution. Of course, at very high inclinations a point is reached where the grating becomes overfilled and the light above or below the grating is lost. A little consideration of the geometry involved will suggest that for a given wavelength, the higher the dispersion the more tilted the grating has to be.

The "anamorphic demagnification" r can be computed from:

$$r = \frac{\cos(t + \theta/2)}{cos(t - \theta/2)}$$

where t is the grating angle (relative to zero order) and θ is the camera-collimator angle. For the RC Spectrograph, $\theta = 46°$; for GoldCam, $\theta = 55°$.

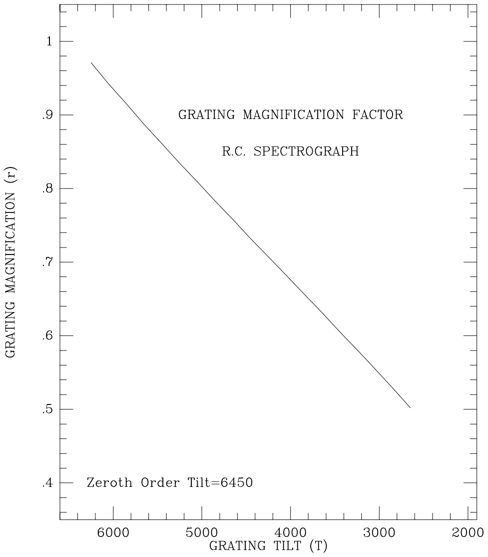

Figure 10: The anamorphic demagnification as a function of grating tilt (in encoder units) for the RC Spectrograph. To obtain the encoder setting corresponding to a particular wavelength and grating, see the table in the Appendix.

We give in Fig. 10 and 11 the anamorphic demagnification as a function of grating tilt. For the RC Spectrograph, we use "encoder units" to measure the grating tilt (zero-order occurs at 6450 and there are 100 encoder units per degree); for GoldCam the units are in degrees with zeroth order being at 25.93°. In practice, simply look up the encoder setting using the tables in the Appendix of this manual (Sec. A.1) and then use Figs. 10-11 to see what additional fraction you can open the slit without degrading the resolution.

Remember that CryoCam, being a straight-through system, has *no* anamorphic magnification.

4.4 Differential Refraction

Alexei Filippenko deserves credit for having reminded us all of the significance of differential refraction in doing spectroscopy (1982 PASP 94, 715). Even at a modest 1.5 airmass, an image at 4000Å is displaced towards the zenith by 1.1$''$ relative to the image at 6000Å. If you are trying to observe over this wavelength range using a 2 arcsec slit, you will suffer large amount of light-loss unless the slit happens to be aligned at the *parallactic angle*, i.e., the position angle on the sky that results in the slit being perpendicular to the horizon. If you are trying to do spectrophotometry in which you care about the relative fluxes of your objects over a large wavelength range then you *must* deal with this in some fashion; even if you are not interested in actual color information, you may still be interested in most of

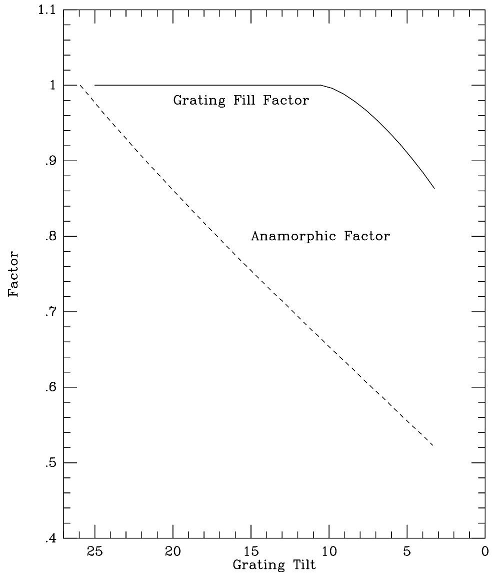

Figure 11: The anamorphic demagnification as a function of grating tilt for GoldCam; to obtain the tilt corresponding to a particular wavelength and grating, see the table in the Appendix.

the light actually going into the slit. What's an astronomer to do?

Your options are as follows:

- Always observe at low airmasses.
- Rotate the spectrograph so that the slit is near the parallactic angle. The telescope displays at both the 4-m and the 2.1-m will display the current parallactic angle; to anticipate this ahead of time, we use the following bit of FORTRAN code:

  ```
  top=sind(ha*15.)
  bot=tand(alat)*cosd(dec)-sind(dec)*cosd(ha*15.)
  pa=atan2d(top,bot)
  if(pa.lt.0.) pa=360+pa
  if(pa.gt.180.) pa=pa−180.
  ```

  where "alat" is the latitude of Kitt Peak (31.958°); dec is the object's declination (in degrees); and ha is the object's hour angle in hours. A graph giving the parallactic angle as a function of hour angle and declination for Kitt Peak (modeled after Fig. 1 in Filippenko 1982) can be found in Fig. 12.

  In practice, rotating the slit has to be performed near the zenith, and so there is some loss of time involved.

- At the 4-m there are atmospheric dispersion correctors available, as described in the following section.

4.4.1 Atmospheric Dispersion Correctors at the 4-m

The 4-m telescope is equipped with a pair of "Risley prisms", which provide excellent atmospheric dispersion compensation (ADC). The Risleys can be inserted into the beam with some light loss (5-8% > 4000Å), but they will then protect you against the losses due to differential refraction.

In Fig. 13 we show how well the Risleys do their atmospheric compensation. The boxes denote the fluxes for a spectrophotometric standard. We then show two observations of this star, both obtained at airmass of 1.8, and both obtained in the worst possible scenario of the slit being 90 degrees to the parallactic angle. We see that the observation obtained with the Risley prisms follows that of the known flux distribution of the star, while that obtained without the Risleys was down by a factor of 3 in the blue. We do note that if you are doing spectrophotometry with the Risleys, you must observe your standards with the Risleys as well, to properly calibrate the small but wavelength-dependent light-losses of the Risleys.

One other logistical consideration to keep in mind when using the Risley prisms is that finding a guide star will be a little bit harder. Because the telescope focus is quite a bit different when the Risleys are in use (+1550 microns!) any guide star must be within the realm of the Risleys in order to be in focus. In practice it seems to work to find a guide star within 125mm of field center. Remember that the vignetting limit is 75mm within field center, so there is a good annulus left.

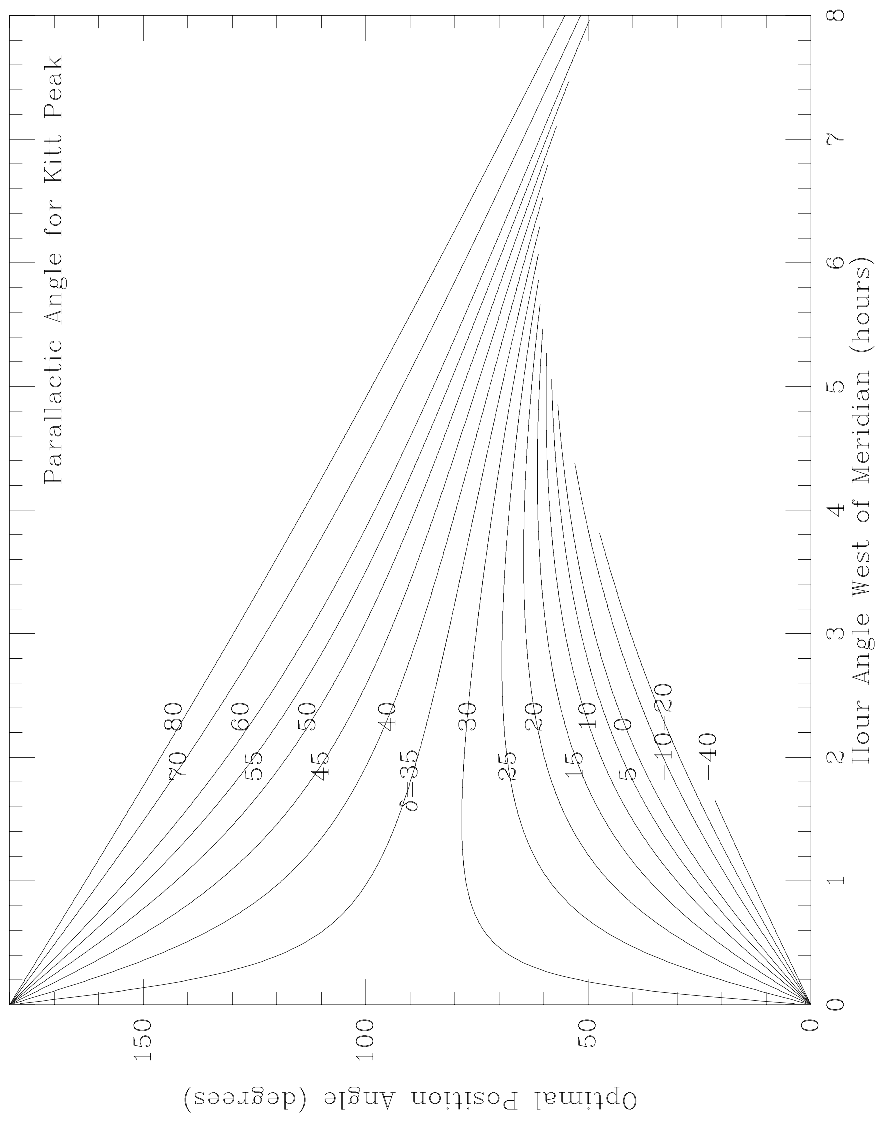

Figure 12: The parallactic angle as a function of hour angle WEST of the meridian for the latitude of Kitt Peak. For negative hour angles, use the complement of the angle indicated; i.e., an object at $\delta = 80$ and and hour angle of -5 hrs has a parallactic angle of 180-110=70 degrees. This figure is a slightly modified version of Figure 1 in Filippenko 1982 PASP 94, 715.

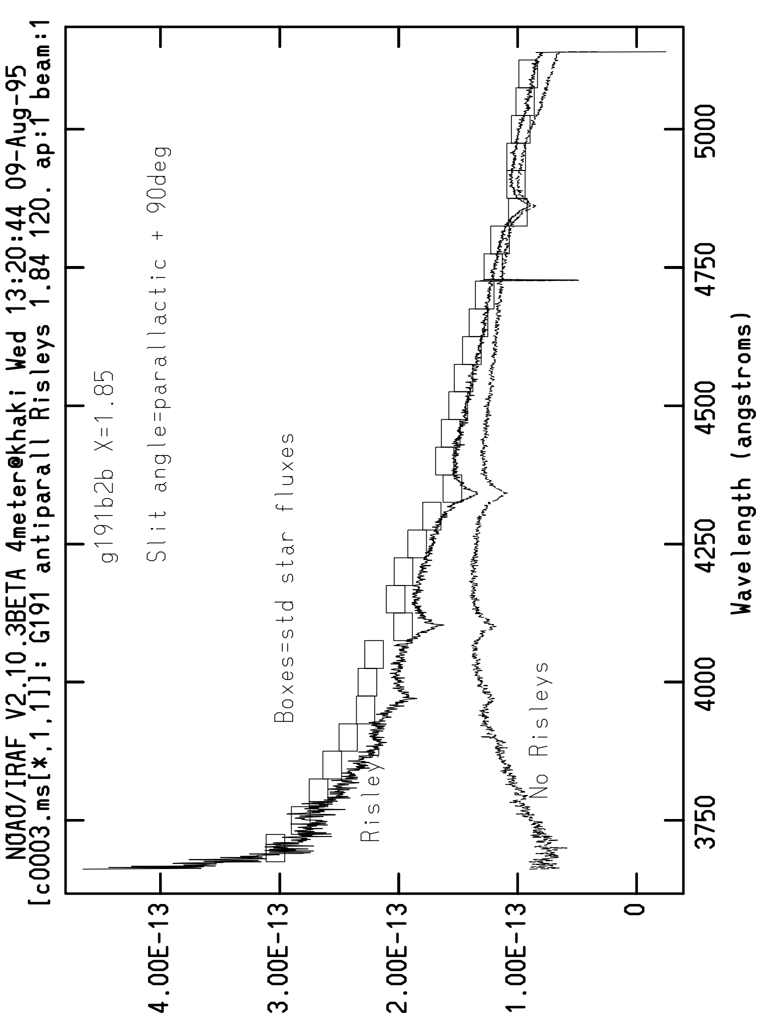

Figure 13: The boxes show the known standard star fluxes; the two spectra show the effects of observing at a high airmass with the slit oriented 90 degrees to the parallactic angle.

4.5 How to Observe with Multi-slits

- At the beginning of the run:
  - Determine the offset between the rotator angle read-out and the actual position angle (PA) on the sky by inserting the 1.0 arcsec wide long slit and running a star east and west along it. This offset may be as large as 1°.
- For each slit mask:
  - Go to the zenith.
  - Insert the new slit mask.
  - Rotate the spectrograph to the new PA + offset.
  - Go to the setup position.
  - Move the slitlet mask "in". Find the setup holes using the backlight of the sky, or, if needed, with the low dome lights turned on. (Remember to turn them off, though!) Mark them using the leaky cursor dots.
  - Move the slitlet mask out and identify the two setup stars. (The separation and angle will help identify which stars are the right ones.)
  - Center the two setup stars on the leaky cursor dots, and tweak the rotator angle if needed.
  - Put the slitlet mask "in" and center the telescope on the stars. Tweak the rotator angle if necessary.
  - Move to the object field:
    - Method 1: If you have a CHECK STAR in your program field, then: Simply zero the telescope coordinates at the setup position, and move to the coordinates of the program field. Initiate guiding, and center up using the check star.
    - Method 2. If you have NO CHECK STAR in your program field, then: Initiate guiding at the setup field and center up carefully. Move to the object field by offsetting the amounts specified on the output of the multi-slit program. Of the two, Method 1 is **STRONGLY** recommended.
  - Move the rear slit viewer out.
  - Begin the exposure.
  - After each exposure on the field, consider repeating the tweaking up.

A Setting Up and Focusing the Spectrographs

Your instrument support person will do all the set-up of the spectrograph on the first afternoon of your run; if you've requested a grating change during your run in advance (when you fill out your Observing Run Preparation form, aka "the pink sheet") someone will do the physical change for you, and help you do the final tweaking. **The items described in this section should be carried out by trained Observing Support personnel to assure safety to our equipment.** We simply summarize in this section the steps that are needed so that you will be up to speed when these steps are performed on the first afternoon.

There are basically three adjustments that need to be made when changing gratings:

1. Tilt the grating (RC Spectrograph, GoldCam) to the desired central wavelength. (CryoCam has no such adjustment, although it is possible to vary the central wavelength slightly by selecting an offset slit.)
2. Focus the spectrograph (compensates for different thickness blocking filters, and small wavelength-dependent focus variations).
3. Align the spectrum on the detector (compensates for the fact that not all the gratings/grisms are perfectly square in the their cells).

A.1 Specifying the Grating Tilt

A.1.1 RC Spectrograph

For the RC Spectrograph, the user can specify the central wavelength desired directly in Angstroms using the 4-m Telescope Control System (TCS) Graphical User Interface (GUI). The user must specify the grating name, the order, and the desired central wavelenth.

We give in the table below the *encoder* units corresponding to a particular wavelength setting. This table may be useful for simply substantiating the setup, and in determining the anamorphic demagnification, as explained in Sec. 4.3.

A.1.2 CryoCam

The wavelength in the center of the chip is determined by the choice of grism. However, there are a number of slit inserts that one can choose that will in fact change the central wavelength by ±12% of the wavelength coverage. The table below shows what offset slit aperture plates are available, and what these shifts would be with the 300 l/mm grisms. Other grisms will scale proportionally.

TABLE

Grating Tilts RC Spectrograph

λ(Å)	BL250	BL400	KPC-10A	BL181	KPC-17B	BL420	KPC-007	KPC-22B	BL450	KPC-18C	KPC-24	BL380
3500	6281	6106(II)	6104	5758(II)		5124(II)	5762	5053(II)	4306(III)		3572(III)	3737(II)
4000	6256	6056(II)	6055	5660(II)	5794	4934(II)	5664	4850(II)	4000(III)	4479(II)	3151(III)	3292(II)
4500	6232	6007(II)	6005	5561(II)	5712	4745(II)	5565	4649(II)	3693(III)	4219(II)	3993(II)	2847(II)
5000	6208	5958(II)	5956		5630	4555(II)	5467		4408(II)	3959(II)	3712(II)	2401(II)
5500	6183	6179		5907	5548	5408	5369	5357	4204(II)	3700(II)	3432(II)	4404
6000		6155		5857	5466	5313	5271	5256	4000(II)	3439(II)	3151(II)	4182
6500		6130		5808	5384	5218	5173	5164	3795(II)	3179(II)	2871(II)	3959
7000		6106		5758	5302	5123		5053	3191(II)	4739	4554	3737
7500		6081		5709		5029		4951	3387(II)	4609	4413	3514
8000		6056		5660		4934		4850	4816	4479	4273	3292
8500						4839		4748	4816	4349	4133	3070
9000						4745		4646	4615	4219	3993	2848

CryoCam Offset Slits

Offset		Shift for 300 l/mm	Slit widths available
15.0mm	blue	−520Å	1.4″ , 1.7″ , 2.5″ , 3.2″ , 10.2 ″ , 10.8″ , 11.1″ , 21.0″
7.5mm	blue	−260Å	1.7″ , 2.5″ , 3.2″
0.0mm	—	0Å	1.0″ , 1.7″ , 2.5″ , 3.2″ , 3.7″
7.5mm	red	+260Å	1.7″ , 2.5″ , 3.2″
11.0mm	red	+380Å	2.5″ , 3.2″
15.0mm	red	+520Å	1.7″ , 2.5″ , 3.2″
22.6mm	red	+700Å	2.5″

A.1.3 GoldCam

The grating tilt of the GoldCam spectrometer must be set by hand; care must be taken not to overtighten the tilt clamp and observers are cautioned to call for help if an adjustment is needed.

The table below shows the encoder setting for a particular wavelength. (The grating tilt of the zeroth order is 25.93.) In reading the dial setting for the grating tilt, it is the number that is covered by the pointer that gives the integral number of degrees.

2.1-m GoldCam Grating Tilts

λ_c (Å)	Tilt (degrees)									
	201/250/400	09	32	58	240	26old/new	35	56	47	36
3000		23.81	21.69(II)	20.33(II)		21.69	17.44(II)	13.20 (III)	13.37(II)	6.83(II)
3500		23.45	20.99(II)	19.39(II)		20.97	16.02(II)	11.08 (III)	11.28(II)	3.64(II)
4000	24.51	23.10	20.28(II)	18.45(II)	21.22	20.26	14.61(II)	8.96(III)	9.19(II)	
4500	24.34	22.75	19.57(II)	17.51(II)	20.63	19.55	13.20(II)	6.84(III)	7.09(II)	
5000	24.16	22.40	18.87(II)	16.56(II)	20.04	18.85	11.78(II)	11.78(II) 5.00(II)		
5500	23.99	22.05	22.05	20.80	19.45	18.14	18.14	10.37 (II)	14.42	8.42
6000	23.81	21.69	21.69	20.33	18.87	17.44	17.44	8.96(II)	13.37	6.83
6500	23.63		21.34	19.86	18.28		16.73	7.55(II)	12.33	5.23
7000	23.45		20.99	19.39			16.02	6.14(II)	11.28	3.64
7500	23.27		20.63	19.92			15.32	4.72(II)	10.23	
8000	23.09		20.28	18.45			14.61	14.61	9.19	
8500			19.93	17.98			13.90	13.90	8.15	

A.2 Focusing the Spectrograph

In principle, one would really like to set the spectrograph collimator to a particular distance from the slit (the distance at which parallel light is formed) and focus the spectrographs by moving the camera lens. For the RC Spectrograph, the standard procedure is for the instrument specialist to focus the UV fast camera to obtain the best image of the slit, and then for the collimator to be adjusted slightly as blocking filters are inserted into or out of the beam. No external adjustment of the camera in GoldCam is possible, but fine laboratory adjustments have been made in the location of the CCD in the GoldCam camera/dewar combination so that the spectrograph collimator gives optimum images.

Similarly, the distance from the camera optics to the chip is fixed in the CryoCam, and focusing is done by moving the collimator lens.

The nominal autocollimate positions are given in the table below, along with reasonable focus steps sizes.

Autocollimate Positions

Spect.	Autocollimate	Focus Step
RCSpec w/ normal slit	480	20
RCSpec w/ multi-slits	290	20
CryoCam	8300	200
GoldCam	500	20

A.3 Aligning the Spectrum on the Chip

The final step involves adjusting the detector so that a comparison line will fall along a row or a column to a few tenths of a pixel. In IRAF the subtraction of the sky spectrum is assumed to be along a row or column, and *not* perpendicular to the object trace. (The object trace basically defines the practical "dispersion" direction, which may not be simply othogonal to the slit due to differential refraction, or if the grating is slightly misaligned in its cell.)

B Overlapping Orders

We all remember from our college optics classes that at a given angle θ from a diffraction grating one will see wavelengths λ corresponding to the extra path distance:

$$d \sin\theta = m\lambda$$

where d is the spacing between groves on the grating and m is the order. Thus at a given angle from the grating you might see light corresponding to 4000Å ($m = 1$), 8000Å ($m = 2$), 12000Å ($m = 3$), and so on. You can count on the atmosphere cutting off any light bluewards of 3200Å, and in the CCD having no sensitivity beyond 12000Å. But, if you are planning to observe from 4000 Å to 5000Å in second order, you need to worry about overlapping first order (8000-10000 Å) and possibly even overlapping third order (2700Å to 3333Å, so in practice just 3200-3333 Å, say); the latter could be a problem if your objects or standards have appreciable blue flux.

Looking at the order-blocking filters in Fig. 4 we find that either a 4-96, BG-38 or BG-39 would do a good job both at blocking longer wavelength light (overlapping first order) and even squashing the possible overlapping first-order UV light in this example.

For convenience we show the effect of overlapping orders in Fig. 14.

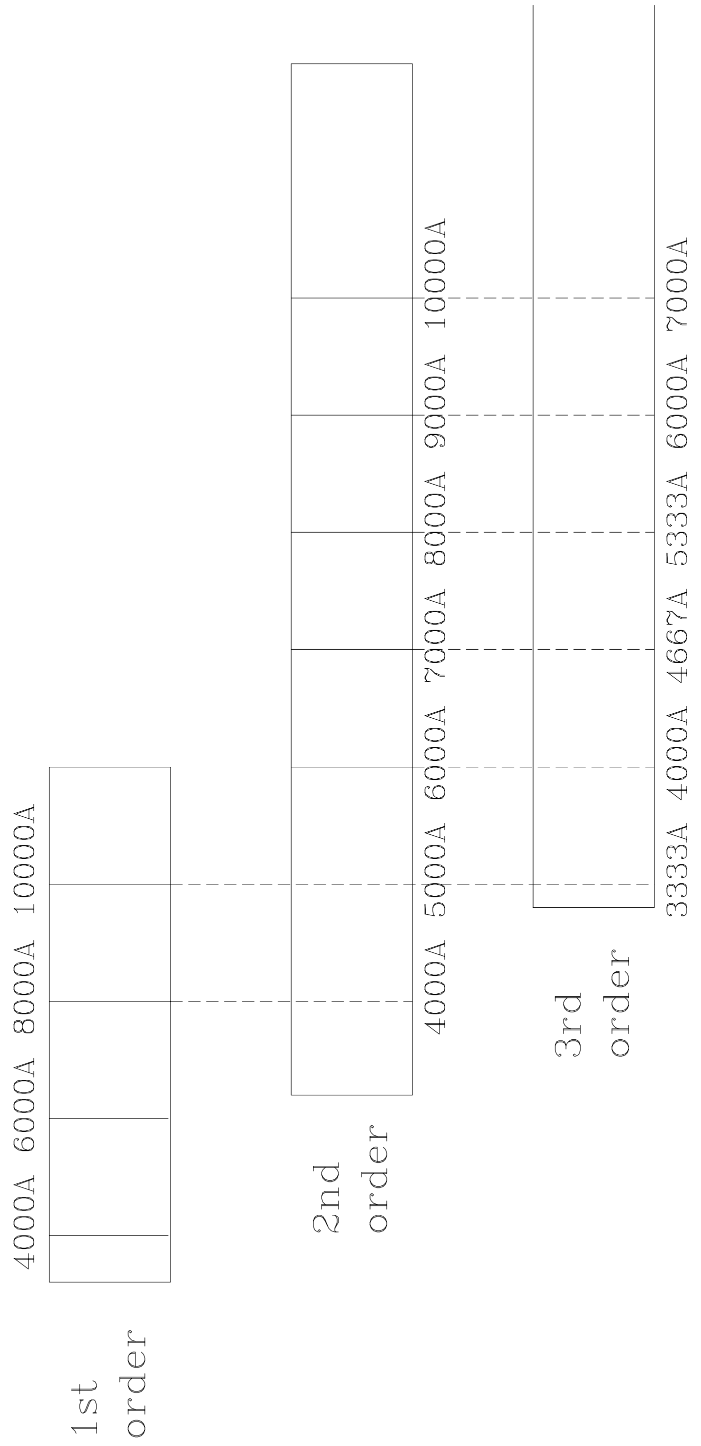

Figure 14: The effects of overlapping orders. The atmosphere cuts off orders on the blue side at approximately 3200Å, while the CCD is effectively dead at 12000A.

C Coming Prepared: Measuring Coordinates

The all-sky pointing accuracy of the 4m and 2.1m telescopes are typically 10" (RMS), with offsetting capabilities of <0.3" over 10'. Thus, you will save a tremendous amount of time if you come prepared with accurate coordinates.

Doing astrometry used to be an arcane art, but modern tools make this assessible even to the likes of us, thanks in large part to the incredible investment made by the folks at the Space Telescope Science Institute. We refer you to their instructions found on the Web at
http://www-gsss.stsci.edu/support/phase2.html
for complete instructions.

D Vignetting Alert at the 4-m!

When using the south guide probe at the 4-m, it is necessary to keep the probe further than $-70 < x < +70$ and $-50 < y < 0$ or the probe will vignette the RC Spec slit. When using slitlet masks, the probe must be kept further than $-70 < x < +70$ and $-70 < y < 0$. Recall that when using the Risley prisms, the probe must be closer than 125mm or focusing the probe will be impossible.