HIRES USER'S MANUAL

KECK
TELESCOPE
HIRES
UCO/LICK
OBSERVATORY

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IMPORTANT NOTE:

This document is currently under revision by Grant M. Hill.

A highlighted note similar in appearance to this one will be placed in the text to indicate how far the revision hasproceeded.

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Chapter 1 Introduction

HIRES was conceived in early 1987 in response to a call for instrument proposals for ?rst-light of the Keck Ten-Meter Telescope. It went through three rounds of proposals before being selected as one of the initial complement of Keck ?rst-light instruments. It took about 5 years to build, at a total cost of about $4.0 million. It was designed and built in the technical laboratories of the UCO/Lick Observatory, at the University of California at Santa Cruz.

The name HIRES stands for High Resolution Echelle Spectrometer. HIRES was designed to take advantage of the Keck telescope's large collecting area to push high resolution optical spectroscopy out to about V=20.0 at typical spectral resolutions of 30,000 to 80,000. A discussion of the various key science drivers which weighed heavily in the design of HIRES can be found in the HIRES Phase C proposal (Vogt, 1988) and will not be discussed here. A preliminary overview of the 'as-built' instrument was published by Vogt, 1992.

HIRES is a fairly standard configuration in-plane echelle spectrograph with grating cross-dispersion. It resides permanently at the 'right' nasmyth focus of the Keck telescope. HIRES is designed primarily to go quite faint (by traditional high resolution spectroscopy standards) on single objects, and to give a relatively large 'throughput' or slit width times resolution product., without the need, in general, to image slice at the entrance slit. The nominal 'throughput' of HIRES is about 39,000 arcsecs, which means that a 1 arcsec entrance slit yields a resolution of about 39,000. It achieves this relatively large throughput, in spite of the very large diameter of the telescope primary, by a combination of a large (12" diameter) collimated beam, a large (48" long) echelle grating (mosaic), and very fast (f/1.0) exquisitely achromatic camera. The optics and image quality are optimized for use over the entire 0.30 to 1.0 micron spectral region (without refocus), and could readily be extended to 2.0 microns by replacing the optical CCD with an IR array detector. A generous amount of room has intentionally been left between echelle orders to allow for adequate sky sampling, a factor which can become quite important in bright or grey time when pushing to faint limits. This interorder room could also be used for image slices, though image slicers have not been provided as of this writing.

Chapter 2 Instrument Description

The HIRES instrument sits permanently on the right nasmyth platform of the Keck I telescope. It is enclosed in a thermally insulated, light-tight, dust-tight room which is kept under 'clean-room' conditions. A word of warning is necessary here. Access is restricted solely to authorized Keck personnel. All personnel entering the HIRES enclosure are required to don appropriate clean-room garb (full suit, booties, cap, and mask). It should never be necessary for astronomers or other users of HIRES to enter the enclosure. Indeed, entry by unauthorized or untrained personnel is likely to result in damage to the HIRES optical components, and also to the person entering (there are powerful remotely-controlled mechanisms which can move without warning).

HIRES is designed to be run remotely, either from the control room at the telescope, from Waimea, and also from just about anywhere in the world over the Internet. It can also be run from multiple locations simultaneously (such as shared observing by a collaborating group).

Revision complete to here. GHill 2006/04/30.

Section 1 Summary of Characteristics

Before discussing the principal components of HIRES, it seems useful to briefly list a summary of HIRES characteristics and capabilities.

1. Spectral range: 0.30 to 1.1 microns
2. Spectral resolution: up to 84,000
3. Slit length: up to 28 arcsecs. Defined by a selection of deckers.
4. Typical spectral span per exposure: 1200 to 2500 A
5. Order separation: 8 to 43 arcsecs
6. Resolving power times slit width: 39,000 arcsecs
7. Detector: Tektronix 2048x2048 CCD (24–micron pixels)
8. CCD readout noise: 5–6 electrons (rms)
9. CCD dark current: <10 e/pixel/hour
10. '2–pixel' projected slit: 0.60 arcsecs
11. Image de-rotation: none
12. Atmospheric dispersion compensation: none
13. Acquisition and guiding: fixed Photometrics CCD-TV staring at a 45 arcsec by 60 arcsec field centered on the entrance aperture.
14. Calibration sources: quartz/halogen, Deuterium lamp, Th-Ar hollow cathode, Iodine absorption cell, Edser-Butler FP, diode laser.

Section 2 Description of the Light Path

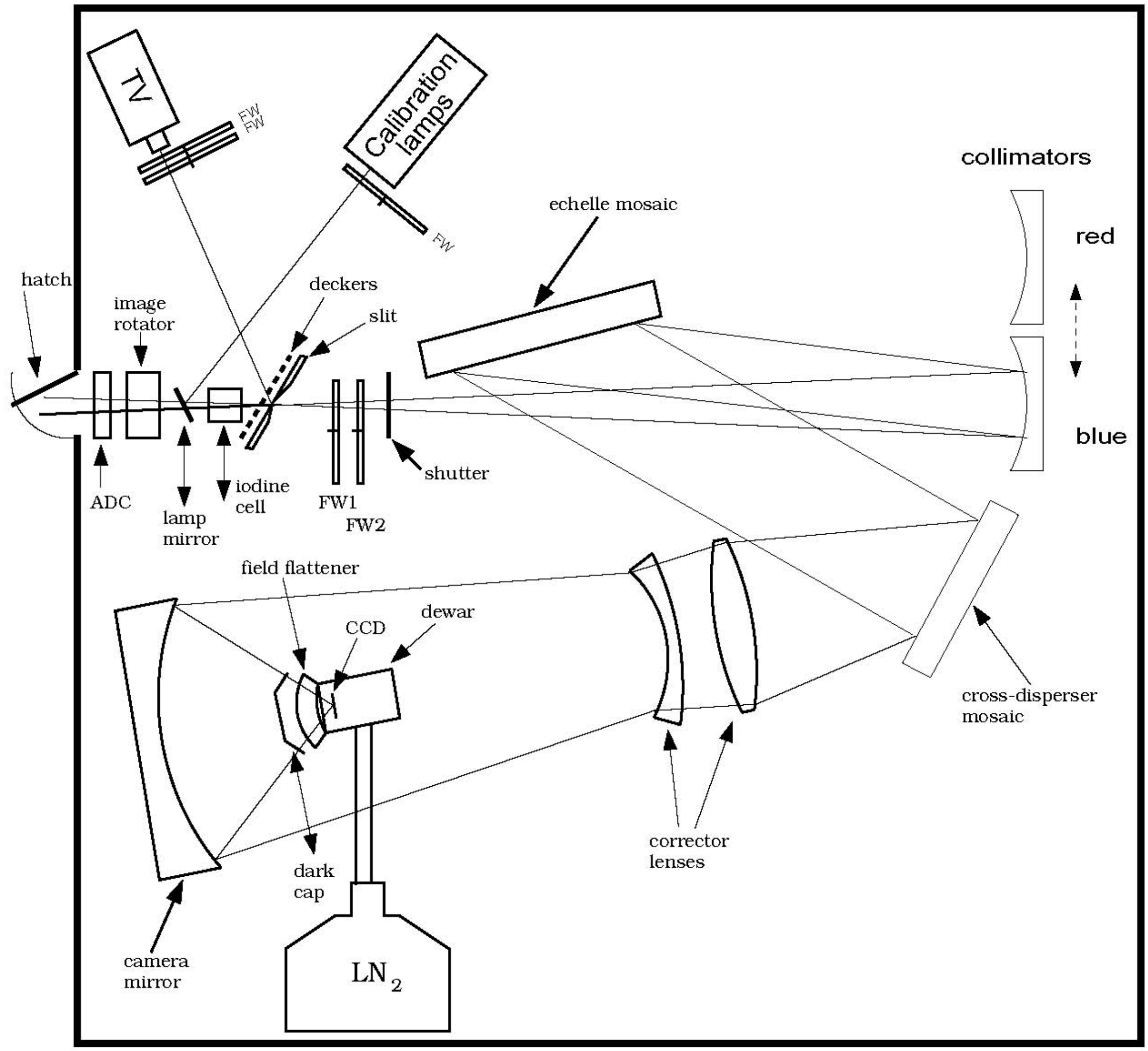
A simplified schematic of the HIRES instrument is shown in Figure 1. This figure was also used as the model for 'xhires', the graphical user interface through which the user controls the instrument. It is well worth studying this conceptual diagram and using it as a guide when setting up the instrument. When configuring HIRES for a given observation, I like to go through this diagram as a photon travels, element by element, checking the options for and settings of each element.

Light from the telescope enters from the left in this schematic, coming to focus at the f/15 nasmyth focus. An entrance hatch at the front of HIRES seals off the slit area such that the instrument can be run during the day under high light-level conditions in the dome. The hatch also protects the slit area from dirt contamination and should be left closed when the instrument is not in use for any prolonged period.

The f/15 (it's f/13.7 actually, out to the farthest corners of the hexagonal primary) beam then proceeds to focus at the HIRES slit plane. The HIRES slit is actually 1.83" behind the nominal telescope nasmyth focal plane, but well within the focus range and good-imagery range of the telescope. The slit plane is tilted such that light can be reflected up at an angle and re-imaged onto a CCD TV acquisition and guiding camera. This camera is a simple ?xed CCDTV staring at a 45 arcsec by 60 arcsec field centered on the entrance aperture of the spectrometer. The TV camera has both color and neutral density filters for brightness and chromatic control on the guide target, and also has variable focus and aperture control.

At the nasmyth focal plane, a bi-parting precision slit is provided for adjusting spectral resolution. A series of decker plates just above and in very close proximity to the slit jaws is provided for de?ning the entrance slit length. Some of these decker apertures (decker plate A slots) are for defining slit length only and are used in conjunction with the slit, while all other decker apertures define both slit length and width and are used in place of the slit jaws. When using the latter, the slit jaws must be fully opened to get them out of the way.

Figure 1 HIRES Schematic



An Iodine absorption cell can be moved into position directly in front of the slit for very precise wavelength calibration. Quartz/halogen incandescent lamps and hollow-cathode lamps, located up near the ceiling of the slit area, provide for flat fielding and wavelength calibration. Light from these calibration lamps gets fed into the HIRES optical axis by reflection off a feed mirror which slides into place when calibration is desired. The calibration lamp system has a filter wheel for chromatic and intensity control, and one position of that filterwheel contains a Fabry-Perot etalon for producing Edser-Butler fringes along the echelle orders to aid in wavelength calibration. Immediately behind the slit are two filter wheels, mainly for filters required for blocking unwanted cross-disperser orders. Behind the filterwheels is a shutter for controlling the start and stop of an exposure.

The f/13.7 beam then expands and gets collimated to a 12” diameter beam by either of two red/blue optimized collimator mirrors. The collimated beam is then sent to an echelle grating (1 x 3 mosaic), and then to a cross-disperser grating (2 x 1 mosaic). It makes a 40º turn off the cross-disperser and into a large (30” diameter entrance aperture) prime focus camera. The camera features two large corrector lenses with very special ‘sol-gel’ anti-reflection coatings, a large light-weighted Hextek primary mirror, and a thick fused silica field flattener which also serves as the dewar vacuum window. Inside the dewar, at the camera’s prime focus is a Tektronix 2048EB2–1 CCD. A slowly-actuated ‘dark-cover’ is also provided at the field flattener/dewar window to keep this sol-gel-coated optic clean, and to keep the CCD reasonably dark if lights must be turned on inside the spectrometer room.

The LN2 dewar near the CCD is filled automatically about once per day from a large LN2 storage dewar sitting outside the HIRES room. The storage dewar needs manual re-filling about once per week by qualified CARA technical personnel.

Section 3 Detailed Description of Principal Components

Entrance Hatch The entrance hatch is a simple hinged door. It is normally kept closed when not using the instrument for any extended period. It serves to isolate the slit area from dome light such that calibrations can be made during the day, or while someone else is using the telescope. It also serves the important function of keeping dirt and airborne contaminants out of the slit area, so please keep it closed when the instrument is not in use.

Atmospheric Dispersion Compensator (ADC) An atmospheric compensator (ADC) will eventually be installed, though there will not be one at first-light. Since the HIRES slit will not, in general, lie along the parallactic angle, losses (particularly in the ultra-violet) could become substantial at the slit if atmospheric dispersion is not correctly accounted for in the guiding. A guiding option which calculates and correctly offsets for atmospheric dispersion is available, though of course is not as effective as the eventual ADC unit will be.

Image Rotator An inage rotator has also been designed for HIRES, but has not yet been funded. So no image rotation will be available at first-light. The consequences of not having control of the position angle of the slit on the sky should be carefully considered when planning and executing observations.

TV Acquisition/Guide Camera A Photometrics CCD-TV is provided for object acquisition and guiding. A Canon 200 mm f/1.8 lens provides a 45 arcsec by 60 arcsec field of view centered on the entrance slit. CCD-TV pixels are about 1/6 arcsec square, but can be made bigger by on-chip binning if desired (with no increase in the field coverage of course). A view of the slit area with the TV camera field is shown in Figure 2. Here one sees a portion of decker plate ‘A’ overlying the widely-open slit.

Two 8–position filter wheels are also provided at the CCD-TV for brightness and color control. One wheel contains neutral density filters, while the other contains colored glass filters. Table 1 shows the available ND and colored filters for the TV. The neutral density filters, in combination with the TV lens aperture stop control and tv integration time, give the camera some 20 stellar magnitudes of dynamic range. The color filters provide some capability for distinguishing and/or guiding on different color sources. For example, a colored filter may be necessary for accurate guiding if the wavelength being sampled by the spectrometer is not the same as that sensed by the CCD-TV. In particular, the Photometrics CCD is not sensitive below about 0.4 microns, so ultraviolet spectral observations require special offset guiding, especially if significant atmospheric dispersion is present.

Table 1 TV Filters

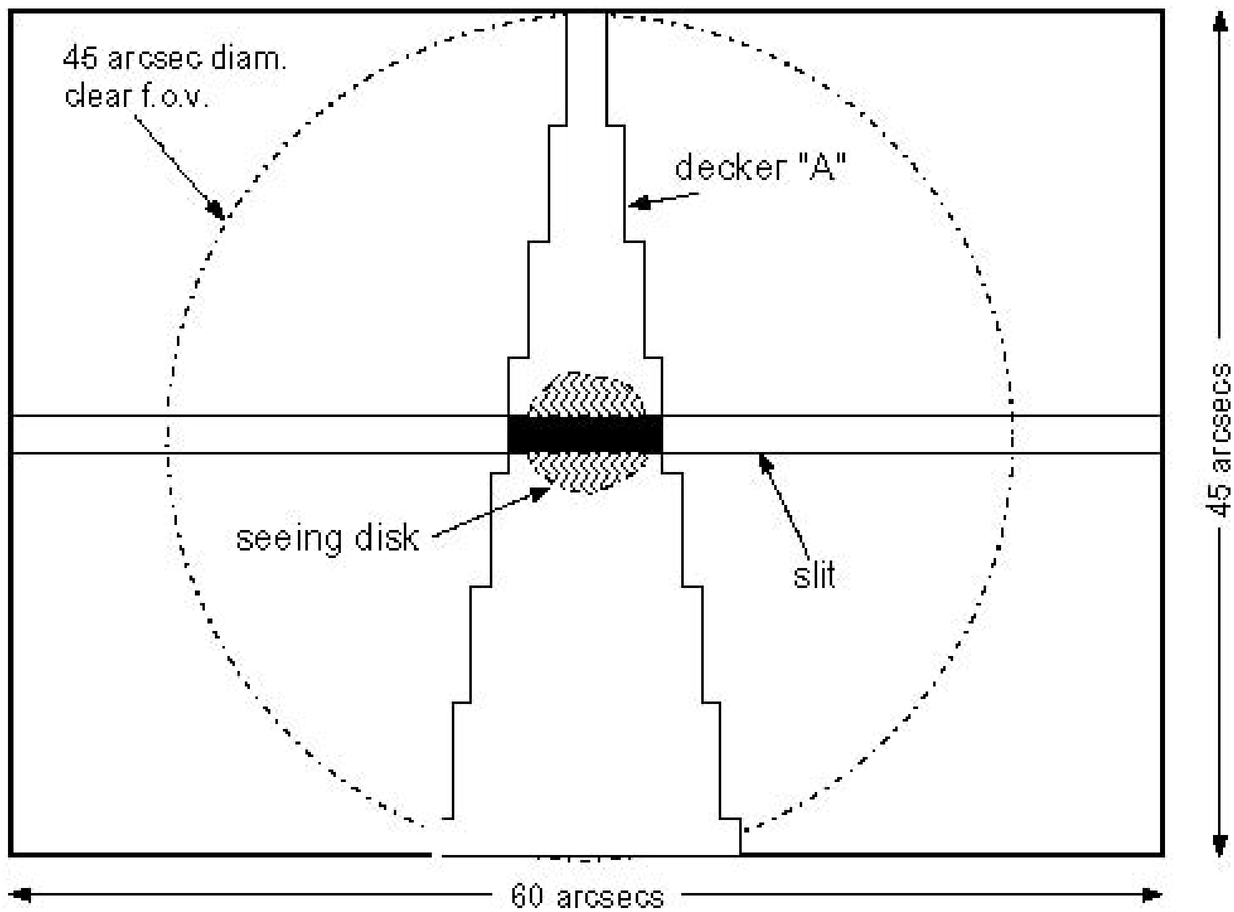
Position	Filter Wheel No. 1	Filter Wheel No. 2
1	clear	clear
2	BG24a (3mm)	d.t.
3	d.t.	ND (50%)
4	BG23 (1mm) + d.t.	ND (10%)
5	BG38 (1mm)	ND (1%)
6	RG610 (1mm)	ND (0.1%)
7	GG495 (1mm)	ND (0.01%)
8	user	user

The aperture and focusing of the TV camera lens is also under computer control. The aperture is generally to be left wide open, but can be stopped down to increase the dynamic range of the camera. Re-focusing will be necessary as one switches from guiding off the slit jaws to guiding off the decker plates. Some refocus is also necessary if different total thickness filter combinations are used. The TV camera system automatically refocuses for the different filter thickness combinations, but presently assumes that the focus for guiding the deckers and for guiding off the slit are the same.

Calibration Lamp System A series of lamps are provided for wavelength calibration and flat fielding. A Thorium-Argon hollow-cathode lamp is provided for the former and a quartz-halogen 3400K incandescent source is provided for the latter. A Deuterium lamp is also provided for flat fielding in the deep ultraviolet. A solid-state laser is also available. It produces a very intense beam and is used only for alignment and scattered light experiments. The laser actually produces a spectrum of intense lines spanning about one full order of the echelle. Should an observer be so foolish as to attempt to observe the light from this laser with the CCD, they can expect to suffer the consequences (not the least of which may be a very prolonged residual image).

All calibration lamps are housed in a light-tight, thermally insulated housing above the slit area. The lamps are mounted on a translating table which runs parallel to the slit.

Figure 2 TV Camera Field



passes through a defining stop which sets the size of the projected The calibration lamp optical system was designed to ensure that calibration light enters the spectrograph as similarly as possible as that coming in from the telescope, at all wavelengths. This is crucial for accurate measurement of instrumental profiles and flat-fielding. Light from the calibration lamps is first collected and collimated by a cemented doublet (HTF1/Fused Silica) lens located just above the filter wheel. The collimated beam then Silica/NaCl/Fused Silica) lens and then off a retractable folding pupil and adds a central obstruction. The beam then passes through a 12-position filter wheel to a cemented triplet (Fused flat which directs the beam into the spectrometer. The triplet lens produces a beam of proper numerical aperture (f/13.7) focused at the slit plane, and a virtual pupil of the correct size and distance (58" diameter, 785" ahead of the slit) to accurately mimic the telescope's exit pupil. The HTF1 element (a glass very similar in dispersive properties and transmission to CaF but without hygroscopic problems) and NaCl element were required in order to control pupil distortion and pupil walk over the very wide chromatic range (0.3 to 2 microns) of the spectrometer. The NaCl element was encapsulated between the fused silica elements to avoid hygroscopic problems. The optical system provides a 2:1 magnification, so the typically 3-5 mm diameter spot of light produced by hollow-cathode lamps is only 6-10 mm or 8-14 arcsec at the slit, far too small for longslit wavelength calibration. For longslit work, the lamp is simply scanned along the slit direction.

A list of filters available in the comparison lamp system is given in Table 2. Position 1 vignets the beam and should never be used. Position 11 contains the Fabry-Perot etalon used for wavelength calibration. Position 12 is presently open and available for public use (though loading one's favorite filter can only be done by a qualified technician, and does take some effort and time).

Table 2 Lamp Filters

Table 2 (Continued) Lamp Filters

Position	Filter
1	not clear, don't use!
2	UG5 (1mm)
3	UG1 (1mm)
4	BG12 (1mm)
5	BG14 (1mm)
6	BG13 (1mm)
7	BG38 (1mm)
8	NG3 (1mm) (T = 10%)
9	GG495 (1mm)
10	Detector Trimmer
11	Etalon
12	user available

The light from the calibration system is fed into the HIRES optical axis by a feed mirror which automatically slides into place in front of the slit when calibration lamps are requested. When stowed, this mirror retracts into a dust-tight housing off to one side. The mirror has angular adjustments which allow the calibration system pupil to be aligned with the telescope pupil. The adjustments must only be made by a qualified technician.

Iodine Absorption Cell An iodine absorption cell can also be slid into position directly in front of the slit. This cell is basically a sealed glass bottle with a small amount of iodine crystal within. When heated to a temperature above 35C, the iodine sublimes and the gas then produces an absorption spectrum on the beam from the telescope as it enters the spectrometer. The iodine absorption spectrum is a rich forest of deep, very narrow lines. This forest of lines starts at about 4800A and ends near 6000A. The absorption spectrum thus yields a very stable zero-velocity reference spectrum superimposed on the spectrum of the object being observed. It is intended to be used primarily for very accurate radial velocity studies involving asteroseismology and searches for planetary companions of stars. A detailed description of the iodine cell and its use for ultra-precise radial velocity work can be found in Marcy and Butler, 1992.

Decker Tray and Deckers Immediately above the slit is a tray containing a series of 4 decker plates. These decker plates are highly reflective (for guiding) and made of type 420 Stainless steel which were EDM'd to shape and then polished in the UCO/Lick optical Lab. These deckers define the length of the effective slit seen by the spectrometer. Some of the deckers (in plate A) define slit length only, while others define both slit length and width. As such, these latter deckers are to be used without the underneath slit (i.e. the slit gets opened up wide so it is out of the way). They may be more effective for guiding on faint objects since there is then only a single focal plane, whereas using the deckers in plate A in conjunction with the slit results in two slightly separated focal planes, with some resulting corruption to the reflected guide image.

If one is using a decker which also de?nes slit width (i.e. spectral resolution and wavelength zero point), one must bear in mind that wavelength zero point will change if the decker tray slide (which moves perpendicular to the slit axis) is repositioned. Thus, one may expect to have to take new wavelength calibrations if the decker tray is repositioned while using such deckers. Also, the collimator mirror must be refocused when using deckers only rather than deckers+slit since the decker plane is about 3/16" above the slit plane. The instrument control system automatically refocuses the collimator for the particular slit/decker/filter thickness/collimator mirror combination used.

Table 3 shows the complete selection of available deckers.

Table 3 HIRES Deckers

Plate	Height (arcsec)	Width (arcsec)	Projected height (pixels)	Projected width (pixels)	Comments
A1	0.3	use slit	1.6	na	
A2	0.5	use slit	2.6	na	
A3	0.75	use slit	3.9	na	
A4	1.0	use slit	5.2	na	
A5	1.36	use slit	7.1	na	
A6	1.5	use slit	7.8	na	
A7	2.0	use slit	10.5	na	
A8	2.5	use slit	13.1	na	
A9	3.0	use slit	15.7	na	
A10	4.0	use slit	20.9	na	
A11	5.0	use slit	26.2	na	
A12	10	use slit	52.3	na	
A13	20	use slit	104.6	na	
A14	40	use slit	209.2	na	
A15	80	use slit	418.5	na	
B1	3.5	0.574	18.3	2.00	R=60,000; 3.5" for sky
B2	7.0	0.574	36.6	2.00	R=60,000; 7" for sky
B3	14.0	0.574	73.2	2.00	R=60,000; 14" for sky
B4	28.0	0.574	146.5	2.00	R=60,000; 28" for sky

Table 3 (Continued) HIRES Deckers

Plate	Height (arcsec)	Width (arcsec)	Projected height (pixels)	Projected width (pixels)	Comments
B5	3.5	0.861	18.3	3.00	R=45,000; 3.5" for sky
C1	7.0	0.861	36.6	3.00	R=45,000; 7.0" for sky
C2	14.0	0.861	73.2	3.00	R=45,000; 14" for sky
C3	28.0	0.861	146.5	3.00	R=45,000; 28" for sky
C4	3.5	1.148	18.3	4.00	R=34,000; 3.5" for sky
C5	7.0	1.148	36.6	4.00	R=34,000; 7.0" for sky
D1	14.0	1.148	73.2	4.00	R=34,000; 14" for sky
D2	28.0	1.148	146.5	4.00	R=34,000; 28" for sky
D3	7.0	1.722	36.6	6.00	R=23,000; 7" for sky
D4	14.0	1.722	73.2	6.00	R=23,000; 14" for sky
D5	0.119	0.179	0.623	0.624	projects to 15x15 microns (for tests)

Slit The slit is a bi-parting mechanism, which means that the slit centroid should not change position as slit width is varied. The slit jaws cannot be closed completely since this would damage their sharp edges. Slit width can be specified either in microns, in seconds of arc (as projected on the sky), or in pixels (as projected on the CCD. A wide-opened slit is about 11.1 mm.

Behind —The— Slit Filter Wheels There are two 12–position filter wheels behind the slit. These are primarily for blocking unwanted orders from the cross-disperser. Eleven positions are for 2” by 2” square or 2” diam. round filters, while position No. 1 is a long narrow clear slot and cannot be loaded with a filter. Table 4 shows filters currently available.

Filter positions marked ‘clear’ are empty and can be used temporarily for a user’s personal filters. Personal filters may only be loaded by the Keck technical personnel and should be removed at the end of one’s run. If users wish any filters to be permanently added to the selection, please contact S. Vogt.

Table 4 HIRES Filters

Position	Filter Wheel No. 1	Filter Wheel No. 2
1	clear	clear
2	RG610	OCLI d.t.
3	OG530	CuSO4
4	GG475	clear
5	KV418	clear
6	KV408	5893/30
7	KV389	6199/30
8	KV380	6300/30
9	KV370	6563/30
10	WG360	clear
11	WG335	clear
12	BG24A	clear

Proper choice of order blocking filters is absolutely crucial to one’s success in isolating any particular spectral region of interest. Ultimately, the user must

Table 5 Some useful ?lter combinations

Cross Disperser Order	Wavelength Range (microns)	Filter Wheel No. 1 Position	Filter Wheel No. 2 Position
1	0.69 -1.1	2 (RG610)	1 (clear)
1	0.63 -0.95	3 (OG530)	1 (clear)
1	0.58 -0.90	3 (OG530)	1 (clear)
1	0.53 -0.85	4 (GG475)	1 (clear)
1	0.48 -0.80	5 (KV418)	1 (clear)
1	0.44 -0.75	6 (KV408)	1 (clear)
1	0.39 -0.70	8 (KV380)	1 (clear)
1	0.35 -0.65	9 (KV370)	1 (clear)
1	0.30 -0.60	11 (WG335)	1 (clear)
2	0.51 -0.67	4 (GG475)	2 (d.t.)
2	0.48 -0.64	4 (GG475)	2 (d.t.)
2	0.44 -0.60	5 (KV418)	2 (d.t.)
2	0.42 -0.58	6 (KV408)	2 (d.t.)
2	0.40 -0.56	7 (KV389)	2 (d.t.)
2	0.38 -0.54	8 (KV380)	2 (d.t.)
2	0.36 -0.52	9 (KV370)	3 (CuSO4)
2	0.34 -0.50	10 (WG360)	3 (CuSO4)
2	0.32 -0.48	10 (WG360)	3 (CuSO4)
2	0.31 -0.46	11 (WG335)	3 (CuSO4)
2	0.30 -0.40	12 (BG24A)	3 (CuSO4)
3	0.30 -0.40	UG5 ?	3 (CuSO4)

bear responsibility for choosing the correct combination of blocking filters, and may have to refer to ?lter transmission curves. In particular, real filters do not have in?nitely sharp cut-on curves, and this can make a difference in some cases. However, as a ?rst-cut guide to selecting appropriate filters, the following table lists some useful combinations.

Figures 3 and 4 show the transmission of the various HIRES filters provided for order blocking

Note that different combinations of filters require refocusing of the collimator, and this refocusing is now handled automatically whenever new filter combinations are selected. The focus change will be approximately T/3 where T is the total thickness of all filters in the beam. Adding filters requires moving the collimator farther from the slit by a distance T/3. All Schott filters in Filter Wheel No. 1 are 3 mm thick. The CuSO4 filter is 5 mm thick. The OCLI detector trimmer (d.t.) is 0.533 mm thick. All Schott and CuSO4 filters have been AR-coated with an optimized multi-layer broad-band overcoat.

Exposure Control Shutter During observing, the CCD is normally left open to the room. Its darkcover is a relatively slow mechanism, intended primarily to protect the sol-gel coating on the field-flattener. Timing of exposures requires a much faster mechanism, so starting and stopping of exposures is controlled by a fast shutter behind the slit. This shutter is actuated by a signal from the CCD controller crate. The minimum exposure time is 1 second.

Collimators The f/13.7 beam is collimated into a 12" diameter beam by either of two identical collimators. These collimator mirrors are spherical with matched radii, and tilted by 1.75º such that the beam is reflected up towards the echelle at an angle of 3.5º. One of the collimator mirrors has an enhanced (2–layer dielectric over aluminum) coating and is for use over the 0.3 to 0.5 micron spectral region. This is called the 'Blue" collimator. The other collimator is coated with an enhanced silver recipe (the 'holy grail') and features somewhat higher reflectivity in the 0.34 to 1.1 micron range, but drops off sharply below 0.34 microns. This collimator is called the 'Red' collimator. Figure 5 shows the reflectivity's of both collimators.
Echelle The echelle is a mosaic of 3 of the largest echelles currently available. The mosaic is 12" by 48" in size. The ruling is 52.68 grooves/mm and the blaze angle is 70.5º . The collimator-to-camera angle (2?) is 10.0º. The echelles are intentionally pistoned in the mosaic such that the two gaps are maximally shadowed, minimizing light loss at the gaps. The echelle mosaic alignment is intended to be passive, and should never need adjustment. Alignment is maintained by clamping the echelles to a large granite subplate, minimally constrained so as not to intro-duce any moments or unwanted forces. The mounting scheme is intended to be

Figure 3 Blue-Blocking Filters

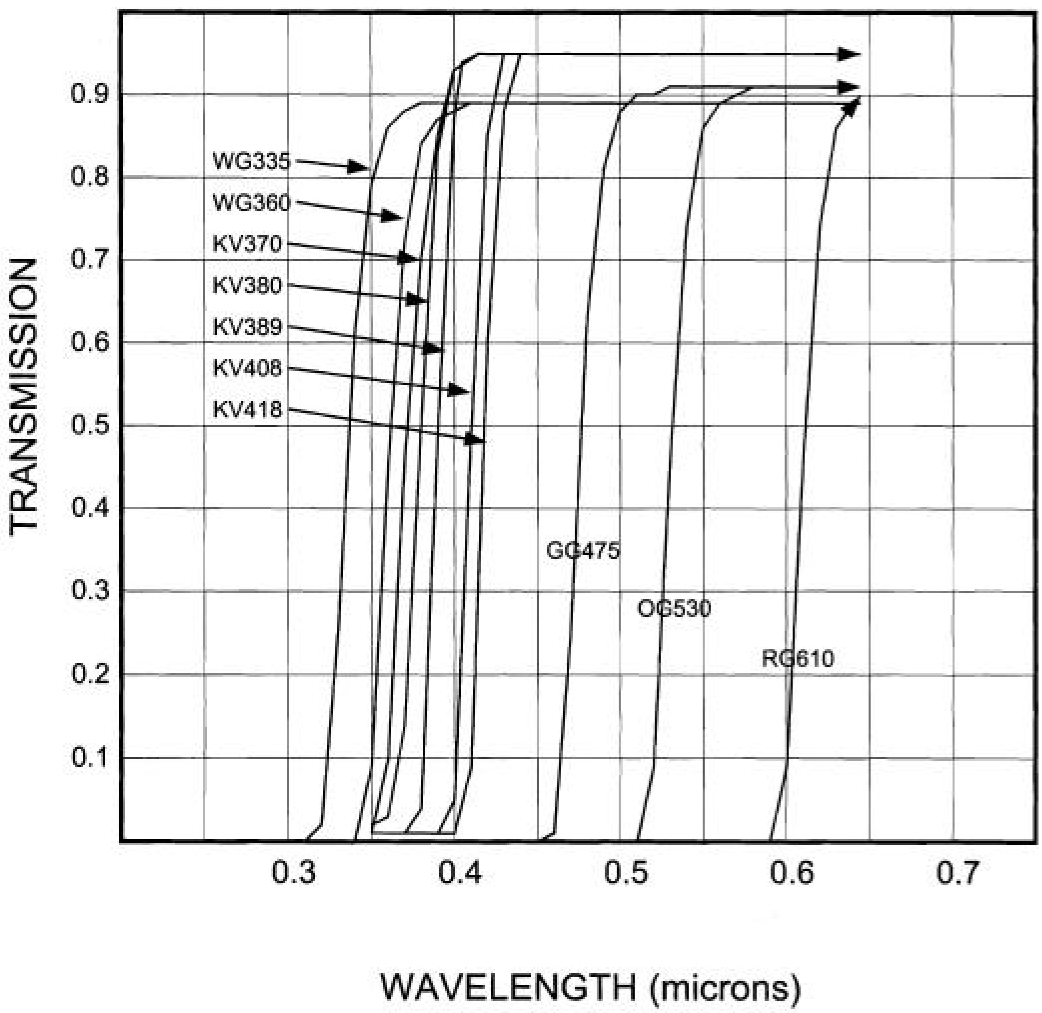


Figure 4 Red-Blocking Filters

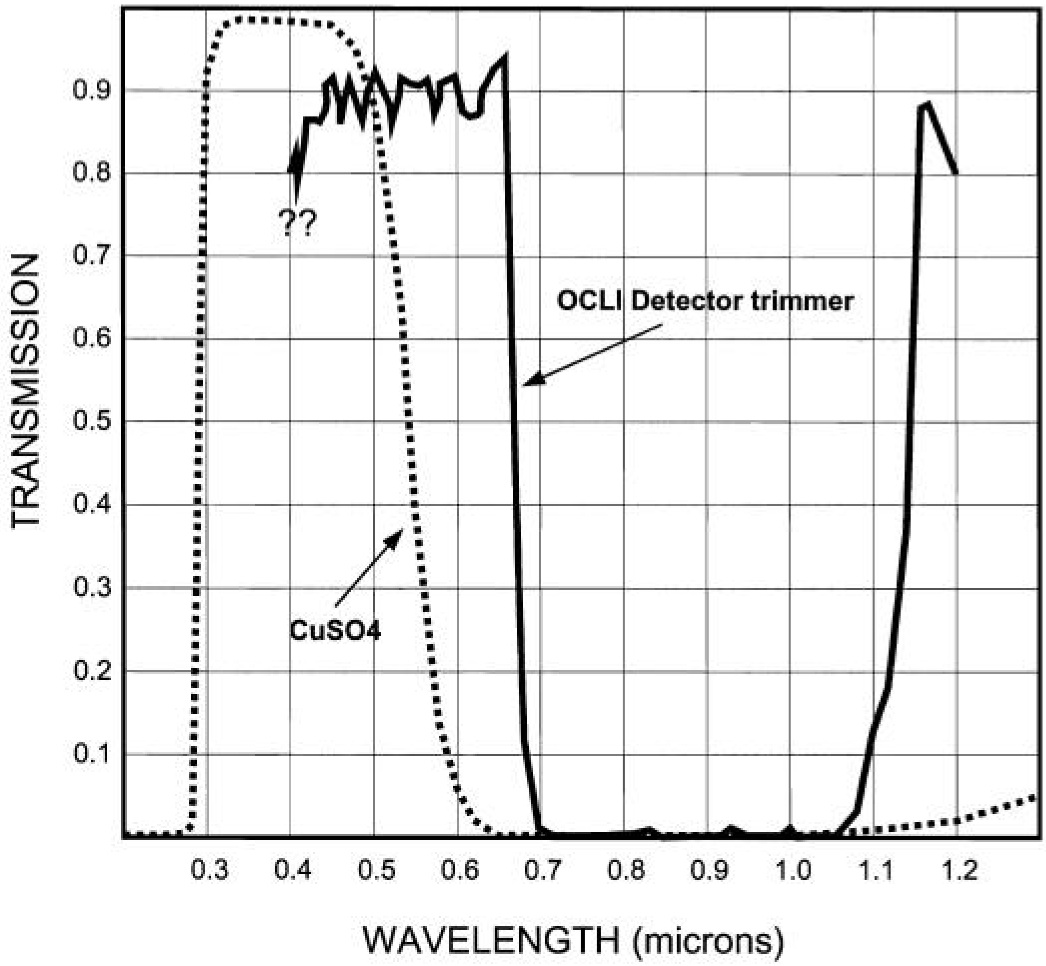
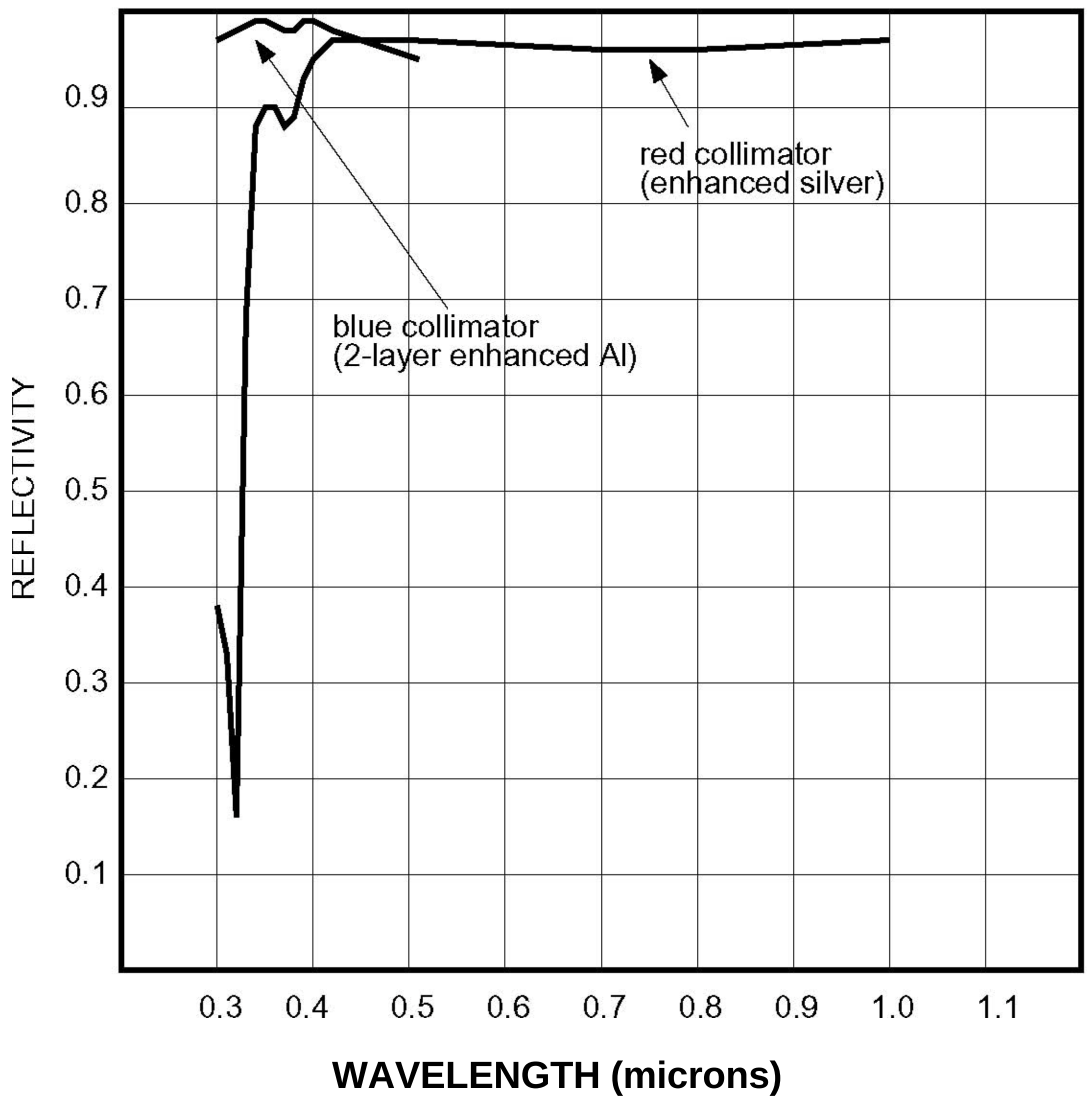


Figure 5 Collimator Re?ectivities



thermally insensitive provided the environment is isothermal (i.e. it will remain aligned at any temperature, provided the temperature is stable).

The echelle is mounted in a precision rotation stage. Rotation of the stage allows the echelle format to be positioned as desired ‘left/right’ on the CCD, and looks to the user as though one is moving the CCD left/right around a fixed echelle format.

The echelle mosaic is housed in a dust-tight enclosure. Since these gratings can never be cleaned, one should never attempt to touch them, or even to get near them. And their cover should be kept closed when not in use.

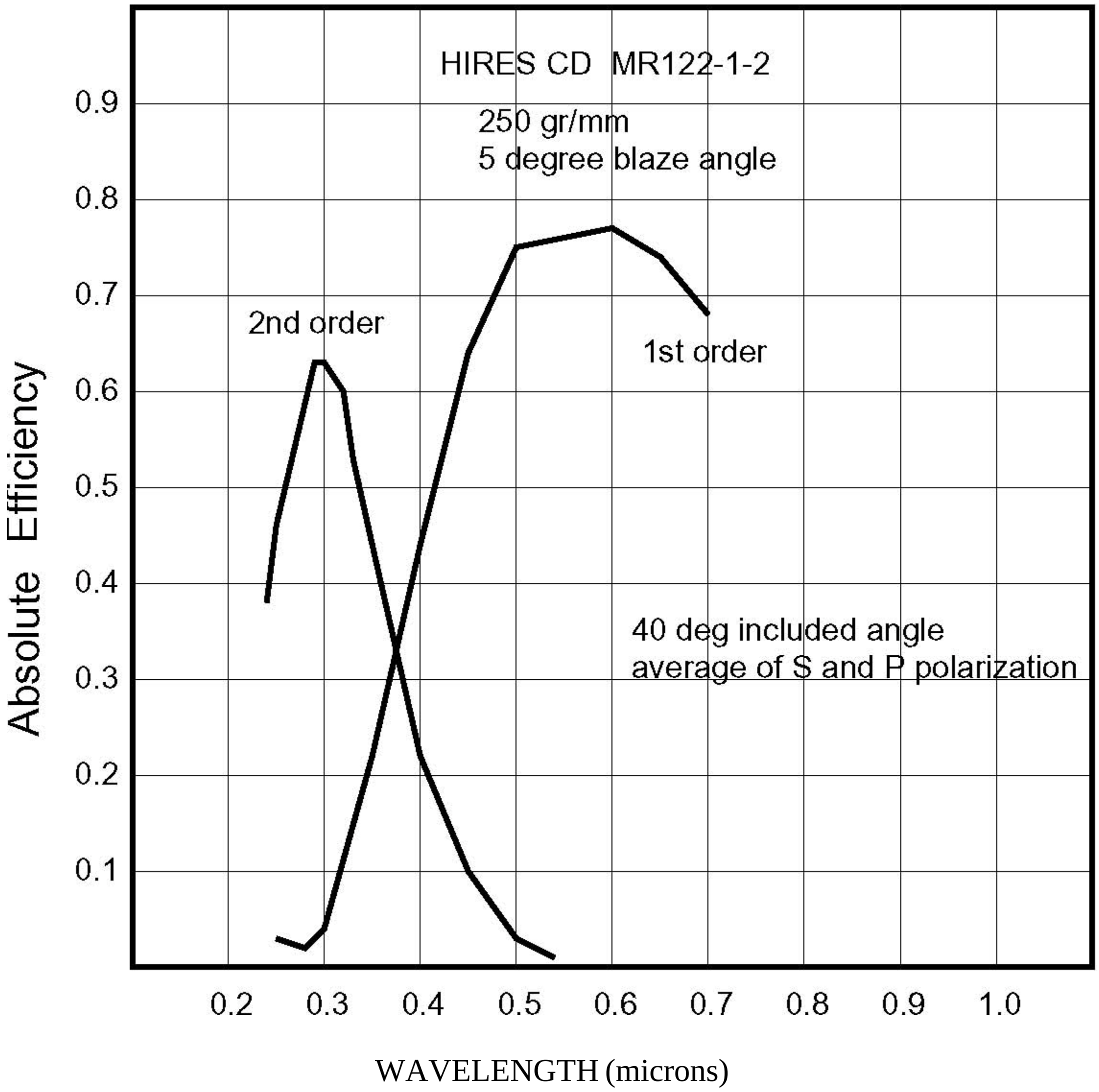
Cross-Disperser (CD) The cross-disperser (hereafter CD) is a mosaic of 2 12” by 16” gratings, mosaiced such that the effective length of any ruling is 24”, and the total ruled width is 16”. The mosaic concept is quite similar to that of the echelle. The cross-disperser ruling is 250 grooves/mm. The collimator—to—camera angle is 40º . The intended blaze angle of this CD was supposed to have been 5.343º , but came out 4.3º . The effect of this error was to put the first order blaze peak near 0.56 microns (rather than the intended 0.7 microns), and the 2nd order blaze peak at 0.28 microns (rather than the intended 0.35 microns).

This CD is intended to be used in 1st order in the visible, and in 2nd order in the ultraviolet/blue. Note that the orders get uncomfortably close together down in the uv with the CD in 1st order, but the spacing doubles in 2nd order. Appropriate order blocking filters will have to be used to eliminate unwanted CD orders. In 2nd order, one will generally be limited to a wavelength span per observation of 3/2 times the bluest wavelength observed because of the need to block 3rd order. In 1st order, a wavelength span of twice the bluest wavelength will be possible (if there is enough CCD real estate).

A plot of the efficiency of the CD is presented in Figure 6 Because of the above-mentioned blaze angle error, the efficiency of this CD below 0.35 microns will be somewhat lower than hoped. A new 1st order CD blazed for 0.39 microns and with 395 grooves/mm is being manufactured to correct this situation.

Like the echelles, the CD is housed in a dust-tight enclosure. Since these gratings can never be cleaned, one should never attempt to touch them, or even to get near them. And their cover should be kept closed when not in use.

Figure 6 Cross—disperser efficiency curves



Camera The camera is an all-spherical f/1.0 (polychromatic) catadioptric system. It uses two corrector lenses, an f/0.76 primary mirror, and a thick meniscus field flattener which also serves as the dewar vacuum window. This style of camera is extremely achromatic. The camera delivers 21.6 micron (rms diameter, averaged over all field angles and colors) images over a 5.2º diameter field of view, over a spectral range of 0.3 to 1.1 microns, with no refocusing. A de-tailed description of this camera was presented by Epps and Vogt (1993). Some sacrifice of image quality was necessary with this final design to accommodate, at the last minute, the unanticipated curved surface of the CCD (65" radius of curvature). Backup designs featuring 12.6 micron rms image diameters over a 6.7º field of view with flat focal plane are also in place for the time when the flat CCD's become available.

Retrofitting to the flat focal plane design requires only fabricating and installing a new field flattener.

Corrector Lenses These lenses are made of Corning 7940 fused silica. The front corrector lens (corrector No. 1) is a biconvex element, and corrector No.2 is a meniscus. These two large corrector lenses are heavy enough and thin enough that they sag under their own weight. Finite Element Analysis (FEA) was done to design mounting cells which would remove most of this sag. The lenses thus have push supports just outside their clear apertures which remove the sag and must be properly adjusted when re-installing these lenses.

The corrector lenses are anti-reflection overcoated with ‘sol-gel’. This sol-gel AR coat is a dip-coat process and is a very fragile overcoat. It must never be touched. The slightest touch (such as lightly brushing with a sleeve, etc.) will damage the coating. These sol-gel coatings can only be done at Lawrence Livermore National Labs, and are thus very difficult to re-do. They can be cleaned by a high pressure ethanol spray, but only after removing from their cells and by qualified technicians. These coatings also have 35 times the surface area of the part they are on, so they are a very effective magnet for dust. Thus their covers must be kept closed as much as possible, and the HIRES enclosure must be periodically wiped down for dust.

Hextek Primary Mirror The camera mirror is a 44” diameter f/0.76 sphere. It is fabricated from a lightweighted mirror blank manufactured by Hextek Corp. in Tucson, Az. The mirror blank weighs only about 183 lbs. It is supported axially at 6 points which attach to the mirror’s honeycomb structure at the center of gravity plane. Radial support is accomplished through a diaphragm/ring structure glued to the center rear surface of the mirror. The mirror is enclosed in a dust-tight housing, and its doors should be kept closed whenever possible for obvious reasons.

Eventually, two identical mirrors will be available, one overcoated with enhanced aluminum, and the other overcoated with a multi-layer silver recipe. At present, only a single mirror is available, overcoated with a standard ‘telescope-grade’ aluminum coating. Switching between mirrors, or removing the one presently available mirror is done with a manually operated overhead crane. The mirror/cell assembly is kinematically located on three ball feet and held in place by both gravity and hold-down clamps.

Field Flattener/Dewar Window The field flattener is a thick meniscus lens made of Corning 7940 fused silica. As with the corrector lenses, it is AR overcoated with sol-gel, so must never be touched at any time, with anything, for any reason, period. This lens also functions as the dewar vacuum window. It is sealed to the dewar with a single o-ring, and positioned axially by a precision machined surface. Radial locating is accomplished with three radial retainer clips. The lens must be properly centered to within 0.02”.

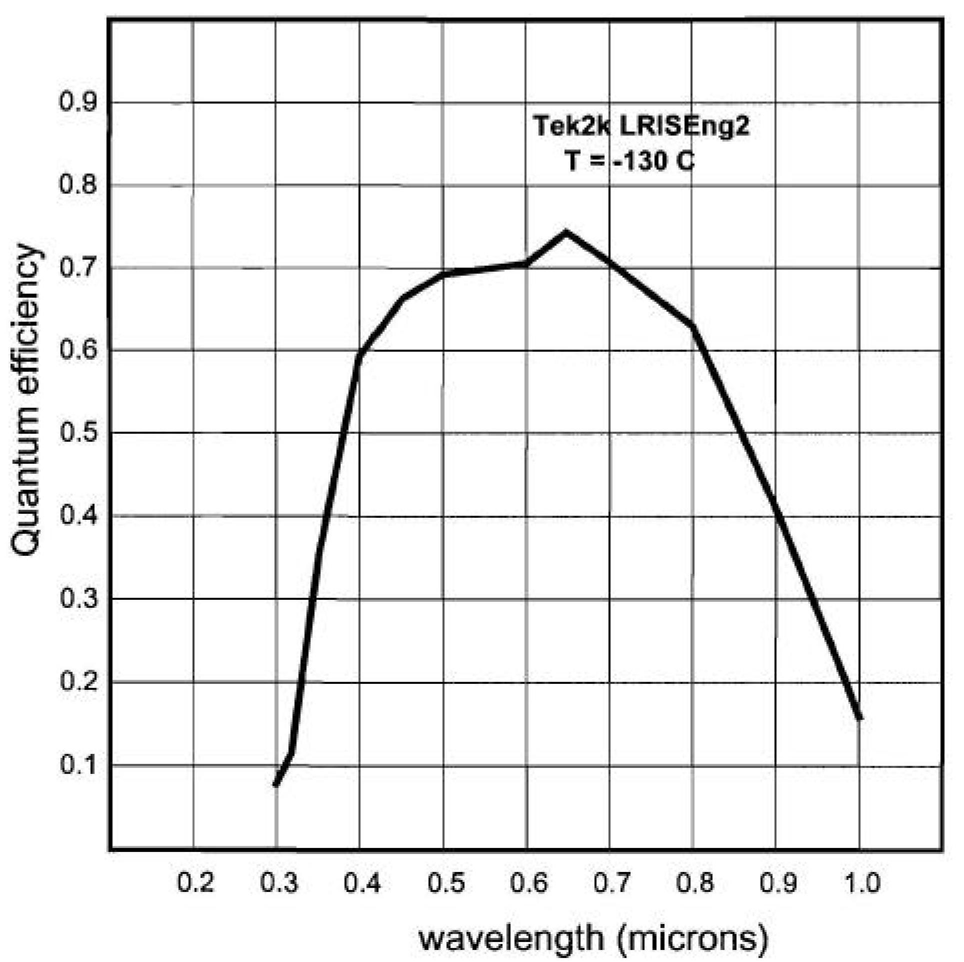
A light shroud around the edge of the lens helps to keep the CCD reasonably dark, but is not completely leak-proof. A slow-operating dark cover, consisting of a cap which moves into place over the field flattener, helps to keep fingers and other foreign invaders away from the sol-gel surface of the lens, and provides some protection from flashlights or other low-level lighting used by personnel entering the room. Again, this dark cover is not expected to be completely light-proof, so care should be taken when entering HIRES to avoid using any more photons than necessary, unless one is prepared to suffer potential image afterglow effects. And the dark cover should always be put back into place when the system is not in use to provide maximum mechanical and dust protection for the sol-gelled lens.

Detector We will be using the engineering-grade CCD from the LRIS instrument at ?rst-light. This detector is a Tektronix 2048EB2 CCD. This CCD is optimized for the visible, and shows a pronounced roll-off in quantum efficiency in the ultraviolet. The science-grade Tek CCD for HIRES has not yet been (nor may ever be) received. The CCD features 24 micron pixels in a 2048 by 2048 format. It is a thinned backside-illuminated chip, with surface treatment and AR coating.

Figure 7 shows the quantum efficiency for this CCD as measured at UCO/Lick at operating temperature. Note that the QE drops very rapidly below 0.38 microns. This is rather a shame since the CCD effectively dies before the 2nd order CD efficiency curve rises to a peak, thus producing a dip in the overall instrument throughput in the 0.35 micron region. All the rest of the HIRES optics transmit very efficiently all the way down to below 0.3 microns.

One very prominent distinguishing cosmetic defect of this CCD is a large felt-tip pin mark near the center of the CCD. It was kindly added by some technician at Tektronix to remind us that this virtually flawless $100,000 CCD is only an engineering-grade device. Unfortunately, the folks at Tektronix seemed to have forgotten how to make science-grade devices, so we are stuck with this annoying blob. It is marked in the HIRES format simulator as a red square, though it is irregular in shape. Take care to avoid this region when positioning critical spectral regions on the CCD.

Figure 7 Tektronix CCD Quantum Efficiency



Dewar Focus Fine focus of the camera can be done by using the dewar focus mechanism. This mechanism moves the entire dewar (CCD plus field flattener) along the camera axis. Total travel is only about 0.03”, but with very high precision. The camera is so fast (f/1.0), that some care is required to get proper focus. Focus errors of 0.001” may degrade spectral resolution unacceptably. A powerful focusing algorithm is being developed which should assist the user in this task. At some point, it will probably be possible to fully automate the focus procedure. The camera frame is a thermally stabilized design, and camera focus should thus not be a function of temperature. During the first 4 months of HIRES use, we have not seen any reason to refocus the camera, but it should be periodically checked.

Focusing can also be done using the collimator focus, and refocusing for various thickness filters, etc, will generally be done using the collimator focus. Changes of ? X in collimator focus are equivalent to changes of ? X/30 in camera focus.

Enclosure, Electronics Bay, and Clean-Room Ante-Chamber The spectro-graph is enclosed in a modular, insulated, light-tight, dust-tight housing. This housing provides about a 9–hour thermal time constant between inside and outside temperatures. There is no attempt to thermally control the interior temperature. Rather, it is expected to track the dome interior temperature from day to day, but not from hour to hour. A slow flow of filtered and dried dome air is continually forced into the enclosure through a hose and adjustable valve (that is the hissing noise you always hear when inside).

All attempt has been made to keep all sources of heat out of the interior of HIRES, and not to dump heat into the dome. Most of the control electronics are contained in a separate Electronics Bay (a similar style thermally insulated enclosure), and heat inside the electronics bay is carried away by the observatory's recirculating liquid coolant system. Electronics inside the HIRES enclosure which drive the CCD, and other electronics which control the TV camera, are contained in their own thermally-insulated 'footlockers'. These footlockers are also cooled by the observatory's coolant system.

A psuedo-clean-room ante-chamber is also provided. Personnel entering HIRES will be required to don appropriate clean-room garb in this ante-chamber. Dust accumulation is a serious concern for HIRES, and personnel entering HIRES are expected to do all they can to eliminate dust and dirt, particularly that brought in on shoes. Sticky mats get a lot of it, and must be renewed frequently. But even the mats do not get it all. Clean room suits with booties are thus mandatory.

Electronics Control System The control system for HIRES is a VME-based system which uses only Keck Observatory standard modules. HIRES is one of an initial complement of five first-light instruments which connect to a scientific instrument LAN at the mountaintop. Each instrument is controlled by its own VME-bus based Sun/3E (68020 CPU) real-time controller running VxWorks which connects over the scientific Ethernet LAN to either of two SUN Sparc-series instrument computers. The main instrument control computer for HIRES is makua.keck.hawaii.edu. Another Sparc station, lanikai.keck.hawaii.edu, is also used during HIRES observing, primarily for data reduction and analysis. Since there are multiple instrument computers, two or more separate instruments can be electronically on-line at the same time, as will often happen as one team prepares an observing run following another. One instrument computer also serves as a back-up for the other. The instrument computers are then connected to the Keck Observatory Ethernet LAN which provides a link with similar computers at the headquarters down in Waimea.

The HIRES VME chassis includes one SUN-3E120 CPU card, one SUN-3E340 Ethernet card, eight Galil DMC 330-10 Motor controller cards, three XYCOM XVME-212 input port cards, three XYCOM XVME-220 output port cards, and one XYCOM XVME-540 Analog logic card. Most moving mechanical devices are driven by Galil DC-servo motors.

Each optical instrument which uses a CCD has its own CCD controller system. The CCD controller is based on the design described in Leach (1988) that utilizes a programmable digital signal processor to generate timing signals and manage communication with the host computer, and allows remote programming of the timing waveforms and CCD clocking voltages. The CCD clocks are generated with digital-to-analog converters while a conventional preamplifier, dual slope integrator and 16-bit analog-to-digital converter process the CCD video signal.

All of the electronics are housed in a separate thermally insulated enclosure adjacent to the spectrometer. This electronics enclosure is cooled via the ob-servatory's recirculating coolant system. Since we were obliged to use standard observatory VME electronics modules, which are not rated for use below 0º C, we will actually be holding the electronics enclosure at a temperature of 5º C.

Software Control System The software for instrument control at Keck Obser-vatory is written in the 'C' programming language and runs under UNIX on a network of Sun computers. The observer controls a given instrument through a software user interface which allows both command-line input through keywords and scripts, and window-style graphical input using X11 windows with the MO-TIF toolkit. Both types of input can be intermixed. The user interface also allows for multiple invocation of control processes, which is important for distributed observing. Here, the primary observer can be quite remote from the telescope (i.e. in Waimea or back in California), while graduate students and/or technical observers at other sites or at the mountaintop can cooperate in the set-up and running of the instrument during an observing run.

The primary tool for interacting with HIRES is a graphical user interface called 'xhires'. It is a self-explanatory 'click-on-icon/pop-up menu'-style control interface. It can be run in active mode where it will actually move spectrograph parts, or in simulator mode (not connected to the real spectrograph). The simulator mode is very useful for practicing before actually going out for a run, and instrument set-ups can be generated and saved for use later during observing. Al Conrad (aconrad@keck.hawaii.edu) wrote xhires and is the contact for this software.

Chapter 3 The HIRES Spectral Format Simulator

Like most echelle spectrometers, the spectral format is larger than the available detector real estate. The HIRES optical system was designed to feed a 2 by 2 mosaic of Ford/Loral 2048 CCD's. This mosaic would have been some 61 mm on a side. What we ended up with at frst-light was a 49 mm square Tektronix CCD. When the length of the free spectral range of any echelle order is longer than the 49 mm dimension of the CCD, holes will appear in the data since those regions of each order falling off the CCD imaging area will not be recorded. These holes begin occurring redward of about 5100 A. Avoiding these holes, and ensuring that the desired spectral range falls properly on the CCD requires accurate positioning of the echelle format on the CCD. For extragalactic objects, redial velocity must also often be taken into account.

To aid the observer in optimal positioning of the CCD on the echelle format a simulator was developed by Steve Allen at UCO/Lick. The underlying mathemat-ics are described in the textbook by the original author of the code, D.J. Schroeder (Astronomical Optics, Academic Press, 1987). These algorithms provide a com-plete description of the Echelle format within the constraints of the 2–dimensional grating equations. They do not handle the more general problem of modelling the 3–dimensional grating equations. Other important algorithms used in the code are based upon the text by E. Hecht & A. Zajac (Optics Addison-Wesley, 1974).

The code is able to model a spectrograph where an Echelle grating is fed by a collimated beam. The beam leaving the Echelle grating may be cross-dispersed by at most 1 cross-dispersing grating and/or up to 9 cross-dispersing prisms.

This simulator also serves as a convenient means by which set-up ?les for most all of the HIRES parameters can be created off-line (i.e. before going to the mountain, while preparing for a run, etc.). These set-up ?les can then be uploaded to Mauna Kea and stored in the instrument computer, prior to starting the observing run.

A detailed description of the HIRES echelle format simulator can be found in Steve Allen's user's manual, which is published as UCO/Lick Technical Report No. 68. But if you don't happen to have a copy of that manual in-hand, I'll simply reproduce (with my own comments added) much of the 'user interaction' section from Steve's manual here.

The executable code for the simulator will reside on the Keck Observatory computer system. Observers will have to get guest accounts at Keck to access this code. Alternatively, binary versions of the code (running under SunOS) may become available from UCO/Lick Observatory and can be FTP'd to the user's institution.

The most common platform on which the instrument simulator will be used is probably a high-resolution monitor running version 11 of the X Window System from MIT. However, it is essential to note that the instrument simulator is NOT an X11–based program. The instrument simulator uses the Lick Mongo package to do its graphics and user interaction.

This allows the instrument simulator to be run on a variety of platforms dating back to Tektronix storage-tube terminals. Because of this the instrument simulator cannot do multiple popup windows and menus as would be expected of a modern, X11–based user interface.

Section 1 Before starting; some words about Con?guration Files

The simulator is a general purpose tool which requires con?guration ?les to give it the information necessary to compute a simulated HIRES spectrometer and its particular detector. The complete description of an Echelle spectrograph requires copious amounts of information. Most of this information does not change, and it is convenient to store it in con?guration ?les. The simulator searches for con?guration ?les in several directories. The ?rst directory searched is the current working directory. Next, if the environment de?nes EFDIR that directory is searched; otherwise the program looks in the built-in default directory1.

The simulator accepts 3 kinds of con?guration ?les. The ?rst 2 kinds of ?les rarely need changing; they describe the telescope/spectrograph optics (*.spc) and the detector at the focal plane (*.det). These ?les will be maintained and updated by Keck Observatory folks, and will be write-protected from general users. The third kind of ?le contains the settings of all the moveable parts of the spectrograph which are expected to change from one observation to the next (*.set). It is this type of ?le that the observer will be creating, modifying, and storing for later use with HIRES.

On the UCO/Lick systems this is /home/hires/sla/echelle/lib.

The con?guration ?les for the Echelle Simulator look like FITS ?les. More detailed descriptions of these con?guration ?les can be found in Steve Allen's UCO/Lick Technical Report No. 68. Con?guration parameters are stored as keyword/value pairs. In accordance with FITS ?les, the keywords are up to 8 characters long. (Many of these keywords are identical to the keywords which will be used by the Keck Data Acquisition System when it is documenting actual observation.) Each keyword is followed immediately by "= " in columns 9–10. The values may be found anywhere after the "= " starting in column 11. The principal difference between the Echelle Simulator con?guration ?les and true FITS headers is the existence of carriage control. Echelle Simulator con?guration ?les contain carriage control and are intended to be edited by any text editor.

Each time the Echelle Simulator is run, it outputs hidden versions of the three con?guration ?les. These are named .ech.spc, .ech.det, and .ech.set. These can be compared with the original inputs and any changes made by user interaction to verify that the program is working as desired.

Upon request of the user, the program also writes out an observation setup ?le in either of 2 formats. The ?rst format is identical to the inputs (described below). The second format contains FIORD commands designed to command the Keck HIRES spectrograph to the given con?guration. The user can also edit these ?les as desired (without going back and rerunning the simulator) using your favorite text editor.

There are several keywords which are de?ned by the Keck HIRES data acquisition system which are not used by the instrument simulator. The instrument simulator accepts these keywords and carries their values from input to output unchanged.

An observer may have a number of key spectral features which need display-ing at their respective positions on the echelle format. The Echelle Simulator will accept a ?le containing the wavelengths of spectral lines and display those lines (with any desired velocity shift) on its graphics. The existence of such a ?le can be indicated using the WAVEFILE keyword in the Setup Con?guration ?le and it can also be indicated interactively during the execution of the program. Each line of the ?le contains a description of one spectral line. The program looks for a wavelength (expressed in °

Angstrom), a boolean value (T or F) which describes whether the line is telluric (and thus should not be redshifted), and a statistical weight. The statistical weight is used by the program during the design of new spectrographs. It is intended to assist the program in choosing an Echelle groove spacing which places certain spectral lines near the blaze.

Section 2 Starting the format Simulator

Starting the Echelle Simulator can be done by typing the command “echelle”, (or “echelle &” if you want to run it in the background and keep the window available for other input). If the user is running the X Window System and the user’s environment de?nes the DISPLAY variable, the simulator will assume that the graphics should be displayed in an X Window. If the DIS-PLAY variable is not set the program will prompt the user to enter one of the terminal types known to Lick Mongo.

The simulator then searches the current directory and the library directory looking for a setup ?le to be used to display the Echelle format. A list of all the setups found in these directories is presented, and the user is asked to choose ‘which setup?’. Only two options are presently of relevence to HIRES users, the others are for other developmental experiments. Pick either #2 for the ?rst-order CD format, or #3 for 2nd order CD format.

Once selected, using the information contained in the setup ?le, the simulator draws a picture of the Echelle format. At this point, it would be wise to position this relatively large graphic window such that it does not completely obscure the prompt line of your present window. You may sometimes be asked to enter data from this window and, unless it’s prompt line is visible, you may forget that this window exists.

In the large window showing the spectral format, for each Echelle order within the speci?ed wavelength limits, one free spectral range (FSR) centered on the Echelle blaze is drawn. Most of the light in any Echelle order is within one FSR of the Echelle blaze wavelength for that order. There is some light in each order more than one FSR away from the blaze, but the intensity drops rapidly.

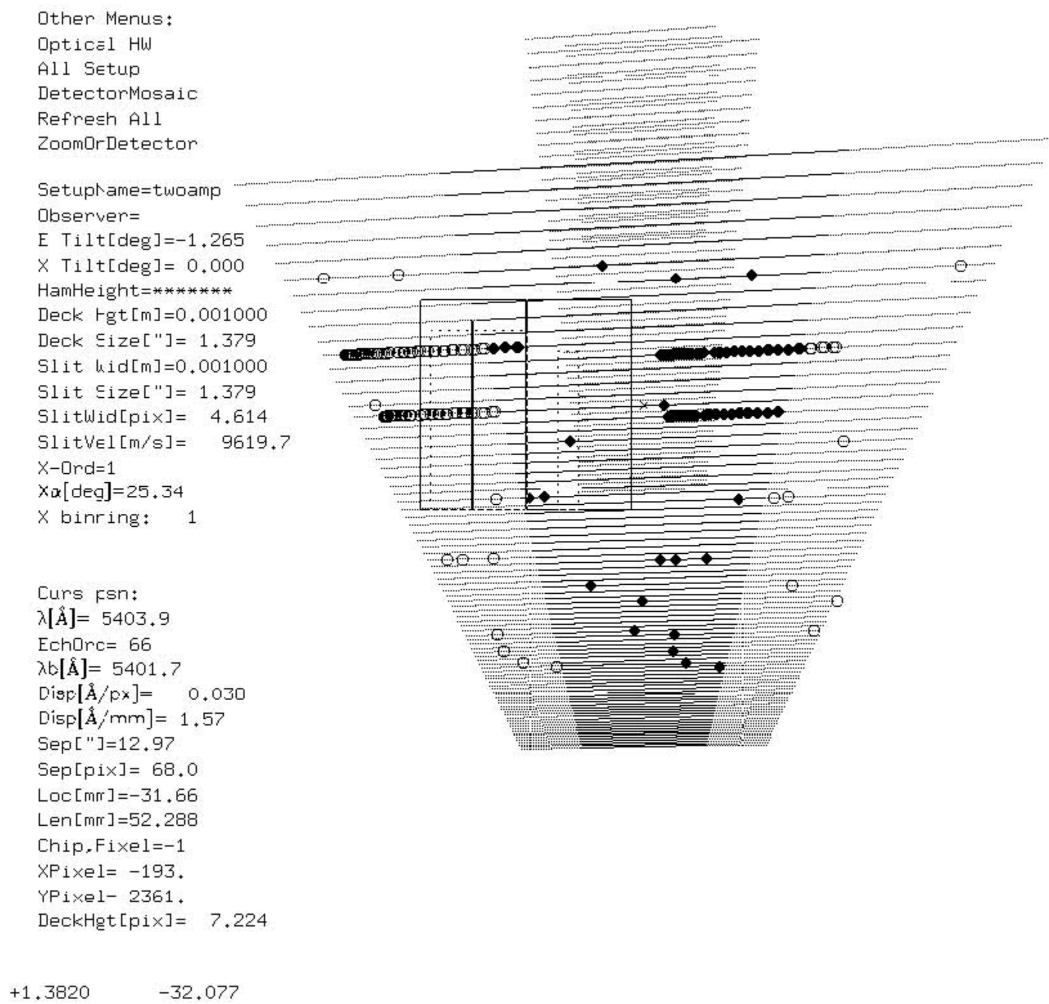
On a display which supports color, the simulator extends the length of each Echelle order by drawing another FSR in grey on either side of the blaze. In the case of an Echelle spectrograph with grating cross dispersers the simulator displays the selected order of cross dispersion and several nearby orders of cross dispersion. Any spectral lines which were de?ned are plotted on the Echelle format twice. The position of the spectral line closest to the blaze is drawn with a ?lled dot, and the position next closest to the blaze is drawn as an open dot. It will usually be best to choose to observe a spectral line in the order where it is closest to the blaze since that will be where most of the light at that wavelength is located. The secondary line locations are shown for cases where the Echelle format is large compared with the detector.

Information concerning the blaze wavelength and/or order number of each echelle order can be toggled onto or off of the display by clicking on appropriate menu items.

The simulator also draws a schematic of the detector(s) properly positioned on the Echelle format. Any bad spots on the detectors are indicated by rectangular regions on the display. If you are windowed down to some subset of the CCD, the readout regions are indicated by dotted lines.

The simulator also displays text lists which give the details about the optics, their settings, and the current location of the cursor. At this point the simulator is ready for interactive graphical use.

Figure 8 Typical appearance of the Simulator during interactive use



Section 3 Graphical Interaction

Most of the user interaction with the program is accomplished with single keystrokes (or mouse clicks) while the graphics are displayed. Many of the possible commands are visible on the “menus” at the left side of the screen. (The scarcity of screen real estate on some types of displays prevents all possible commands from being visible.) There are 3 methods by which the user can graphically interact with the program:

1. Accelerator Key
2. Mouse Drag
3. Menu Click

A glance through the following tables will reveal that some parameters may be modi?ed using more than one of these methods.

Accelerator keys are single keystrokes. An accelerator which is associated with a Boolean parameter will toggle that parameter from one state to the other. An accelerator which is associated with a string or numeric parameter will prompt the user for a new value. If the display is an X11 server, the prompt will change the cursor into a question-mark, and the prompt will be visible at the bottom of the screen. On other displays the prompt will appear on the text screen, if one exists, or on the graphics screen. (Again, this is where you will want to be sure your text screen is not buried under the graphic screen).

Mouse drag can only be used on X11 displays. Dragging can be done with ?xed-size objects or with rubber objects. The Instrument Simulator allows the readout window (if windowed down to some subset of the full CCD format) to be indicated by dragging a rubber rectangle over the display. The position of the detector(s) can be modi?ed by dragging a ?xed-size rectangle (of the same size as the detector). When dragging a ?xed-size rectangle, it may be “grabbed” at any of 9 locations de?ned by the corners and points halfway between.

Menu click can be used for items which are displayed in the lists of text at the side of the display. It requires that the display have some kind of moveable cursor. The cursor is moved over the menu item and any unassigned key or mouse button is hit. The user will then be prompted for a change in the same manner as for accelerator keys.

Modifying the display

The overall display can be modi?ed by the use of single accelerator keystrokes or menu clicks.

Menu Label	Accelerator Key	Action
Show OpticalHW	!	Display the complete menu of optical hardware.
Show All Setup	$	Display the complete menu of instrumental setup.
DetectorMosaic	%	Display more information about the detector(s).
Default Setup	ˆ	Restore the originally displayed menus.
Refresh All	R	Redraw everything.
ZoomOnDetector	Z	Zoom the display to show only the region where the detector is currently located.

Exit2CmdLinMod	Q	Quit the graphical interaction and begin command line interaction (see Section 4 below).
DisplayWavelen	control-L	(Un)Display the wavelengths of every ?fth order.
Display Orders	control-O	(Un)Display the order numbers of every ?fth order.
Mark Detector	D	(Un)Plot a temporary outline of the detector(s) at the current location of the detector. These outlines will be visible in a hardcopy.
-	control-I X Mouse 1	Identify the spectral line nearest to the cursor.
-	M X Mouse 2	Move the detector(s) over the Echelle format.
-	W X Mouse 3	De?ne the readout window of the detector(s).

Modifying the Setup

Keyword Name	Label on Menus	Accelerator Key
SETUPNM	SetupName=	None
DETFILNM	DetectorFile=	None
SPCFILNM	Tel/Spg File=	None
OBSERVER	Observer=	None
ECANGLE	ECangle[deg]=	(M) (X Mouse 2)
XDANGLE	XDangle[deg]=	(M) (X Mouse 2)
HAMHGT	HamHeight=	(M) (X Mouse 2)
ECANGRAW	Raw E Tilt=	(M) (X Mouse 2)
DECKER	Decker Name	None
DECKRAW	RawDeckPos=	None
DECKPOS	DeckerPos[m]=	None
DECKNNAM	DeckPosName=	None
DECKHGT	Deck Hgt[m]=	None

DECKSIZE	Deck Hgt["]=	None
DECKPIX	DeckHgt[pix]=	None
DECKSPEC	DeckSpec=	None
SLITWID	SlitWidth[m]=	None
SLITSIZE	SlitWidth["]=	None
SLITPIX	SlitWid[pix]=	None
SLITVEL	SlitWid[m/s]=	None
SLITRAW	RawSlitWidth=	None
FILTER	Filter 1 Pos=	None
FILTER2	Filter 2 Pos=	None
FILNAME	Filter1 Name=	None
FIL2NAME	Filter2 Name=	None

Modifying the Optics

The Echelle Simulator can be used during intial design studies of new Echelle spectrographs. It is possible to modify the properties of many of the optical elements while the program is running. Under normal circumstances these capabilities are not desired by the user, and they are disabled.

Keyword Name	Label on Menus	Accelerator Key
COLL	Collimator:	None
COFOCUS	CollFocus[m]=	None
CAMERA	Camera:	None
CAFOCUS	Cam Focus[m]=	None
XDORDER	XD Order #	O
XBIN	X binning:	None
YBIN	Y binning:	None
XDALPHAD	XD? [deg]=	None
XDBETAD	XD ? [deg]=	None
RADVEL	Rad Vel[m/s]=	None
RADVELZ	Rad Vel as Z=	None
WAVLMAX	MaxDispWavel=	None

WAVLMIN	MinDispWavel=	None

Keyword Name	Label on Menus	Accelerator Key
TELESCOP	Telescope=	None
INSTRUME	Instrument=	None
PRIMDIAM	Dtel[m]=	T
COLLDIAM	Dcoll[m]=	C
CAMFOCLN	CamFocL[m]=	F
COLFOCLN	ColFocL[m]=	None
NXDPRISM	#Prisms=	N

Keyword Name	Label on Menus	Accelerator Key
PRAPEXD	Apex[deg]=	A
PRAPEXn	Apexn[deg]=	None
FOCSCALE	FocScal["/mm]	None
FPROTANG	FPRotAng[deg]=	None
NXDGRAT	# XD Grat:	X
PRGLAS	Glass=	None
PRGLASn	Glassn=	None
ECTHETAD	EC?[deg]=	H
ECTHETA	EC?[rad]=	None
XDSIGMAI	XD[groov/mm]=	I
XDSIGMA	XDs [µm]=	None
ECSIGMAI	EC[groov/mm]=	S
ECSIGMA	ECs a[µm]=	None
PRANGIND	Ang Ind[deg]=	None
PRFACEn	ø[deg]=	None
XDALFBET	XD*a*-ß[d]=	None
XDDELTAD	XDblaze[deg]=	None
ECDELTAD	ECblaze[deg]=	B
ECDELTA	ECblaze[rad]=	None

Section 4 Command Line Interaction

When the user has "quit" from the graphical interaction (by simply typing 'q' while in the graphic window), the program enters another mode where the interaction is done on the text screen. All commands in this mode must be followed by a carriage return <CR>.

Command	Action
W	Write a ?le format.out describing the Echelle format.
G	Go back to start and ask for new con?guration.
F	Get a new ?le with spectral line wavelengths.
L	Make a PostScript plot.
R	Refresh graphics and return to graphical interaction.
M	Minimize deviations of lines from blaze wavelength.
Q	Quit the program.
I	Return to graphical interaction.
D	Write a KICS setup ?le to disk, and optionally execute it.

Chapter 4 Preparation for Observing

This section is not yet written. Some possible items for inclusion are:

1. checklist for caveats on program object observability, etc.
2. ?nder charts, coordinates, offset stars, ...
3. blind offsets and faint object acquisition and guiding
4. choice of targets
5. choosing wavelength ranges, resolutions, sky sampling,...
6. estimating exposure times
7. common acquisition/observation problems?
8. running the simulator creating and uploading set-up ?les
9. plan on arriving early?
10. remote observing?
11. pre-observing run checklist

Chapter 5 Observing at Keck

Some of these sections are not yet complete...

Section 1 Arrival at the Mountain-top

Section 2 Starting Up the Instrument

The mountain staff will take care of starting up the xhires and xpose control windows, plus any other instrument status information windows desired by the user. The HIRES CCD dewar gets ?lled automatically about once per day. It is a good idea to note the dewar level and decide whether an automatic ?ll may occur during the eveining observing hours. The auto?ll procedure does dump some cold into the spectrograph, and probably moves the CCD dewar by a very small amount due to the added weight of the liquid nitrogen, plus various thermal excursions in the surrounded metal structure. For highest precision work, I advise that one NOT allow an auto?ll during observing. Thus if an auot?ll during the night looks probable, take time in the late-afternoon to force an auto?ll before starting calibrations.

Section 3 Selecting a Spectral region

Collimator choice The most fundamental decision a user wil have to make concerns optimizing the ef?ciency of the optical train for the desired spectral region. The ?rst choice in this regard concerns which collimator (red or blue) to use. Consult the curves in Figure 5 for this choice.

Cross-disperser choice The next decision concerns both ef?ciency for the spectral region and desired order separation. At present, we have only one CD, but this can be used in either 1st or 2nd order. Most applications redward of 0.4 microns will use the 1st order, while most blueward of here will use 2nd order. Consult both the ef?ciency curves of Figure 6, and the HIRES spectral format simulator for this decision.

Order-blocking ?lters Once the CD order decision is made, you will have to think carefully about how to block unwanted orders from the CD. Here, Table 5and Figures 3 and 4 will help in this decision. Once these ?lters are selected, the collimator will be automatically refocussed for the new ?lter thickness combination.

Section 4 Choosing the Entrance Aperture

slit width The user must set the slit width to give the desired spectral resolution. Basically, the de-projection factor (from actual slit width to projected slit width in the echelle dispersion plane at the CCD) is about 1/8.715 which results in a scale of about 12.44 arcsecs/mm at the CCD in the echelle dispersion direction. The present CCD pixel size is 24 microns or 0.024 mm. Thus a 2–pixel projected slit is about 0.60 arcescs wide as projected on the sky. The resultant spectral resolution will be some thing like a gaussian quadrature sum of the projected slit, the pixel size, and the camera aberrations blur circle. Effectively, this 0.6 arcsec slit translates to a spectral resolving power of about 54,000 —60,000. A 0.9 arcsec slit width projects to about 3 pixels width and results in a resolving power of about 45,000. A 1.1 arcsec slit projects to 4 pixels width and yields a resolving power of about 34,000. In the limit of larger slits (where camera aberrations and ?nite pixel widths are small), the effective 'throughput' (slit width times resolving power product) is about 39,000 arcsecs.

The slit must be used with one of the notches in Decker Plate A to de?ne slit length and keep orders from overlapping. If instead the user wishes to use one of the apertures from Decker plates B-D (which de?ne both slit width and length), the slit must be opened fully to keep it from blocking any light. This is done at present by doing the command 'm slitwid=11.1', but will eventually be an option in 'xhires'.

slit length Slit length (de?ned either by one of the notches in Decker plate A, or by one of the apertures on the other decker plates) must be chosen according to the available order separation at the spectral region of interest and the need for sky subtraction. Consult the echelle format simulator for the minimum order separation available in your chosen spectral region, and set the slit length to be less than this. If sky is not important to measure, a slit length only a bit bigger than the seeing disk is adequate. However, it is generally prudent to make the slit length as long as possible to measure as much sky as possible, but short enough such that one still leaves rooom for some rows of 'dark' between orders.

decker vs. slit considerations The guide star image looks much worse when guiding off the slit+decker A combination than it does guiding off a simple decker. Thus, for faint object work, use of the deckers alone will be preferable. For work requiring a longer slit, or narrower slit than 0.6 arcsecs requires use of the normal slit jaws.

In any case, once either the slit, or the decker is selected, the collimator will automatically be refocussed properly. (Basically, the system looks to see if decker plate A is being used. If so, it assumes you are to be using the slit jaws. If not, it wil refocus for the decker plates). There is about a 1/8" difference in the focal planes of these two entrance apertures.

Section 5 CCD Readout Mode

windowing binning fast/slow readout modes MPP (full well vs. dark current) modes Multiple vs. single ampli?er modes

Section 6 Focussing

Section 7 Taking Calibration Exposures

Flat ?elds Wavelength calibration and instrumental pro?le Th-Ar hollow cathode lamps

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E-B bands Iodine Absorption Cell Spectrum Dark Frame(s) Bias (zero) Frame(s) Day/Twilight Sky and/or Moon Spectra

Section 8 End of the Evening

Final calibration frames?ShutdownDewar auto-?ll

Section 9 End of the Observing Run

Section 10 Observing Checklist

Section 11 Observing Log Sheets

Chapter 6 Data Reduction

Section 1 FIGARO

FIGARO is the CARA standard for quick-look data reduction at Keck Obser-vatory. The HIRES data frames are normally written to disk in FITS format, and FIGARO can read these FITS format ?les. The FITS format is the default standard for HIRES. However, there is a switch selectable option which allows the user to write the data in FIGARO-style format and thus bypass the FITS—to—FIGARO conversion, if so desired.

At this time, due partly to lack of a well-supported and fully-developed FIGARO system, and partly to lack of in?nite software manpower resources, a FIGARO HIRES reduction suite of routines is not available from the HIRES development team. No doubt existing FIGARO/echelle packages will work with enough patience and tuning.

Section 2 IDL, KHOROS, and Others

Since the HIRES data is in FITS format, many other data reduction/analysis packages can be used. Gibor Basri and co-workers at U.C. Berkeley prefer IDL, and have many useful scripts and routines written to do echelle data reduction. Others like the Khoros package. All should work just ?ne, though each will have its own particular bugs and irregularities to overcome before becoming user-friendly for a task as complex as echelle data reduction.

Section 3 IRAF

IRAF is the reduction environment recommended by the P.I. for HIRES. An optimized version of IRAF utilities, which have been set up to know about many of the actual instrument parameters lives on the CARA network and will be maintained by the project's software of?ce.

First-time users of IRAF and/or echelle spectrometers would be very well-advised to obtain a copy of A User's Guide to CCD Reductions with IRAF (Massey, 1992). This is an excellent guide to basic IRAF data reduction of echelle CCD images. Read it carefully before starting any reductions. In fact, a careful read through before observing will give you a much better feeling for what kind of calibration frames to obtain with your program object data, and how they will be used.

I will now try to walk you through a very basic set of reductions on a typical data set from HIRES. This will be only a simple example, but will illustrate many of the most important aspects of the data reduction. I will assume you are generally familiar with running IRAF, in using its eparameters feature, in ?nding your way around within its libraries of routines, and understanding what kinds of data it creates and where such data lives.

Getting set up with data in the appropriate directory I will also assume that you have logged onto some Sun Sparc station running X11 windows, with the latest version of IRAF installed, and that you have moved over into some directory which contains your images. This directory will also end up containing (as subdirectories) all the databases, etc. generated by IRAF when it munches on your data. I like to break my directory up as IRAF in the top level, and then subdirectories containing groups of data ?les which are to be combined together in a reduction. For this example, I will assume we have obtained a group of exposures of the day sky (solar) spectrum plus calibration spectra at some place in the echelle format, and that these data ?les have been put into the directory: /u/vogt/IRAF/demo.

The data frames to be used in this sample reduction are:

solar.?ts (a 100–second observation of the solar spectrum)

quartz.?ts (the spectrum of a quartz-halogen incandescent lamp)

dark.?ts (an 1800–second observation of the dark level in the spectrograph)

zero.?ts (a 'zero-length' (<1s) exposure on dark to determine bias levels)

thar.?ts (a 1–second observation of the Thorium-Argon hollow-cathode lamp, used for wavelength calibration)

Note that, for full-blown data reductions, one might well have several zero frames, several quartz frames, and several dark frames. These would then be combined into more noise-free calibration frames by median-?ltering out cosmic rays, by simple averaging to reduce readout noise, and by suitable interpolation, if necessary between bracketing calibration exposures. There are a number of strategies which can be used within IRAF to combine calibration data frames to squeeze out the last bit of instability from the instrument as needed for the particular project.

Note also that these frames could (and generally would) end up with much more abstract names, such as n0045.?ts, or data0131.?ts, when read into the subdirectory in which you plan to work. If they do, you might wish to consider changing their names before you get started to more obvious descriptions of what they represent so that you don't get confused later in the reductions. For example, quartz's might be labelled quartz1, quartz2, etc. Darks of various exposure times might be called dark100s, dark500s, etc. Try to stick with short names to minimize typing, and keep names fairly distinct so that you can make most use of command line interpreters when wild-carding to again save typing.

You should now start up, from a separate xwindow, the SAOIMAGE tool. The reason we start this up from a separate xwindow is because it sends text at you from time to time, and it is annoying to have that chatter break in on your IRAF text.

Now, from a different xterm window than the one you used to start up SAOIMAGE, move into your IRAF directory and type <cl> to get IRAF going. Then 'cd' into the demo subdirectory where the images are (I don't understand why you can't just start IRAF from this demo subdirectory, but that's ok for now).

Reading FITS ?les into IRAF The very ?rst task is to get your FITS ?les read into IRAF, as *.imh ?les. Get into the parameter editing mode of the 'r?ts' task by typing epar r?ts. This is what you will see:

IRAFImage Reduction and Analysis FacilityPACKAGE = dataioTASK = rfits

fits_fil= solar.fits,quartz.fits,thar.fits,dark,fits,zero.fits FITS data sourcefile_lis= 1 File listiraf_fil= solar,quartz,thar,dark,zero IRAF filename(make_im= yes) Create an IRAF image?(long_he= no) Print FITS header cards?(short_h= yes) Print short header?(datatyp= ushort) IRAF data type(blank = 0.) Blank value(scale = yes) Scale the data?(oldiraf= no) Use old IRAF name in place of iraf_file?(offset = 0) Tape file offset(mode = ql)

On the ?rst line, for ?ts_?l, enter the names of the ?les to be read in (I've already typed in the ?ts_?l and iraf_?l lines for you). These ?lenames will all be entered on one line, with commas (and no spaces) between names. They are: solar.?ts,quartz.?ts,thar.?ts,dark.?ts,zero.?ts. Using the same sequence of names for the iraf_?l parameter will give the IRAF ?les the same names, but the extension will be' .imh'. I like to do it this way to avoid getting confused with renamed ?les.

It is also very important that the datatyp parameter be set to either ushort (unsigned short), or real, and that the scale parameter be set to 'yes'. Once ?nished, type <:g> to exit and execute. You may now wish to check your directory to see that all the corresponding *.imh ?les have been created. You might also want to check your disk space with a <df .> to make sure you have enough room to keep going.

Once data ?les are read in with r?ts and converted to *.imh ?les, each *.imh ?le will actually be carried around as both a header ?le (*.imh) and a corresponding *.pix 'pixel' ?le (i.e. where all the pixel information is kept). The pixel ?les live in a directory speci?ed by the logical variable imdir. In my setup, imdir is set to HDR$pixels/. This setup puts the pixel information in a subdirectory called ‘pixels’ and you can ‘cd’ there and ‘ls’ them to see that they really do now exist. The main point here is that IRAF image ?les are actually associated pairs of header and pixel ?les. Thus, when copying, deleting, etc. such ?les, it is generally much easier to use the commands imcopy, or imdel, etc. since these commands also keep track of all the housekeeping for the associated image ?les.

Checking Header Information It is useful at this point to check your headers to see that all looks well, and, more importantly, that you have the right keywords describing the type of images in each case. Initially, this is a must since we are still working out FITS keyword assignments, but soon, this step will not be necessary, unless of course you screwed up and recorded, say, an object frame which was really a dark frame, or something else. In this case, you would want to go in and edit the appropriate keywords to keep IRAF from getting confused over which ?les are which.

You can use ccdlist to get a brief review of your ?les, or imhead (with long = yes) to check out what’s in their headers, followed by hedit if necessary to actually make any changes. For example, to add the keyword IMAGETYP and set it equal to ‘object’ in the header for ?le solar.imh, you would do: hedit solar imagetyp object ver-, or else do it from the epar route on hedit.

Setting the Instrument Parameters Once you are satis?ed that you have all the necessary ?les read in and converted to IRAF *.imh ?les, with appropriate names and keywords, you are ready to begin the actual data processing. The ?rst step is to inform IRAF what instrument set-up con?guration you are using, and get it loaded. Type setinstrument to load the setinstrument package for HIRES. You will be asked the question: Instrument ID (type ? for a list) (hires):. Assuming it is the HIRES instrument ?le you will be using, hitting a simple <return> will load the default option hires and then move you onward to the ccdred task in the imred package.

You will not see the parameter list for setinstrument, , but it can of course be accessed by epar’ing on setinstrument. It looks like this:

Image Reduction and Analysis FacilityPACKAGE = ccdredTASK = setinstrument

instrume= hires Instrument ID (type ? for a list)(site = keck) Site ID(directo= ccddb$) Instrument directory(review = yes) Review instrument parameters?query = Instrument ID (type q to quit)(mode = ql)

CCDRED You are now in the epar mode in the parameter list for the package ccdred. This is what you’ll see:

Image Reduction and Analysis FacilityPACKAGE = imredTASK = ccdred

(pixelty= real real) Output and calculation pixel datatypes(verbose= yes) Print log information to the standard output?(logfile= logfile) Text log file(plotfil=) Log metacode plot file(backup =) Backup directory or prefix(instrum= ccddb$keck/hires.dat) CCD instrument file(ssfile = subsets) Subset translation file(graphic= stdgraph) Interactive graphics output device(cursor =) Graphics cursor input(version= 2: October 1987)(mode = ql)

A crucial parameter here is pixelty, which must be ‘real’ for both output and

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calculation types. This does eat up more disk space, but you run the risk of data over?ow if you don't do this. Note that the instrum parameter is already set up for you. When done with this parameter list, exit by typing <:g> to exit and execute. This will move you over into the epar mode in the ccdproc task of the ccdred package.

CCDPROC You will now be in the epar mode of the task ccdproc:

Image Reduction and Analysis FacilityPACKAGE = ccdredTASK = ccdproc

images = solar,quartz,thar,dark,zero List of CCD images to correct(ccdtype= object) CCD image type to correct(max_cac= 32) Maximum image caching memory (in Mbytes)(noproc = no) List processing steps only?

(fixpix = no) Fix bad CCD lines and columns?(oversca= yes) Apply overscan strip correction?(trim = yes) Trim the image?(zerocor= yes) Apply zero level correction?(darkcor= yes) Apply dark count correction?(flatcor= no) Apply flat field correction?(illumco= no) Apply illumination correction?(fringec= no) Apply fringe correction?(readcor= no) Convert zero level image to readout correction?(scancor= no) Convert flat field image to scan correction?

(readaxi= line) Read out axis (column|line)(fixfile=) File describing the bad lines and columns(biassec= [2100:2112,*]) Overscan strip image section(trimsec= [23:2070,*]) Trim data section(zero =) Zero level calibration image(dark =) Dark count calibration image(flat =) Flat field images(illum =) Illumination correction images(fringe =) Fringe correction images(minrepl= 1.) Minimum flat field value(scantyp= shortscan) Scan type (shortscan|longscan)(nscan = 1) Number of short scan lines

(interac= yes) Fit overscan interactively?(functio= spline3) Fitting function(order = 3) Number of polynomial terms or spline pieces(sample = *) Sample points to fit(naverag= 4) Number of sample points to combine

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(niterat= 5) Number of rejection iterations(low_rej= 5.) Low sigma rejection factor(high_re= 1.75) High sigma rejection factor(grow = 3.) Rejection growing radius(mode = ql)

Input the names of the images you wish to 'correct' (i.e. reduce), or the name of a ?le which contains a list of the images to be corrected. For our example, these will be solar.imh, quartz.imh, thar.imh, dark.imh, and zero.imh. Type them all in on one line, with commas, but no spaces between. The ccdtype parameter being set to 'object' tells the routine to perform dark current correction only to ?les with IMAGETYP = object in their FITS headers. The max_cac parameter can be increased as allowed by available memory to speed processing time. Oversca = yes means we will be correcting each image for row-to-row baseline variations using the overscan strip (presently image columns 2070 to 2112). The baseline will be measured in the overscan area for each row and then a smoothed version of this baseline measure will be subtracted row-by-row from the image. Trim = yes will trim each image, stripping off the ?rst 22 prescan columns (which do not contain real image pixels) and the columns beyond 2070 which, at present, are reserved for overscan pixels. Zerocor = yes will cause the image with IMAGETYP = zero in its FITS header (i.e. our ?le named zero.imh) to be subtracted from each image to remove the bias level (curently set near 1100 dn). Darkcor = yes will instruct the routine to use the image with the IMAGETYP = dark keyword in the FITS header (i.e. our ?le called dark.imk) to determine the dark current (dn/pixel-sec), and then scale that dark current to the correct exposure time for each image, before then subtracting that dark current. The other processing switches won't be used right now. Most are fairly self-explanatory.

Readaxi = line tells the routine that the readout axis is along the row (line) direction. We don't have a ?x?le image yet for descibing and ?xing bad lines or columns. The biassec and trimsec parameters shown here are correct for de?ning the overscan and trim regions for the present single-ampli?er readout con?guration. They will be different for dual-ampli?er readout, and they may change also as we do more optimizing of the CCD. Check the locations of these araes yourself to see that things are where you expect them. You don't need ?le names for zero, dark, ?at, etc. since these ?les will already have the correct IMAGETYP FITS header keywords, and the routine will be smart enough to recognize them as such. For this example, we will be ?tting the overscan region interactively using a cubic spline.

So, before moving on, let's summarize what we are now about to initiate when we <:g> out of this parameter list. We are set up to do overscan correction, bias (zero) frame correction, and dark current correction of each object image (note that we are including our 'quartz' and our 'thar' images as object images which also need correcting). The images will also be trimmed of their prescan and overscan regions. When happy with the set-up, type <:g> which will send you onward.

Note: if IRAF has some trouble locating or otherwise deciding upon correct image types for your data ?les, it may well return immediately to the command line prompt without actually doing anything, nor telling you that it didn't do anything. The processing will take a while, so if it returns immediately, something is probably wrong.

If all is well, IRAF will begin trimming the frames, and extracting baseline information. Since we speci?ed interactive baseline ?tting, it will put you into the interactive baseline ?tting mode for each frame. Try playing with the baseline ?tting from the tektronix plot window displayed. If totally lost as to what to do next, from the tektronix plot window just type <?> and you'll get a help summary. But you must <q> twice out of the help summary to get back to interactive mode in the tektronix window.

Useful commands to play around with in interactive ?tting of the baseline (or for many interactive ?tting tasks) are :high (high reject level, sigma units), :low (low reject level), :niter (number of iterations), :order, and :show (to display these parameters). Try to get as low order of a spline as possible that ?ts the baseline reasonably well. When done, type <q> to quit out of each interactive ?tting session and move on to the next frame to be baselined.

When all ?nished in ccdproc, go take a look at your ?les with ccdlist. and you should see all the processing operations that have now been done on them, along with the dates of when the operations were done. This may begin to give you a warmer feeling that something useful is now happening to your data.

Tracing the Echelle Orders The next step is to use the quartz spectrum to locate the positions and track the shapes of all the echelle orders. We generally use the quartz since it is a nice high S/N smooth spectrum with easy to ?nd orders. But one could use a spectrum of a star, or some other reference if desired. The

point is that you want the echelle orders of this reference frame to correspond as closely as possible to where your object orders will be.

To ?nd and trace the echelle orders, we will use the task apall. Here is its parameter list:

IRAFImage Reduction and Analysis FacilityPACKAGE = echelleTASK = apall

input = quartz List of input images(output =) List of output spectra(format = echelle) Extracted spectra format(referen=) List of aperture reference images(profile=) List of aperture profile images

(interac= yes) Run task interactively?(find = yes) Find apertures?(recente= yes) Recenter apertures?(resize = no) Resize apertures?(edit = yes) Edit apertures?(trace = yes) Trace apertures?(fittrac= yes) Fit the traced points interactively?(extract= yes) Extract spectra?(extras = yes) Extract sky, sigma, etc.?(review = yes) Review extractions?(line = 900) Dispersion line(nsum = 10) Number of dispersion lines to sum

DEFAULT APERTURE PARAMETERS

(dispaxi= 1) Dispersion axis (1=along lines, 2=along columns)(lower = -20.) Lower aperture limit relative to center(upper = 20.) Upper aperture limit relative to center(apidtab=) Aperture ID table (optional)

DEFAULT BACKGROUND PARAMETERS

(b_funct= chebyshev) Background function(b_order= 1) Background function order(b_sampl= -28:-21,21:28) Background sample regions(b_naver= -3) Background average or median(b_niter= 0) Background rejection iterations(b_low_r= 3.) Background lower rejection sigma(b_high_= 3.) Background upper rejection sigma(b_grow = 0.) Background rejection growing radius

APERTURE CENTERING PARAMETERS

(width = 40.) Profile centering width(radius = 40.) Profile centering radius(thresho= 10000.) Detection threshold for profile centering

AUTOMATIC FINDING AND ORDERING PARAMETERS

nfind = 30 Number of apertures to be found automatically(minsep = 50.) Minimum separation between spectra(maxsep = 1000.) Maximum separation between spectra(order = increasing) Order of apertures

RECENTERING PARAMETERS

(apertur=) Select apertures(npeaks = INDEF) Select brightest peaks

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(shift = yes) Use average shift instead of recentering?

RESIZING PARAMETERS

(llimit = INDEF) Lower aperture limit relative to center(ulimit = INDEF) Upper aperture limit relative to center(ylevel = 0.1) Fraction of peak or intensity for automatic widt(peak = yes) Is ylevel a fraction of the peak?(bkg = no) Subtract background in automatic width?(r_grow = 1.1) Grow limits by this factor(avglimi= yes) Average limits over all apertures?

TRACING PARAMETERS

(t_nsum = 8) Number of dispersion lines to sum(t_step = 16) Tracing step(t_nlost= 128) Number of consecutive times profile is lost befo(t_funct= spline3) Trace fitting function(t_order= 3) Trace fitting function order(t_sampl= *) Trace sample regions(t_naver= 1) Trace average or median(t_niter= 10) Trace rejection iterations(t_low_r= 2.5) Trace lower rejection sigma(t_high_= 2.5) Trace upper rejection sigma(t_grow = 0.) Trace rejection growing radius

EXTRACTION PARAMETERS

(backgro= none) Background to subtract(skybox = 1) Box car smoothing length for sky(weights= none) Extraction weights (none|variance)(pfit = fit1d) Profile fitting type (fit1d|fit2d)(clean = no) Detect and replace bad pixels?(saturat= INDEF) Saturation level(readnoi= 4) Read out noise sigma (photons)(gain = 2.38) Photon gain (photons/data number)(lsigma = 4.) Lower rejection threshold(usigma = 4.) Upper rejection threshold(nsubaps= 1) Number of subapertures per aperture(mode = ql)

Obviously there are a large number of parameters in this very generalized and powerful task. The ones shown here worked well for a shot in 1st order of the cross-disperser, in the 4800 to 7000 angstrom range, where the decker used projects to a height of about 38 rows. You will probably have to modify several parameters if your order spacing and/or order widths (set by the decker length usually) are different.

Some of the most crucial parameters to set properly are width and radius. I'm told that the width parameter must be just slightly bigger than the width (in rows or lines) of the widest echelle order. In our example, this is about 38 rows, so I set width to 40. Also, the radius parameter should be set to the same value. Eventually, we will be able to use the instrument keywords and/or set up routines to set this parameter automatically, but for now, you must display your image in SAOIMAGE (using the task display), roam around looking at order widths, and decide upon the correct value for width .by measuring the width of the widest order. Actually, all orders should be very nearly all the same width, save for slight anamorphic and distortion effects.

Here are some other noteworthy parameters. The parameter line is the column where the order tracing routine starts its search. I've set it at 900 to avoid starting in the 'dark blob' near chip center, which may confuse the algorithm. (This blob is a mark from a felt-tip pen, kindly put on this $100,000 CCD by some technician at Tektronix to remind us that this is an engineering-grade device). The parameters lower and upper de?ne the lower and upper limits of the tracing aperture relative to order center. The parameter b_sampl de?nes the background sample region, and has been set to run just outboard of the tracing window here. The parameter n?nd must be at least as big as the number of orders to be found. The parameter minsep must be set correctly, but the parameter maxsep can be any number much larger than your order separation.

So when ready type <:g> to exit and execute apall, and start answering interactive mode prompts. It will ask questions about whether or not you want to resize apertures for quartz, edit apertures for quartz, etc. Your answers will depend on whether this is your ?rst time through, or whether you have already run the routine, and have previous aperture information stored away in the database subdirectory, so answer carefully. When satis?ed with each ?t to each order, type <q> to quit and move on to the next order. As with all interactive question and answer sessions within IRAF, If you get tired of answering 'yes's, just type YES (all caps).

If all the parameters are set reasonably well, apall should have no problem ?nding all orders. If it does have problems (and you should check by going through in interactive mode at least once), then try playing around with parameters. And you can always do an end-run around the auto —order —?nding routines and just mark them by eye interactively if you wish. It is very important at this stage to verify that your apertures are reasonably well ?t to the orders, so I suggest looking at them in detail in the interactive mode of apall. Be sure that apertures from adjacent orders do not ever overlap, and that all orders (except perhaps for the ?rst and/or last, which are often partial since they fall off the chip edges) are present and accounted for.

When ?nished, you will be asked if you want to write the apertures to the database. You should answer yes, and IRAF will create a subdirectory called 'database', where it saves all the aperture information (along with lots of other information to come).

Now you can extract and review each quartz order to check that they all look reasonable. If you wish some hard copies, just type .snap and you'll get a laser print of the Tektronix plot window. If the orders all look good, you have successfully located and traced all the echelle orders, and are done with apall.

Generate the Flat-Field Image The next task is to generate a ?at-?eld image (from the quartz) which can remove pixel-to-pixel (predominantly high spatial frequency) variations. We do this using the task apnormalize. This task will take the quartz image, remove the low spatial frequency variations (i.e. blaze pro?le), and create a normalized ?at-?eld image which I will call '?at'.

The reason we would like to normalize out the low— frequency quartz spectrum variations is that doing a straight division by a quartz frame will give excess weight to those pixels where the quartz illumination happens to be low (either away from blaze or away from the center of the aperture). One could not go on to perform an optimal extraction if you ?at ?elded in this manner.

Here is the apnormalize parameter ?le for doing this, using 'quartz.imh' as the input and' ?at.imh' as the output:

Image Reduction and Analysis FacilityPACKAGE = echelleTASK = apnormalize

input = quartz List of images to normalizeoutput = flat List of output normalized images(referen=) List of reference images

(interac= yes) Run task interactively?(find = no) Find apertures?(recente= no) Recenter apertures?(resize = no) Resize apertures?(edit = no) Edit apertures?(trace = no) Trace apertures?(fittrac= yes) Fit traced points interactively?(normali= yes) Normalize spectra?(fitspec= yes) Fit normalization spectra interactively?

(line = INDEF) Dispersion line(nsum = 10) Number of dispersion lines to sum(cennorm= no) Normalize to the aperture center?(thresho= 10.) Threshold for normalization spectra

(backgro= none) Background to subtract(weights= none) Extraction weights (none|variance)(pfit = fit1d) Profile fitting type (fit1d|fit2d)(clean = no) Detect and replace bad pixels?(skybox = 1) Box car smoothing length for sky(saturat= INDEF) Saturation level(readnoi= 4) Read out noise sigma (photons)

(gain = 2.38) Photon gain (photons/data number)(lsigma = 4.) Lower rejection threshold(usigma = 4.) Upper rejection threshold

(functio= spline3) Fitting function for normalization spectra(order = 3) Fitting function order(sample = *) Sample regions(naverag= 1) Average or median(niterat= 3) Number of rejection iterations(low_rej= 3.) Lower rejection sigma(high_re= 3.) High upper rejection sigma(grow = 0.) Rejection growing radius(mode = ql)

If you do it interactively (as you should the ?rst time through), you will have the opportunity to play with all the ?tting parameters. Try to use the lowest order spline as possible when ?tting out the quartz's low frequency variations or you will risk introducing ripples into your ?at-?elded spectrum.

Again, be careful how you answer questions about resizing and editing apertures, etc. If you want to stick with the apertures you just found in apall, be sure not to ?nd, recenter, resize, or edit the aperutres.

When ?nished, you should do a sanity-check, using the task display to display ?at.imh and visually inspect for unexpected results, etc. You should have nice uniform intensity quartz spectrum orders, with lots of clear dark space in between. If you histogram equalize the image, you may also be able to see the 'meteor', which is a scattered light feature of the spectrograph. It generally runs diagonally across the chip, and is brightest when crossing each order. You will also see the prominent dark blob near CCD center. Again, if you need hardcopy output, use the print button under the etc menu in SAOIMAGE.

Flat-Fielding the object images With the normalized ?at-?eld image in hand from the previous step, you are now ready to use the task ?atten (located in the generic package) to remove the high-spatial-frequency pixel-to-pixel response variations. We will ?at-?eld correct both solar.imh and thar.imh, using the ?at-?eld image ?at.imh. The ?attening routine resides in a package called generic, so load this package by typing generic, and then epar into ?atten. The parameter list for ?atten should look like this:

IRAFImage Reduction and Analysis FacilityPACKAGE = genericTASK = flatten

images = solar,thar Images to be flattenedflatfiel= flat Flat field(minflat= INDEF) Minimum flat field value

(pixtype= real) Flattened image pixel datatype(keeplog=)_.keeplog) Keep log of processing?(logfile=)_.logfile) Log file(imlist = tmp$ims7334a)(imfd = tmp$ims7334a)(input =)(flat = flat)(flt = flat)(mode = ql)

Note that ?atten will write the ?at-?elded images back over the originals, so if you want to go back to un?attened solar.imh and thar.imh, you will have to imdel these ?les and r?ts in both solar.?ts and thar.?ts again. It is also a good sanity check now to display the newly-?attened solar and thar ?les. They should look clean, with nice dark spaces between orders, and perhaps a bright line along the edges of each order. Note that they have only had the high frequency pixel-to-pixel variations removed at this point, and will still show the low-frequency blaze pro?le variation in intensity. That will be removed later. It is also humbling and scary to roam around a bit on the histogram-equalized thar frame, searching for ghosts. You'll see a number of them, as well as the 'meteor'.

Removing scattered background light The next task is to measure and remove the scattered background light. This is light which shows up between the orders, and which results from scattered light, ghosts, and other re?ections inside the spectrograph. You will use the task apscatter in the echelle package of routines, so 'bye' out of the generic package if you aren't already out, and get into the echelle package now.

Basically, apscatter will allow one to interactively ?t a function (using to the interorder light, both in the row and column directions. This 2–d functional ?t to the background is then subtracted from the given image. Note here that scattered light will depend strongly on the illuminating source, and thus each individual data frame will have different scattered light characteristics. Furthermore, features like the 'meteor' would require quite high order to ?t accurately, and may be quite tricky to remove. In many cases, it may be better (depending on the data and application) to simply steer clear of the regions contaminated by the meteor.

So here is the parameter list for apscatter, set up to use solar.imh as the input, quartz.imh as the reference image for the apertures, and to write the output as solar.ds.imh (solar de-scattered). Note that we are again getting our aperture information from the quartz image:

Image Reduction and Analysis FacilityPACKAGE = echelleTASK = apscatter

input = solar List of input images to subtract scattered lightoutput = solar.ds List of output corrected images(scatter=) List of scattered light images (optional)(referen= quartz) List of aperture reference images

(interac= yes) Run task interactively?(find = no) Find apertures?(recente= no) Recenter apertures?(resize = no) Resize apertures?(edit = no) Edit apertures?(trace = no) Trace apertures?(fittrac= no) Fit the traced points interactively?(subtrac= yes) Subtract scattered light?(smooth = yes) Smooth scattered light along the dispersion?(fitscat= yes) Fit scattered light interactively?(fitsmoo= yes) Smooth the scattered light interactively?(line = 900) Dispersion line(nsum = 10) Number of dispersion lines to sum(buffer = 1.) Buffer distance from apertures(apscat1=) Fitting parameters across the dispersion(apscat2=) Fitting parameters along the dispersion(mode = ql)

Note that we've set all the ?nd, recenter, resize, edit, and trace aperture parameters to no since we will be using the apertures found from the quartz spectrum. The line=900 was set to try to avoid the dark blob, but the routine started anyway at column 1024, so this didn't seem to matter.

It will start by giving you a cut down column 1024. Identify what you think are the 'scattered light' points, and ?t them interactively using :order, :low, :high, and :niter commands to adjust the order, the low and high reject threshholds, etc. In general, you'll want to set the :high threshhold pretty low, to reject high points which come from edges of orders, etc.. And you'll want to set the :low threshold pretty high so as not to reject many low points (because most of them will contain useful dark information). Again, try to stay with as low an order as you can to avoid introducing ripples.

When satis?ed with each column's ?t, type 'q' to quit and you will be prompted for a new column value. You must reply with a 'col 100' to ?t along column 100 etc. I suggest ?tting at every 100 columns across the CCD. You can go across the CCD once, ?tting every 100 columns, and you can return to places later for re-?tting if necessary until you've got it just the way you want. There is presently a diffuse halo in the scattered light (like the 'ring nebula' at very low light level, centered roughly on the center of the CCD. You may notice the double-peaked signature of this halo as your cuts move across the chip. It may require even 5–7 orders to ?t well. But out near the edges, away from this halo, a lower order spline should suf?ce. Hopefully, anti-re?ection coating the ?eld-?attener lens will reduce this halo.

Once you've got a full set of columns ?t, quit out of the routine. It will then go away for a long time (many mnutes) calculating the proper smoothed ?t to the background in the row direction. When it returns, it will display a row cut across the image at row 1024, and you must repeat the above process for a series of rows across the image. Again, it is good to do a ?t every 100 rows across the CCD, keeping the order as low as possible. When ?nished, quit out of the routine. You should then use display and/or implot to examine your de-scattered light result to see that all looks as expected.

Extracting Orders and Compressing to 1–d Spectra You are now ready to use apsum to extract the orders and compress them into 1–d spectra. We will extract both solar.ds.imh, and thar.imh (for this demo, I didn't bother correcting the thar.imh for scattered light since I will only use it for wavelength calibration anyway). Here is the parameter ?le for this:

Image Reduction and Analysis FacilityPACKAGE = echelleTASK = apsum

input = solar.ds,thar List of input images(output =) List of output spectra(format = echelle) Extracted spectra format(referen= quartz) List of aperture reference images(profile=) List of aperture profile images (interac= yes) Run task interactively?(find = no) Find apertures?(recente= no) Recenter apertures?(resize = no) Resize apertures?(edit = no) Edit apertures?(trace = no) Trace apertures?(fittrac= no) Fit the traced points interactively?(extract= yes) Extract apertures?(extras = no) Extract sky, sigma, etc.?(review = yes) Review extractions?(line = INDEF) Dispersion line(nsum = 10) Number of dispersion lines to sum

(backgro= none) Background to subtract (none|average|fit)(weights= none) Extraction weights (none|variance)(pfit = fit1d) Profile fitting type (fit1d|fit2d)(clean = no) Detect and replace bad pixels?(skybox = 1) Box car smoothing length for sky(saturat= INDEF) Saturation level(readnoi= 0.) Read out noise sigma (photons)(gain = 1.) Photon gain (photons/data number)(lsigma = 4.) Lower rejection threshold(usigma = 4.) Upper rejection threshold(nsubaps= 1) Number of subapertures per aperture(mode = ql)

By not putting explicit names in the list of output spectra, we will be accepting the default whereby extracted spectra keep the same name, but with addition of a .ec exptension. Again, we will be using the quartz.imh image as the reference for apertures. Also, for this run, we will not be extracting 'sky' (since there really is none in these data). We will do a simple sum along columns in the aperture window for this extraction, but of course more complex extractions (such as optimally-weighted summation) can also be done here. You should review each extracted order interactively, or use splot to again sanity-check for correctness.

Wavelength Calibration We will now use the task ecid to do a wavelength calibration using the thar.ec.imh spectrum. IRAF has a catalog of some 3000 Th-Ar lamp emission lines, and will use this information, in conjunction with the many line positions found in your thar reference spectrum to compute a very accurate wavelength solution for each order. You might wish to obtain a copy of

A CCD Atlas of Comparison Spectra: Thorium-Argon Hollow Cathode 3180 A — 9540 A (Willmarth, 1987) from NOAO. It is helpful for recognizing and indentifying features in your Th-Ar spectrum. Unfortunately, it doesn't look that similar to the speci?c lamp used in HIRES, so don't expect line strengths or line strength ratios to be the same. Only line spacings can be trusted, and some lines won't even be there. A better aid is the Th-Ar atlas we are currently working on, taken with the actual HIRES lamp. Graduate student Mike Keane at UCO/Lick is championing this. Hopefully it will soon be available as a UCO/Lick Technical Report. You may also wish to run a session of the HIRES echelle simulator to aid in ?nding features. If you get it set up fairly closely to how the data was obtained, you can read wavelengths off at any column in any order quite rapidly.

Wavelength ?tting is a bit tricky since, if you get a few wrong identi?cations near the start, you can end up going down an incorrect path, and arrive at an incorrect solution. This is largely because there are so many Th-Ar lines, that the routine can almost always ?nd one near where it thinks one should be. And then, if you let it start ?nding its own lines, without properly constraining it enough, it will quickly accumulate a list of incorrectly-identi?ed lines which will overwhelm your relatively small list of proper identi?cations, and converge on the wrong solution!

So you have to start out slowly, giving it a few tens of lines scattered across the format, and letting it ?nd small numbers of its own. When con?dent that it is ?nding lines correctly, then you can turn up maxfeat to the maximum of 3000 and really let it go hog wild. But to begin with, I'd suggest setting maxfeat at about 20, and inputting 10 to 20 features manually. Of course the easiest landmarks to identify are the very bright Argon lines which appear redward of about 7000 A, but if you don't have any of these in your spectrum, stick with the strongest features at ?rst. Here is a reasonable starting parameter list for ecid:

Image Reduction and Analysis FacilityPACKAGE = echelleTASK = ecidentify

images = thar.ec Images containing features to be identified(databas= database) Database in which to record feature data(coordli= linelists$thorium.dat) User coordinate list(match = 1.) Coordinate list matching limit in user units(maxfeat= 20) Maximum number of features for automatic identif(zwidth = 10.) Zoom graph width in user units(ftype = emission) Feature type(fwidth = 4.) Feature width in pixels(cradius= 5.) Centering radius in pixels(thresho= 10.) Feature threshold for centering(minsep = 2.) Minimum pixel separation(functio= chebyshev) Coordinate function(xorder = 4) Order of coordinate function along dispersion(yorder = 4) Order of coordinate function across dispersion(niterat= 5) Rejection iterations(lowreje= 3.) Lower rejection sigma(highrej= 3.) Upper rejection sigma(autowri= no) Automatically write to database?(graphic= stdgraph) Graphics output device(cursor =) Graphics cursor input(mode = ql)

Another, much easier way to wavelength calibrate is to use the solution from a previous calibration run, and use ecreidentify to match to the previous solution, making slight shifts, etc. This works quite well if the reference spectrum is near to the one you are working on. I have not yet tried to see how far one can reach out to reference spectra which are signi?cantly offset. Eventually, we hope to build a library of Th-Ar reference spectra which can be used at any place around the HIRES format, and thus always allow wavelength calibration to be done by ecreidentify. If you had a reference spectrum called thar.ref.ec, this is what your parameter list for ecreidentify would look like:

Image Reduction and Analysis FacilityPACKAGE = echelleTASK = ecreidentify

images = thar.ec Spectra to be reidentifiedreferenc= thar.ref.ec Reference spectrum(shift = 0.) Shift to add to reference features(cradius= 5.) Centering radius(thresho= 10.) Feature threshold for centering(refit = yes) Refit coordinate function?(databas= database) Database(logfile= STDOUT,logfile) List of log files
(mode = ql)

Anyway, here we go now in ecid. The ?rst thing which will be displayed is a plot of the 1st aperture. Move the cursor to a line you think you recognize and type <m> to mark. If it beeps without marking, try shifting the cursor a tiny bit to the right (often you have to position the cursor slightly right of line center to get it to mark that line). It will then respond with the column number and await an input wavelength. If you change your mind and do not want to mark that line, just hit return, and then (without moving the cursor) hit <d> for delete, then <r> (for redraw the plot). Using the <m> and <d> keys, you can mark (or delete) and enter wavelengths for as many features as you wish. A <.> will give you the position of the feature nearest the cursor. When done marking lines in any order (or at any time), you may switch to other orders using the <j> and <k> keys to move backwards or forward among your orders. Many other helpful options can be displayed as usual using <?> in the plot mode.

I try to mark a few lines in the ?rst several orders, a few near the center, and a few near the last few orders before letting the routine go to try ?nding its own lines. When ?nished marking a reasonable sampling of identi?ed lines across the orders, you are ready for some initial ?tting. Type <f> in the plot window (this stands '?t dispersion').

One uses a combination of maxfeat and threshhold to control the number of peaks found. It will only ?nd peaks above the speci?ed threshhold, and will ?nd up to maxfeat of these. We have the maxfeat parameter set at only 100 right now, so it will ?nd a maximum of only 100 peaks (above threshhold), but that's ok for a ?rst timid try. Make sure they are reasonably well distributed across the full ?eld of apertures, you don't want it to ?nd all of them near the beginning, etc. You will now be presented with a plot of ?tting residuals vs. pixel. Use the cursor and the <d> key to delete bad points, and the <f> to re-?t (the 'affect all features' switch is already turned on). If you've done things right, most of your residuals should be down well below a pixel by this point. If you already know which order corresponds to a given aperture, you can use the 'o' option in ?t to set this. If you are not setting the order number directly, check to see if it solved correctly for the order offset (the offset between your aperture number and the true interference order at the echelle). If it got the offset correct, this is a good indicator that you are on your way to a solid and correct solution. Be careful though, it could still be off slightly in echelle order, you may need more features to really nail this down.

Now, you can type <q> to quit out of this ?tting subroutine and return to displaying the orders again. You can now either manually hunt down and mark other features to improve the ?t, or quit out and write your initial solution to the database. To identify other lines quickly by hand (say by looking at the Th-Ar atlas), simply move the cursor near a line, and hit spacebar to mark the nearest line. It will then prompt you with the pixel position, and the computed wavelength from the current solution. If this computed wavelength matches (within a window set by the match parameter) a line in the linelist database, it will return the tabled wavelength. Otherwise, it returns with INDEF and waits for you to input a wavelength. If you are happy with its tabled wavelength, just hit return.This enormously speeds the entering of many more lines to really pin down the dispersion ?t. Use <j> and <k> to move among the orders now, identifying a decent sampling of lines throughout the orders. I keep the Th-Ar atlas by the keyboard at this point, and just run through the format picking out the stronger lines, and verifying that the wavelength predicted for each marked feature agrees to within 4 places with the atlas. Whe done, again type <f> for ?t dispersion. Again, use cursor and <d> key to zap out 'outliers', and re-?t.

Once you feel sure that you have a solid preliminary solution, you can let the routine ?nd many more lines automatically. But this time, increase maxfeat to 3000 to allow it to ?nd all the features contained in the linelist database. But be careful, if you haven't yet input enough correct line id's, and/or your match parameter is too large, it can quickly ?nd many incorrect id's and head off toward an incorrect solution. Use <y> to ?nd up to maxfeat features above threshhold, and then <l> to 'match' features to entries in the linelist database (using the current dispersion solution). Again, when all the features have been identi?ed, type <f> to re-?t the dispersion.

Now, with so many features, it becomes time to tune in the order of the ?tting functions in x and y. Again, check your residuals and zap out outliers as needed. Use :xorder and :yorder to vary the order of the ?t in either direction. Use :show to see the ?tting parameters, and the rms ?t. You can watch the rms ?t statistic as you play with :xorder and :yorder to decide upon the best compromise. Try always to use the lowest order number possible consistent with the desired (or expected) ?tting accuracy. In my limited experience, I have found that 4 works well for both xorder and yorder, and rms ?ts of 0.0022 Angstroms are commonly achieved.

You can also display your ?tting residuals in many other meaningful and entertaining ways by using the <x> and <y> keys to rede?ne the abcissa and ordinates of the residual plot. Try <yo> and then <xp> to show a map of where all your identi?ed features were located. Check for areas (clusters?) where many points may have been deleted. If necessary, you may have to go back in and pin down more lines in these areas. Try <yv> and <xw> to show velocity residuals with wavelength, etc. When convinced that the solution looks solid and correct, quit out and save what you've done to the database. Next time through (near this position on the format) you can use this spectrum as a reference, and use ecreidentify to do the wavelength solution quickly and painlessly! You are now done computing the wavelength solution for the Th-Ar reference spectrum.

Attach Dispersion Solution to the Solar Spectrum We must now use the task refspec to attach the dispersion solution just found for the Th-Ar reference spectrum to our program object spectrum solar.ds.ec.imh. Here is the parameter ?le for this:

Image Reduction and Analysis FacilityPACKAGE = echelleTASK = refspectra

input = solar.ds.ec List of input spectra(referen= thar.ec) List of reference spectra(apertur=) Input aperture selection list(refaps =) Reference aperture selection list(ignorea= no) Ignore input and reference apertures?(select = match) Selection method for reference spectra(sort =) Sort key(group =) Group key(time = no) Is sort key a time?(timewra= 17.) Time wrap point for time sorting(overrid= no) Override previous assignments?(confirm= yes) Confirm reference spectrum assignments?(assign = yes) Assign the reference spectra to the input spectr(logfile= STDOUT,logfile) List of logfiles(verbose= no) Verbose log output?answer = yes Accept assignment?

(mode = ql)

This now takes the solution computed for thar.ec.imh and attaches it to solar.ds.ec.imh. At this point though, you only know the true wavelength for each pixel in each order. You will generally want to linearize (or logarithmize or whatever) the dispersion to some convenient sampling scale with the task of the next section.

Attaching wavelength references is generally far more complex than simply attaching a single solution to a single frame. Often, one will have pre-and post— Th-Ar spectra and will want to interpolate between these. Or one may wish to attach a solution from a group of reference spectra, and to perhaps a group of program objects. Or one may wish to attach the closest reference spetrum in time. There are keywords and options for doing many such operations. The point is that refspec is much more powerful than illustrated here.

Applying Dispersion Correction to Object Spectrum We would now like to use the task dispcor to linearize the dispersion of our program object spectrum solar.ds.ec.imh. Epar into the parameter list now for dispcor:

Image Reduction and Analysis FacilityPACKAGE = echelleTASK = dispcor

input = solar.ds.ec List of input spectraoutput = List of output spectra(lineari= yes) Linearize (interpolate) spectra?(databas= database) Dispersion solution database(table =) Wavelength table for apertures(w1 = INDEF) Starting wavelength(w2 = INDEF) Ending wavelength(dw = INDEF) Wavelength interval per pixel(nw = INDEF) Number of output pixels(log = no) Logarithmic wavelength scale?(flux = yes) Conserve flux?(samedis= no) Same dispersion in all apertures?(global = no) Apply global defaults?(ignorea= no) Ignore apertures?(confirm= no) Confirm dispersion coordinates?(listonl= no) List the dispersion coordinates only?(verbose= yes) Print linear dispersion assignments?(logfile=) Log file(mode = ql)

There are many options here, but we want just a simple ?ux —conserving linear interpolation. After running this task, you should do a quick sanity check and use splot to browse around the spectrum, checking against known reference spectra (easy to ?nd for the Sun), to see that obvious fetures like H-? , Na D, etc. ended up with accurate wavelengths. In splot, use the <(> and <)> keys to move among the orders, and <wx>, <wl>, and <wr> to expand in x, and move left and right around any feature. You'll see that you have a pretty decent looking spectrum at this point, but that there is still the strong echelle blaze pro?le dominating the continuum shape. We will remove that in the next section.

Flattening the Continuum To ?atten the continuum, we will use the task continuum. We will use solar.ds.ec.imh as the input, and save the continuum-?attened version as solar.?nal.ec.imh. Here is the parameter ?le:

IRAFImage Reduction and Analysis FacilityPACKAGE = echelleTASK = continuum

input = solar.ds.ec Input imagesoutput = solar.final.ec Output images(lines = *) Image lines to be fit(type = ratio) Type of output(replace= no) Replace rejected points by fit?(wavesca= yes) Scale the X axis with wavelength?(logscal= no) Take the log (base 10) of both axes?(overrid= no) Override previously fit lines?(listonl= no) List fit but don't modify any images?(logfile= logfile) List of log files(interac= yes) Set fitting parameters interactively?(sample = *) Sample points to use in fit(naverag= 1) Number of points in sample averaging(functio= spline3) Fitting function(order = 1) Order of fitting function(low_rej= 2.) Low rejection in sigma of fit(high_re= 0.) High rejection in sigma of fit(niterat= 10) Number of rejection iterations(grow = 1.) Rejection growing radius in pixels(markrej= yes) Mark rejected points?(graphic= stdgraph) Graphics output device(cursor =) Graphics cursor inputask = YES(mode = ql)

Note that we've set high_rej = 0, and low_rej = 2 in order to try to avoid having the continuum ?t being pulled down by absorption lines. But these ?tting parameters should be played with according to the user's judgement. Again though, try to stick with the lowest order possible on continuum ?ts.

Show and Tell of the Final Result

You will now have, in solar.?nal.ec a respectable solar spectrum. There are several ways to explore this ?nal result, and make hard copies. You can certainly use splot to plot order by order. I like to use specplot which can display all orders at once. Here is the parameter ?le:

Image Reduction and Analysis FacilityPACKAGE = echelleTASK = specplot

spectra = solar.final.ec List of spectra to plot(apertur=) Apertures to plot(bands = 1) Bands of 3D images to plot(autolay= yes) Use automatic layout algorithm?(autosca= yes) Scale to common mean for automatic layout?(fractio= 0.) Fraction of automatic minimum separation step(units = wavelength) Coordinate units(scale = 1.) Default intensity scale

(offset = 0.) Default intensity offset(step = 0.) Default separation step(ptype = 1) Plotting type(labels = user) Type of labels(ulabels=) User labels (file)(xlpos = 1.02) X label position (fraction of range)(ylpos = 0.) Y label position (fraction of mean)(sysid = yes) Include system banner and step value?(yscale = yes) Draw Y axis scale?(title = /u/vogt/IRAF/demo/solar.final.ec.imh) Plot title(xlabel = wavelength) X axis label(ylabel = intensity) Y axis label(xmin = INDEF) X axis left limit(xmax = INDEF) X axis right limit(ymin = 0.) Y axis bottom limit(ymax = INDEF) Y axis top limit(logfile=) Logfile(graphic= stdgraph) Graphics output device(cursor =) Cursor input(mode = ql)

If you set fractio= 0, the continuum level for all orders will remian at a constant ordinate value all the way across the spectrum plot. The spectrum will be very highly compressed in the wavelength direction, but can be expanded about any point with the <wx> command as many times as you need, and then <wl> and <wr> to pan left and right. (Unfortunately, there doesn't seem to be an 'unexpand' key stroke, so you have to <wa> to redraw the entire plot if you've overexpanded, or get tired panning left/right in too small increments).

It is instructive to look carefully at the order overlap regions to see how well these overlap regions agree. These are independently observed and reduced spectral regions, and offer a useful consistency check. Some disagreement is expected in the continuum level because it is very hard to rectify the continuum of each echelle order right near the near the ends of each order (splines have a way of heading off on their own at the end of a data set). But the shapes and relative depths of all spectral features should match very closely if everything has been done properly.

Once you have a view of some piece of the spectrum you like, you can get a hard copy by simply typing .snap. If you are correctly set up in the system, this should output the hardcopy directly to the local laser printer.

That brings us to the end of our initial foray into IRAF data reduction of HIRES spectra. You are now no doubt well aware that this was only a very simple (but entirely respectable) shot at reducing a data set. IRAF is a very powerful data reduction environment, with lots of rooms and corridors to explore. Data sets which push the limits of dark current, cosmic ray exposures, low S/N, etc. may require more calibration frames, and more extensive reduction treatments.

Chapter 7 HIRES Exposure Estimator

An exposure estimating program, ?rst written by UCSC graduate student Don Penrod, and later enhanced by UCSC graduate student Michael Keane, is available to help the user estimate signal-to-noise under various conditions. This S/N estimator is fully self-prompting, and very easy to use. It knows about the overall ef?ciency of the telescope and spectrometer. It also includes provisions for calculating slit losses under various seeing conditions, absorption by the atmosphere at any input airmass, and effect of moonlight on sky background subtraction.

This program resides on the UCO/Lick network computer system as /home/umbra/mk/bin/sparc/sn. Keck observatory should also have a version for public release. Contact aconrad@keck.hawaii.edu for assistance. Be sure you get an up-to-date version, there are some older versions ?oating around with incor-rect ef?ciency numbers. Then just answer the questions as prompted. If in doubt about an input value, the default will often suf?ce. The program also remembers all previously used values, and reuses these as new defaults to speed up repetitive inquiries. Ef?ciencies used for the S/N calculations are our best estimate from actual ?rst-light performance at the telescope during commissioning.

Here is a sample of the prompts you will receive when computing the S/N for a given set-up of HIRES:

Wavelength of interest (A) [5500.]:Blaze center (A) [5517.]:Free spectral range (A) [86.20]:Enter cross disperser order [1]:

Spectrograph efficiency at 5517A (blaze peak) is 18.4%Blaze function is 87.9%Single order efficiency at 5500A is 16.1%Extinction at 5500A is 0.12 magnitudes/airmass

Enter slit height(arcseconds) [13.13]:Enter slit width(arcseconds) [1.000]:Enter seeing FWHM(arcseconds) [0.8000]:

Slit throughput is 74.1 %Slit width projects to 3.5 pixelsStar rows 13Sky rows 56

Enter dark count (electrons/unbinned pixel/hour) [2.000]:Enter readout noise (electrons/pixel) [4.300]:Enter binning factor (dispersion) [1]:Enter binning factor (cross dispersion) [4]:Enter magnitude of star [19.00]:What type of magnitude? (Johnson=1, AB=2) [1]:Lunar phase (days) [0.]:

Sky brightness at 5500A is 21.9 magnitudes/arcseconds**2Enter airmass [1.300]:Enter exposure time (seconds) [3600.]:

Star counts= 284. 16.9Sky counts= 73. 8.6Dark counts= 26. 5.1Readout= 2.2Net star= 284. 20.3

Net	S/N=	14.	per	41.	mA	pixel
26.	per	142.	mA	resolution	element	

The entries within the square brackets are the default parameters which will be used if you just hit <return> on each line. If you enter new values, the defaults will be updated to your latest values. In the summary table of counts at the bottom, the middle column represents signal level from each source, and the right column lists the relative contribution of each source to the total noise.

One normally exits the S/N estimator with a ‘cntrl-d’. If you wish to generate a ?le of the results you create when running the S/N estimator, before you run the program type ‘script ?lename’ where ?lename is the name of the ?le where your S/N estimator will be saved. Then remember to ‘exit’ from that script after terminating the S/N estimator program with a cntrl-d.

Chapter 8 References

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Appendix A Some useful numbers

This section not yet completed.

Appendix B Spectrograph Technical Data

This section not yet completed.

Appendix C Detector Technical Data

This section not yet completed. Some items for potential inclusion:

format

?at ?led response

dark current

cosmetic defects

noise and gain

full-well capacity

cosmic ray rate

orientation and useful ampli?ers

Appendix D Telescope Technical Data

This section net yet completed.Some items for potential inclusion:
Effective light gathering area:
Image scale at f/15 nasmyth: 1.3789684 arcsec/mm at nasmyth (see p. 6.5 of HIRES book V of 4/30/92 notes)
Typical pointing accuracy:
Typical guiding accuracy:

Zenith blind spot limits: 1.1?

Altitude limits: 33.3? (nasdeck region — 5.3? to 146.2? azimuth), ˜15? elsewhere (dome shutter starts vignetting)
Field rotation at nasmyth: yes indeedy...

Appendix E Tables of Spectral orders
FORMAT IN FIRST-ORDER OF THE CROSS-DISPERSER
****

ECHELLE: grooves/mm = 52.68

Blaze Angle = 70.4 Theta = 5.0

DIAMETERS:Collimated Beam =0.3028 mTelescope = 10.90 m
Collimator Focal Length = 4.1547 mCamera Focal Length = 0.7627 m
CD GRATING: 250.gr/mm ORDER = 1

Order Blaze(A) FSR(A) DEL(mm) DEL(asec) HEIGHT(mm) LENGTH(mm) DISP(A/mm)119 2994.8 25.2 0.510 3.958 -55.026 28.94 0.87118 3020.2 25.6 0.518 4.025 -54.512 29.18 0.88117 3046.0 26.0 0.527 4.094 -53.989 29.43 0.88116 3072.3 26.5 0.536 4.165 -53.458 29.68 0.89115 3099.0 26.9 0.545 4.238 -52.917 29.94 0.90114 3126.2 27.4 0.555 4.313 -52.367 30.20 0.91113 3153.9 27.9 0.565 4.389 -51.807 30.47 0.92112 3182.0 28.4 0.575 4.468 -51.237 30.74 0.92111 3210.7 28.9 0.585 4.549 -50.658 31.02 0.93110 3239.9 29.5 0.595 4.632 -50.068 31.30 0.94109 3269.6 30.0 0.606 4.717 -49.467 31.59 0.95108 3299.9 30.6 0.617 4.805 -48.855 31.88 0.96107 3330.7 31.1 0.629 4.895 -48.233 32.18 0.97106 3362.1 31.7 0.640 4.988 -47.598 32.48 0.98105 3394.1 32.3 0.652 5.084 -46.952 32.79 0.99104 3426.8 32.9 0.665 5.182 -46.293 33.11 1.00103 3460.1 33.6 0.678 5.283 -45.622 33.43 1.00102 3494.0 34.3 0.691 5.387 -44.938 33.76 1.01101 3528.6 34.9 0.704 5.494 -44.240 34.09 1.02100 3563.9 35.6 0.718 5.605 -43.529 34.43 1.04
99 3599.9 36.4 0.733 5.719 -42.804 34.78 1.0598 3636.6 37.1 0.747 5.836 -42.064 35.14 1.0697 3674.1 37.9 0.763 5.957 -41.309 35.50 1.0796 3712.3 38.7 0.778 6.082 -40.539 35.87 1.0895 3751.4 39.5 0.795 6.210 -39.753 36.25 1.0994 3791.3 40.3 0.811 6.343 -38.950 36.63 1.1093 3832.1 41.2 0.828 6.480 -38.130 37.02 1.1192 3873.8 42.1 0.846 6.622 -37.293 37.43 1.1391 3916.3 43.0 0.865 6.768 -36.438 37.84 1.1490 3959.8 44.0 0.884 6.920 -35.564 38.26 1.1589 4004.3 45.0 0.903 7.076 -34.670 38.69 1.1688 4049.8 46.0 0.924 7.238 -33.757 39.13 1.1887 4096.4 47.1

0.945 7.405 -32.823 39.58 1.1986 4144.0 48.2 0.966 7.578 -31.868 40.04 1.2085 4192.8 49.3 0.989 7.758 -30.891 40.51 1.2284 4242.7 50.5 1.012 7.944 -29.891 40.99 1.2383 4293.8 51.7 1.036 8.136 -28.867 41.49 1.25
78

82	4346.2	53.0	1.061	8.336	-27.819	41.99	1.26
81	4399.8	54.3	1.087	8.543	-26.745	42.51	1.28
80	4454.8	55.7	1.114	8.758	-25.645	43.04	1.29
79	4511.2	57.1	1.142	8.981	-24.517	43.59	1.31
78	4569.0	58.6	1.170	9.213	-23.362	44.15	1.33
77	4628.4	60.1	1.200	9.454	-22.177	44.72	1.34
76	4689.3	61.7	1.232	9.704	-20.961	45.31	1.36
75	4751.8	63.4	1.264	9.965	-19.713	45.91	1.38
74	4816.0	65.1	1.298	10.236	-18.433	46.53	1.40
73	4882.0	66.9	1.333	10.519	-17.118	47.17	1.42
72	4949.8	68.7	1.370	10.813	-15.767	47.82	1.44
71	5019.5	70.7	1.408	11.120	-14.379	48.50	1.46
70	5091.2	72.7	1.447	11.440	-12.952	49.19	1.48
69	5165.0	74.9	1.489	11.774	-11.484	49.90	1.50
68	5241.0	77.1	1.532	12.122	-9.974	50.64	1.52
67	5319.2	79.4	1.577	12.487	-8.420	51.39	1.54
66	5399.8	81.8	1.624	12.869	-6.820	52.17	1.57
65	5482.9	84.4	1.674	13.268	-5.172	52.97	1.59
64	5568.5	87.0	1.725	13.686	-3.473	53.80	1.62
63	5656.9	89.8	1.779	14.124	-1.722	54.66	1.64
62	5748.2	92.7	1.836	14.583	0.085	55.54	1.67
61	5842.4	95.8	1.895	15.065	1.950	56.45	1.70
60	5939.8	99.0	1.958	15.572	3.876	57.39	1.73
59	6040.4	102.4	2.023	16.104	5.866	58.36	1.75
58	6144.6	105.9	2.092	16.665	7.922	59.37	1.78
57	6252.4	109.7	2.164	17.254	10.050	60.41	1.82

56	6364.0	113.6	2.241	17.876	12.251	61.49	1.85
55	6479.7	117.8	2.321	18.533	14.531	62.61	1.88
54	6599.7	122.2	2.406	19.225	16.894	63.77	1.92
53	6724.3	126.9	2.496	19.958	19.343	64.97	1.95
52	6853.6	131.8	2.591	20.733	21.885	66.22	1.99
51	6987.9	137.0	2.691	21.555	24.524	67.52	2.03
50	7127.7	142.6	2.797	22.426	27.267	68.87	2.07
49	7273.2	148.4	2.910	23.351	30.119	70.27	2.11
48	7424.7	154.7	3.030	24.334	33.087	71.74	2.16
47	7582.7	161.3	3.157	25.381	36.178	73.26	2.20
46	7747.5	168.4	3.293	26.497	39.401	74.85	2.25
45	7919.7	176.0	3.437	27.689	42.764	76.52	2.30
44	8099.7	184.1	3.592	28.962	46.276	78.26	2.35
43	8288.0	192.7	3.757	30.326	49.948	80.08	2.41
42	8485.4	202.0	3.934	31.788	53.790	81.98	2.46
41	8692.3	212.0	4.124	33.358	57.816	83.98	2.52
40	8909.6	222.7	4.328	35.048	62.039	86.08	2.59
39	9138.1	234.3	4.548	36.870	66.473	88.29	2.65
38	9378.6	246.8	4.786	38.837	71.135	90.61	2.72
37	9632.0	260.3	5.042	40.966	76.044	93.06	2.80
36	9899.6	275.0	5.320	43.275	81.220	95.65	2.88

FORMAT IN 2ND ORDER OF THE CROSS-DISPERSER
****

ECHELLE: grooves/mm = 52.68

Blaze Angle = 70.4 Theta = 5.0

DIAMETERS:Collimated Beam =0.3028 mTelescope = 10.90 m
Collimator Focal Length =4.1547 mCamera Focal Length = 0.7627 mCD GRATING: 250.gr/mm ORDER = 2
Order Blaze(A) FSR(A) DEL(mm) DEL(asec) HEIGHT(mm) LENGTH(mm) DISP(A/mm)119 2994.8 25.2 0.995 7.916 4.863 28.94 0.87118 3020.2 25.6 1.011 8.051 5.866 29.18 0.88117 3046.0 26.0 1.028 8.189 6.885 29.43 0.88116 3072.3 26.5 1.046 8.330 7.922 29.68 0.89115 3099.0 26.9 1.064 8.476 8.977 29.94 0.90114 3126.2 27.4 1.082 8.625 10.050 30.20 0.91113 3153.9 27.9 1.101 8.778 11.141 30.47 0.92112 3182.0 28.4 1.120 8.936 12.251 30.74 0.92111 3210.7 28.9 1.140 9.098 13.381 31.02 0.93110 3239.9 29.5 1.160 9.264 14.531 31.30 0.94109 3269.6 30.0 1.181 9.435 15.702 31.59 0.95108 3299.9 30.6 1.203 9.610 16.894 31.88 0.96107 3330.7 31.1 1.225 9.791 18.107 32.18 0.97106 3362.1 31.7 1.248 9.976 19.343 32.48 0.98105 3394.1 32.3 1.271 10.167 20.602 32.79 0.99104 3426.8 32.9 1.295 10.364 21.885 33.11 1.00103 3460.1 33.6 1.320 10.566 23.192 33.43 1.00102

3494.0 34.3 1.345 10.774 24.524 33.76 1.01101 3528.6 34.9 1.371 10.989 25.882 34.09 1.02100 3563.9 35.6 1.398 11.210 27.267 34.43 1.04
99 3599.9 36.4 1.426 11.437 28.679 34.78 1.0598 3636.6 37.1 1.455 11.672 30.119 35.14 1.0697 3674.1 37.9 1.484 11.914 31.588 35.50 1.0796 3712.3 38.7 1.514 12.163 33.087 35.87 1.0895 3751.4 39.5 1.546 12.421 34.616 36.25 1.0994 3791.3 40.3 1.578 12.687 36.178 36.63 1.1093 3832.1 41.2 1.611 12.961 37.773 37.02 1.1192 3873.8 42.1 1.646 13.244 39.401 37.43 1.1391 3916.3 43.0 1.681 13.537 41.064 37.84 1.1490 3959.8 44.0 1.718 13.839 42.764 38.26 1.1589 4004.3 45.0 1.756 14.152 44.500 38.69 1.1688 4049.8 46.0 1.795 14.476 46.276 39.13 1.1887 4096.4 47.1 1.836 14.810 48.091 39.58 1.1986 4144.0 48.2 1.878 15.157 49.948 40.04 1.2085 4192.8 49.3 1.921 15.516 51.847 40.51 1.2284 4242.7 50.5 1.966 15.887 53.790 40.99 1.2383 4293.8 51.7 2.013 16.273 55.779 41.49 1.2582 4346.2 53.0 2.061 16.672 57.816 41.99 1.2681 4399.8 54.3 2.111 17.086 59.902 42.51 1.2880 4454.8 55.7 2.163 17.516 62.039 43.04 1.2979 4511.2 57.1 2.217 17.962 64.228 43.59 1.3178 4569.0 58.6 2.273 18.426 66.473 44.15 1.3377 4628.4 60.1 2.331 18.908 68.774 44.72 1.3476 4689.3 61.7 2.392 19.409 71.135 45.31 1.3675 4751.8 63.4 2.454 19.930 73.558 45.91 1.3874 4816.0 65.1 2.520 20.472 76.044 46.53 1.40
80

73	4882.0	66.9	2.588	21.037	78.597	47.17	1.42
72	4949.8	68.7	2.659	21.626	81.220	47.82	1.44
71	5019.5	70.7	2.732	22.239	83.914	48.50	1.46
70	5091.2	72.7	2.809	22.879	86.684	49.19	1.48
69	5165.0	74.9	2.890	23.547	89.533	49.90	1.50
68	5241.0	77.1	2.974	24.245	92.464	50.64	1.52
67	5319.2	79.4	3.061	24.974	95.481	51.39	1.54
66	5399.8	81.8	3.153	25.737	98.587	52.17	1.57
65	5482.9	84.4	3.249	26.535	101.786	52.97	1.59
64	5568.5	87.0	3.349	27.371	105.084	53.80	1.62
63	5656.9	89.8	3.454	28.247	108.484	54.66	1.64
62	5748.2	92.7	3.564	29.166	111.992	55.54	1.67
61	5842.4	95.8	3.680	30.130	115.613	56.45	1.70
60	5939.8	99.0	3.802	31.143	119.353	57.39	1.73
59	6040.4	102.4	3.929	32.209	123.217	58.36	1.75
58	6144.6	105.9	4.064	33.329	127.212	59.37	1.78
57	6252.4	109.7	4.205	34.509	131.344	60.41	1.82
56	6364.0	113.6	4.354	35.753	135.622	61.49	1.85
55	6479.7	117.8	4.512	37.065	140.053	62.61	1.88
54	6599.7	122.2	4.678	38.451	144.646	63.77	1.92

Appendix F System ef?ciency

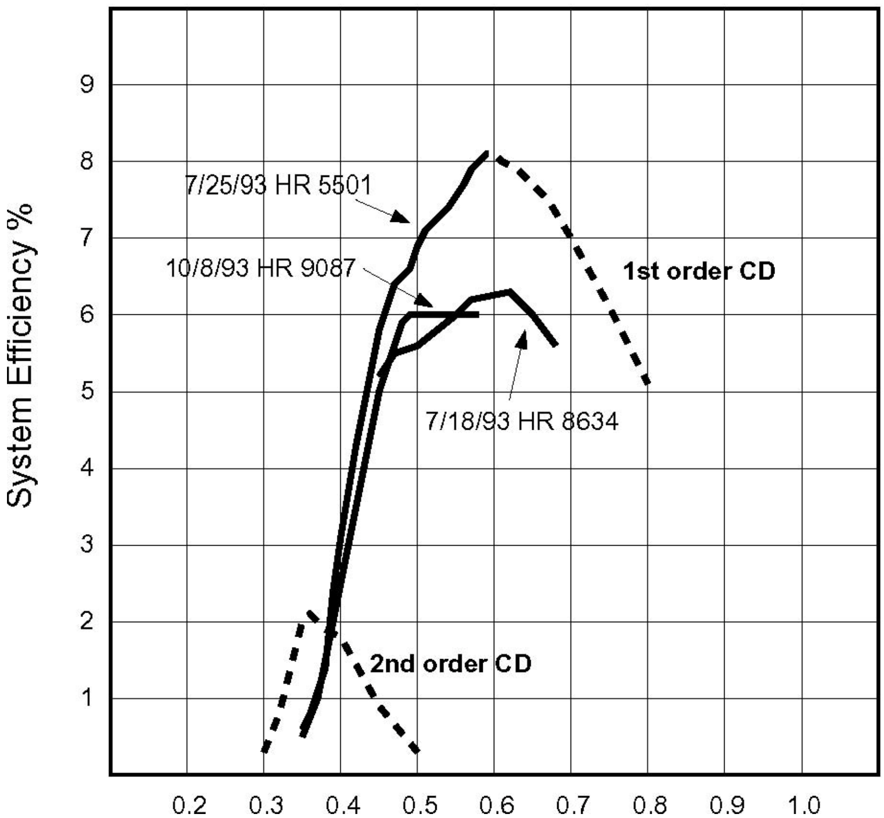
A plot of the overall system ef?ciency is shown in Figure 9. This plot shows the results of several attempts at measuring system ef?ciency, on several different dates with different ?ux standard stars. Since conditions were not always perfectly photometric, some variation is expected. The ordinate is the combined absolute ef?ciency of telescope + HIRES + Tektronix CCD. It does not include losses from the slit, from an ADC, from an image rotator, or from atmospheric absorption.

Solid line curves represent measured ef?ciencies, based on actual measure-ments of ?ux standards through a wide open slit. Dotted line curves are predicted ef?ciencies based on the measured 1st order ef?ciency, and knowledge of the wavelength dependence of the optical system ef?ciency. Since these curves also include the ef?ciencies of the three telescope mirrors, they may be expected to decline as the telescope gets dirty. By way of passing interest, HIRES by itself peaks at about 13% ef?ciency. But there are three aluminum telescope mirrors out there in the telescope ahead of HIRES in the photon path. Each telescope mirror (primary, secondary, and tertiary) when cleaned, has only about 85% ef?ciency. So (1–0.853) or almost 40% of the light is lost to the telescope and thus never makes it to the HIRES entrance slit (HIRES is attached to effectively a 7.7–meter telescope)! Clearly there are gains to be had with using silver on some or all of the telescope mirrors, but at the price of losing the region below about 3400A. Keck II will apparently have all-silver mirrors. It is my hope that we may be able to borrow the silver tertiary for HIRES on Keck I occasionally.

Also worth noting is that all of the HIRES lenses and mirrors transmit ex-tremely well down to the atmospheric cut-off. The rapid fall-off in system ef?-ciency towards the ultraviolet is due partly to the roll-off of the cross-disperser's blaze function in 1st order, and also to the roll-off in Q.E. of the ?rst-light engineering-grade Tektronix CCD. A uv-blazed ?rst order CD is under construc-tion to improve this.

This plot is simply meant to be a rough guide as to which order to choose of the cross-disperser, and what the approximate throughput will be. Ef?ciencies are for the center of the echelle free-spectral range at any order. For more accurate ef?ciency estimates, one must include also the slit losses for given seeing, and atmospheric absorption, as well as the effects of sky background, dark current, readout noise, and binning on the ?nal signal-to-noise of the data. This is easily done using the HIRES S/N estimator program described in a previous section. Our best-estimate of actual system ef?ciency has been incorporated into this simulator. Feedback from observers though on their measured ef?ciencies are always welcome, not only to aid in converging on the true ef?ciency numbers, but also to check for and guard against system ef?ciency decline with time.

Figure 9 Spectrometer + Telescope Ef?ciency



Wavelength (microns)

Appendix G Special considerations for low S/N and/or long integration observations

This section not yet completed.

Appendix H Future HIRES upgrades

The instrument described thus far is simply the core version of the ?nal in-strument. There were not enough funds available to build the entire instrument by ?rst-light. In the future, as further funding becomes available, and providing science needs dictate, I expect to add a number of useful features. For instance, one can add new cross-dispersers to best match the order separation/wavelength coverage required of any given project. It may prove worthwhile in the future to consider adding other echelles, particularly if detector formats evolve consider-ably. For example, an R-1.5 echelle optimized for wide wavelength coverage in the ultraviolet in conjunction with a ?rst-order uv cross-disperser would be quite useful for QSO work. Or a coarser echelle could be used to provide shorter orders in the red and near-IR to avoid gaps in the spectrum. The addition of each new echelle or cross-disperser is relatively expensive, but easy to fund from individual research grants if the science warrants. The ?rst addition will be probably an image rotator. This is quite necessary for highest performance of the instrument when doing long exposures on faint objects, both to compensate for ?eld rotation and to eliminate light losses at the slit from atmospheric dispersion. The prob-lem of atmospheric dispersion of point-like objects can be overcome by using the rotator to set the HIRES slit along the parallactic angle such that the dispersed image lies along the slit. Field derotation will also be required for long exposures on gravitationally-lensed QSO's. Ultimately, an atmospheric dispersion compen-sator must also be provided as well to provide dispersion compensation on lensed QSO's or other extended objects.

When probing the chemical abundances of globular cluster members, a multi-?ber input feed would be quite desirable and would yield enormous speed gains in the multiplexing. Probably, the ?ber-head would feed both HIRES and the Low Resolution Imaging Spectrograph (LRIS). HIRES ?bers would terminate at the curved focal plane of a spherical collimator which would drop down in front of the normal collimators. A cross-disperser which gives much more order separation in the visible would also probably be used in this mode and could provide enough interorder space for perhaps 100 objects while still achieving good wavelength coverage. Also, a mirror could be installed in place of the cross-disperser for multi-object or longslit single-order work. Infrared arrays (HgCdTe) are also now becoming available which provide excellent sensitivity and low-noise imaging capability out to at least 2.6 microns. The HIRES optical train is designed to be quite ef?cient and to produce quite good images out to these wavelengths, and such an IR array could be easily installed in the camera in place of the conventional CCD's. A different cross-disperser would also be purchased for use with this detector. HIRES is nominally designed to be used up to resolutions of about 100,000 without image slicers. However, in conditions of bad seeing, or for much higher resolution work, image slicers can be added to maintain high throughput at the slit. The collimators are oversized to accept the square beam from a Richardson-style slicer, and the camera's image quality will be good enough to provide resolutions of at least 200,000. CCD's with 7.5 micron pixels will also be required for such resolutions, and appear to be now available in 40962 formats. One could also envisage a double-pass very high resolution mode, with the cross-disperser rotated to send the light back to the echelle, but tipped slightly such that the collimator could also act as the camera and produce an image up near the slit. This image could be picked off by a small mirror and sent to a detector mounted up near the slit. Finally, HIRES can also be extended out through the 'future expansion door' in the wall near the cross-disperser. A symmetrical outrigger could be added to the optical bench structure, and the cross-disperser used to steer the light to perhaps a different focal length camera.

Image rotator:

Atmospheric Dispersion Compensator:

Image slicers (or adaptive optics?):

tip/tilt system

Appendix I Acknowledgments

HIRES was built by a superb team of people at UCO/Lick Observatory. Former UCO/Lick director Bob Kraft and present director Joe Miller contributed much useful scienti?c, technical, and managerial input. Neal Jern was the overall project manager. Jack Osborne and Bruce Bigelow were the mechanical engineers. Harland Epps did the optical design optimization. Carol Osborne assisted with drafting. Master Optician Dave Hilyard did the optical fabrication, with help from opticians

Darrie Hilyard, and Gerard Pardeilhan. Terry Ricketts did the electronics design. Lance Bresee and Cal Delaney assisted with the electronics fabrication and checkout. Bob Kibrick, Richard Stover, Al Conrad, Dean Tucker, Steve Allen, Kirk Gilmore, and Mike Keane provided software support. Erich Horn, Jeff Lewis, Terry P?ster, Dick Kanto, and Jim Ward did the mechanical fabrication. Bill Brown assisted with optical coatings. Lloyd Robinson and Mingzhi Wei developed the CCD detectors. Marlene Couture and Joe Calmes did the accounting, with Ted Cantrall providing help with the project scheduling and purchasing.