

HIRES Instrument and Data Format

1.0 HIRES Instrument

HIRES, the High Resolution Echelle Spectrograph, is installed permanently at the right Nasmyth focus of the Keck-1 telescope, and was commissioned in the summer-fall of 1993. The capabilities and functionality of the instrument are well described in Vogt et al (1994) and the HIRES User's Manual. The instrument has arguably been the most powerful high-resolution optical spectrograph ever built. It has been used in a wide range of astronomical studies. These include investigations into the large scale structure and history of the universe through absorption of high-Z quasar spectra; the structure and chemical evolution of stars and the related evolution of galaxies; the chemistry and dynamics of solar system bodies; and the discovery of hundreds of extra-solar planets through precise time-series analysis of small doppler motions of such planets around their parent stars.

The instrument has achieved outstanding results partly through its high opto-mechanical stability and long well-serviced continuity of operation. HIRES was designed to be versatile through the optical spectrum covering 300 - 1000 nm by use of interchangeable optical components optimized for either blue or red sides of the bandpass, in conjunction with a wide degree of control of the imaged spectrum by the user. The interchangeable large optics include the collimating mirrors and cross disperser grating mosaic. The cross-dispersers are changed out between blue and red-blazed grating mosaics by observatory personnel for specific scheduled research programs. Through an exacting calibration procedure the opto-mechanical position of the cross-dispersers is recovered, ensuring the long-term stability required of the spectrograph. HIRES is highly user-configurable through the remote operation of motorized stages to select spectral and spatial resolution, filter bandpasses, grating settings to position wavelength regions of interest precisely on the CCD, and focus settings of optics and the CCD to achieve high data quality. It is also supplied with internal calibration sources and supplemental instrumentation including the iodine cell velocity reference, sky position image rotator, and photon-counting exposure meter.

1.1 The Upgraded HIRES CCD Mosaic

On 18 August 2004, HIRES underwent a major upgrade of its detector. The CCD upgrade resulted in significant improvements in the HIRES detector, dewar, and CCD electronics. The new detector consists of a mosaic of three 2048 x 4096 15- μm pixel MIT/Lincoln Labs CCDs, compared to a single 2048 x 2048 24- μm pixel Tetrax CCD of the old detector. The new device has dramatically: 1) improved the blue/UV response shortward of 3800 \AA (by a factor of ~ 8), 2) increased the wavelength coverage for single instrument setting, 3) provided finer sampling of the point-spread function (PSF), and 4) reduced the CCD readout noise and readout time. New software was developed and old software enhanced to handle the new electronics and higher data density. In addition, a new field flattener was created to accommodate the increased

mosaic size and the flat focal plane characteristics of the new CCDs. Table 1.0 below shows a comparison of the CCD characteristics between the two devices. Other, most up-to-date characteristics of the detector mosaic can be found at <http://www2.keck.hawaii.edu/inst/hires/usernotes.pdf>.

Table 1.0: Comparison of CCD characteristics

	Old CCD	Upgraded CCDs
Manufacturer	Textronix	MIT/Lincoln Labs
Array size	One 2048 x 2048	Three 2048 x 4096
Pixel size	24 μm	15 μm
QE (@ 3200 \AA)	8%	65%
CTE	-	0.999997
Dark current	< 10 $e^-/\text{pixel}/\text{hour}$	2 $e^-/\text{pixel}/\text{hour}$
Readout noise	5-6 e^-	< 3 e^-
Readout time	Several minutes	< 30 sec.

The figure below shows the layout of the new CCD mosaic compared to the old system, and how it is situated in the dewar and oriented with respect to the spectral orientation. The gaps between the CCD chips are about 100 μm (6-7 pixels).

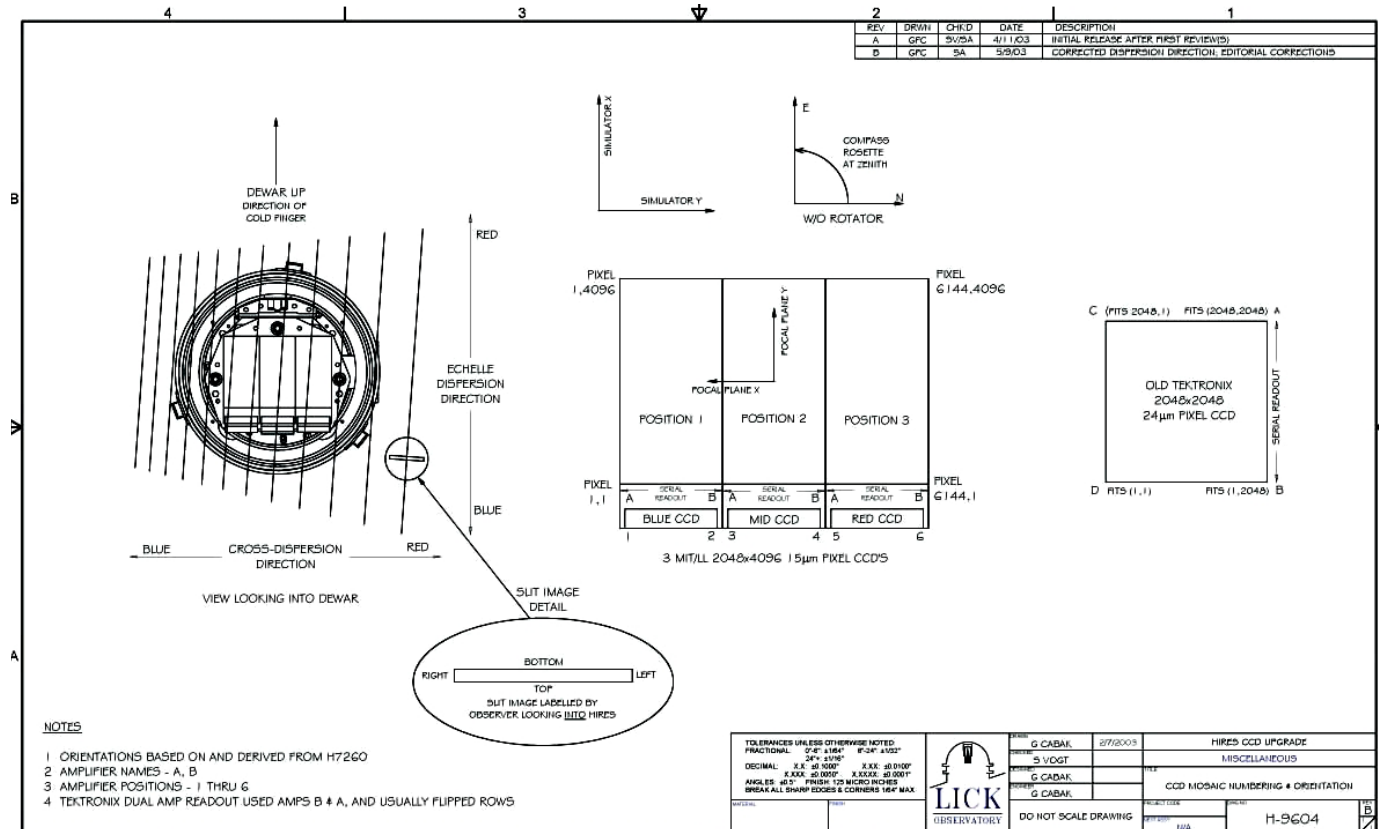


Figure 1.0: Layout of the new HIRES upgraded CCD mosaic

At the focus of the spectrograph camera, the CCD detector is held at -130 C operating temperature continuously through the use of an automated liquid nitrogen filling system. The CCD focus is highly stable and has required re-calibration infrequently.

2.0 HIRES Image Format

The data produced by the new HIRES CCD mosaic are in multiple-extension FITS file format. This consists of a primary header, which is the first header of the FITS file, followed normally by three or more extensions, called header data units (HDUs). Each HDU contains the two standard components of any FITS file: (a) an ASCII text header holding a list of keywords that describe the data unit of that HDU, and (b) the binary data following it. For a description of the keywords in the primary header unit, visit

http://www2.keck.hawaii.edu/koa/public/keywords/koa_keywords.php.

The number of extensions is determined in part by the number of amplifiers used, and can be controlled by the PANE and PANELIST keywords. In normal operations, single-amp readout would produce three extensions (HDUs), one for each CCD in the mosaic. In dual-amp readout mode, the number of HDUs would double to six. A schematic of the data mosaic in the single-amp mode is shown in Figure 2.0.

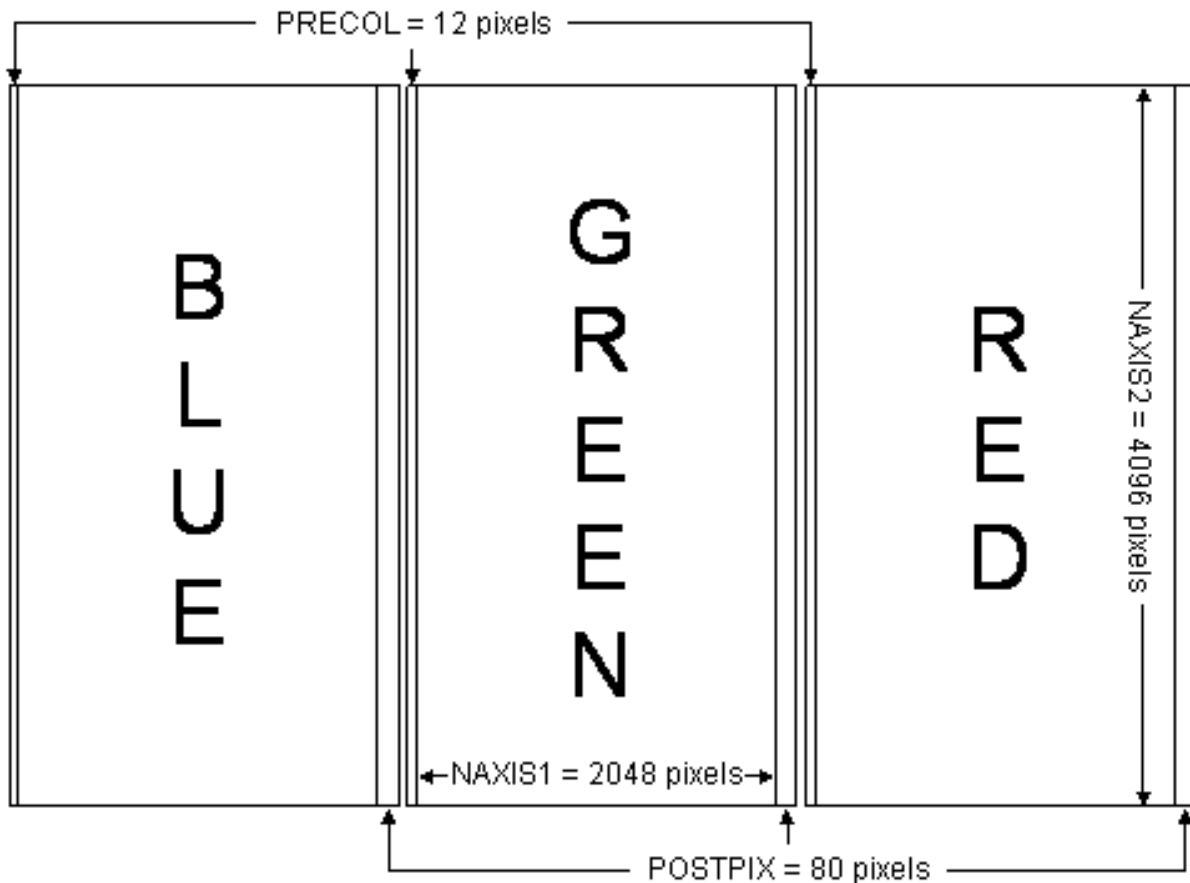


Figure 2.0 Schematic layout of the three HIRES CCDs in their default, single-amplifier, unbinned format.

In its current default, single-amp, unbinned format of Figure 2.0, each of the blue, green and red CCD chips has a separate prescan region 12 columns wide (keyword PRECOL), and a postscan region 80 columns wide (keyword POSTPIX). The available image area of each chip is 2048 pixels wide (NAXIS1) and 4096 pixels high (NAXIS2). The blue, green and red chips are also referred to as CCD = 1, 2 or 3, respectively. The spectral orders run roughly up and down in the vertical direction on the chips in this schematic. Wavelength increases from bottom to top and from left to right on each chip, as in Figure 1.0.

The HIRES CCD electronics and software are capable of reading out the current 2048 x 4096 pixel, three-CCD mosaic in a number of different modes. The most important readout parameters, corresponding keywords, and default values are listed in Table 2.0. These values correspond to single-amplifier, low-gain readout with single pixel binning. Currently, only one amplifier, SINGLE:B, is functional. Amplifier modes SINGLE:A or DUAL:A+B are not usable at this time. An image recorded with these parameters would be 52,761,600 bytes in size (assuming a fixed size for the image header).

Table 2.0: Default HIRES CCD readout parameters

Readout parameter	Keyword	Default value
Number of readout amplifiers	AMPMODE	SINGLE:B
Number of video inputs	NVIDINP	3
Pixel binning factor	BINNING	1,1
Number of prescan columns	PRECOL	12
Number of postscan columns	POSTPIX	80
CCD readout amplifier gain	CCDGAIN	low
Mosaic readout mode	MOSMODE	B, G, R
CCD readout speed	CCDSPEED	fast

In order to increase the signal to noise ratio in the data, the astronomer frequently bins the image in the spatial (horizontal in Figure 2.0) direction. An example bias image (e.g. zero second, no light exposed on the image) taken with single-amplifier readout and binned by 2 in the spatial direction (2x1 binning) is shown in Figure 2.1, corresponding to the same layout displayed in Figure 2.0. This image is 26,461,440 bytes long and has a smaller postscan region (40 columns per chip). An example of a flat field image taken with an internal quartz lamp is shown in Figure 2.2. Note the roughly vertical orientation of the spectral orders and the increasingly wider separations between them with wavelength. The spectrum is recorded from an internal halogen light source directed into the entrance slit of the spectrograph. It is used by dividing out of the science object spectra to correct for instrumental response. The diagonal streak [most clearly seen in the middle (green) chip] is light that is dispersed twice by the spectrograph, and is a scattered light defect. Sometimes called the “meteor”, such scattered light is not present in all HIRES spectra, but mainly shows up in bright flat field and star images at certain HIRES spectral settings. More details on internal calibration images are found in section 3.1.

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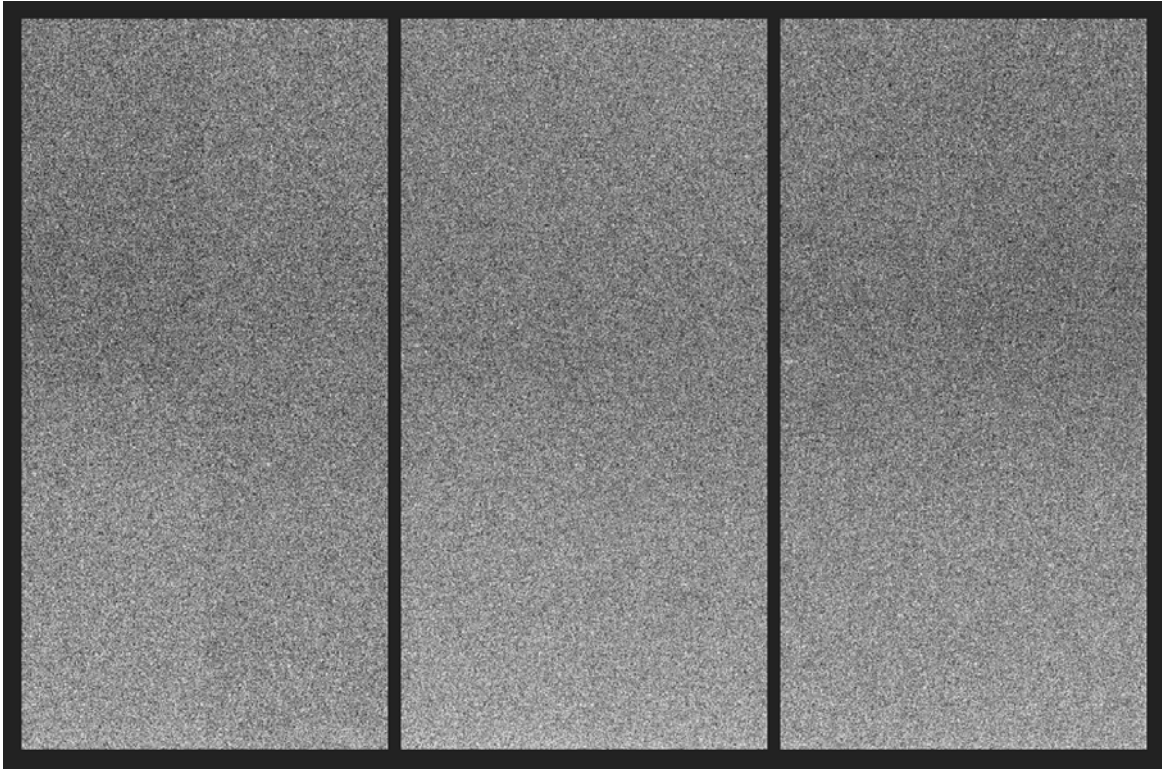


Figure 2.1 Hires bias image in its 2x1 binning format. Orientation is as in Figs. 1.0 and 2.0

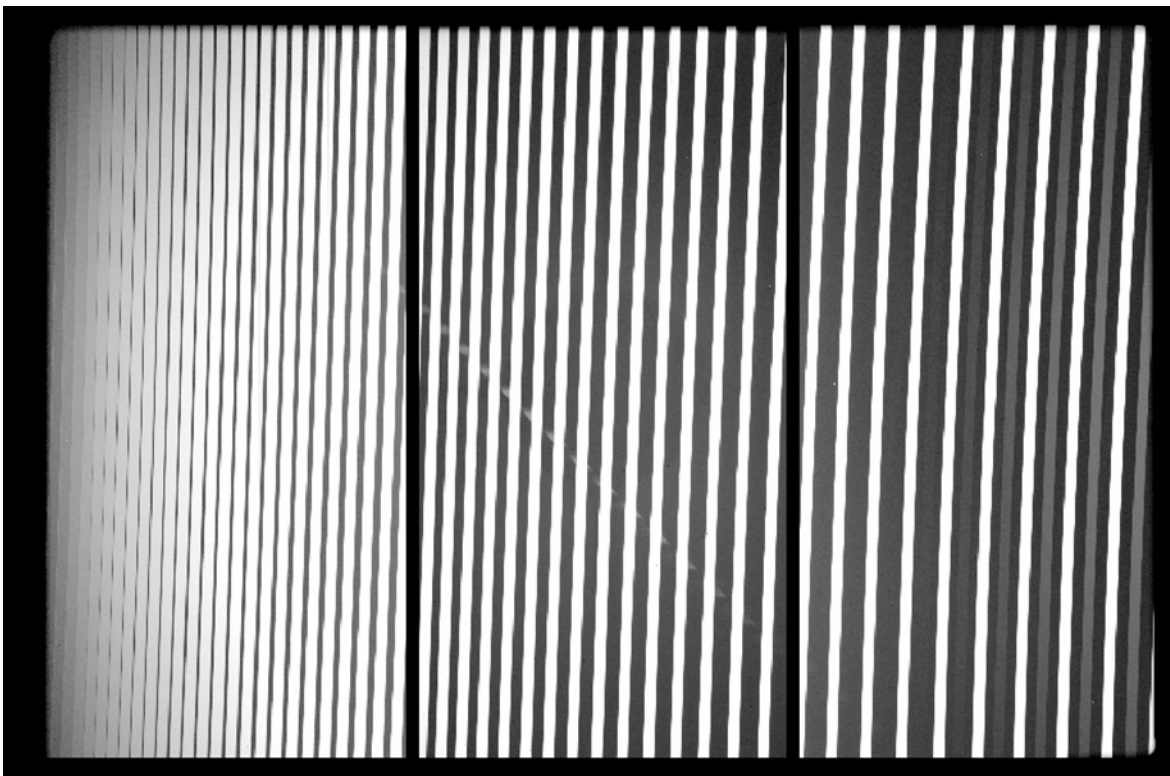


Figure 2.2 Hires flat field image in its 2x1 binning format. Orientation as in Figs. 1.0 and 2.0

3. HIRES Configurations and Image Types

The HIRES is very broadly configurable through its user interface which controls the selection and positions of instrumental components through remote operation of motorized stages. The HIRES user interface is shown in Figure 3.0. The user interface provides a schematic of the instrument light path, a status display with broadcasts of the current position of each motorized stage, and individual and compound control of the motorized stages through pop-up menus and a multitasking utility (called GO). Components which form a basic HIRES instrumental configuration include:

- Slit or decker size
- Wheels behind the slit filter (2 each 12 position)
- Collimator selection, including focus, which is accomplished through a look-up table
- Echelle grating position
- Cross-disperser type
- Cross-disperser grating position

Table 3.0 lists keywords which describe the above configuration parameters.

Table 3.0: HIRES Instrumental Configuration Parameters

Configuration parameter	Keyword	Possible values
Slit decker	DECKNAME	30 (ascii, configurable but generally fixed)
Filter wheel 1 selection	LFIL1NAME	12 (same)
Filter wheel 2 selection	LFIL2NAME	12 (same)
Collimator	COLLBLUE or COLLRED	blue (not blue), red (not red)
Echelle position	ECHRAW and ECHANGL	integer and real
Cross-disperser type	XDISPERS	BLUE, RED
Cross-disperser position	XDRAW and XDANGL	integer and real

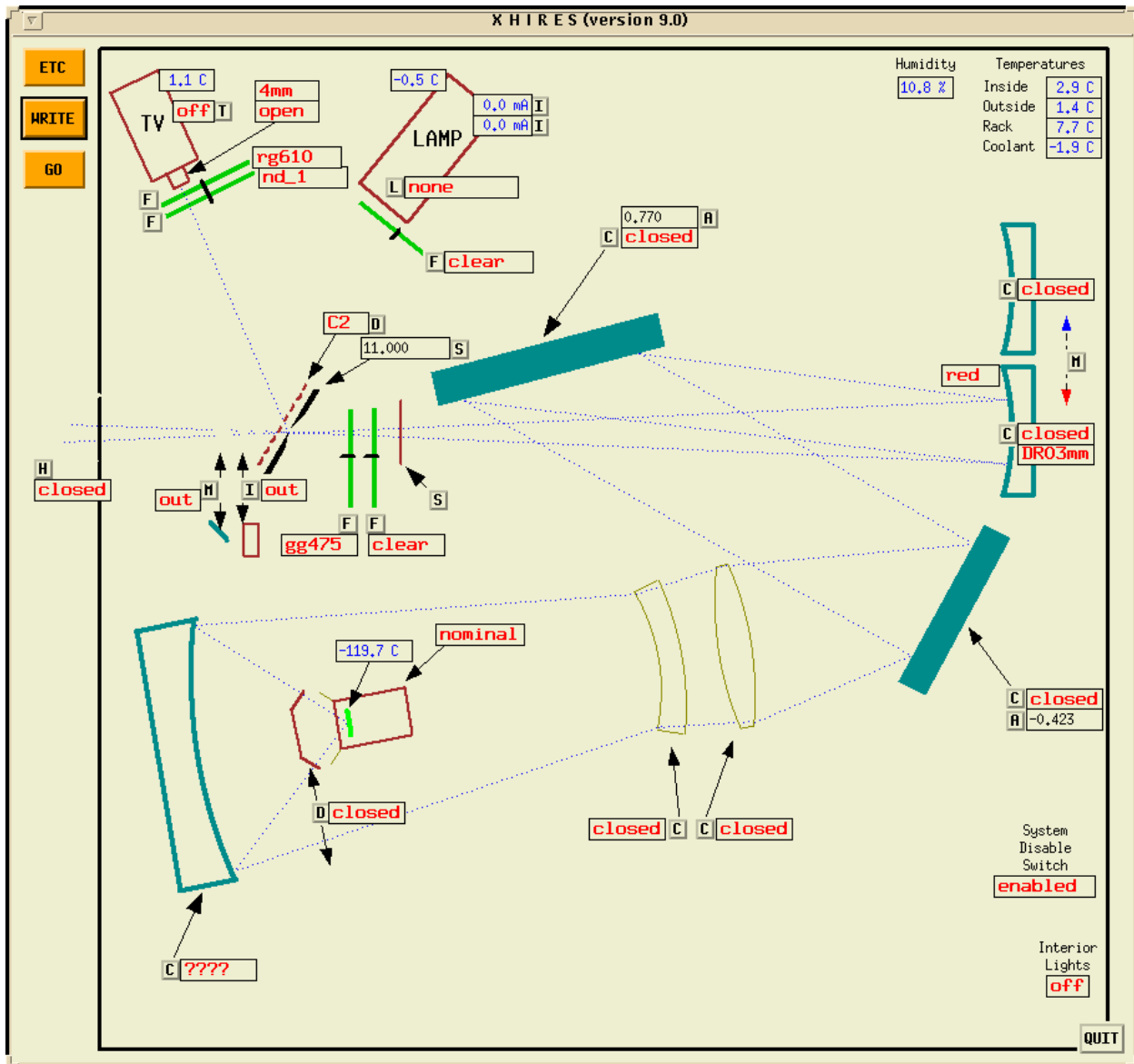


Figure 3.0: HIRES user interface. Each motorized stage of the instrument is controlled through a menu which pops up when the stage button is selected. The current position of each stage and cover is broadcast to the interface every few seconds.

3.1 HIRES Calibration Images

Calibration images are defined as data taken with internal illumination or without any illumination. Standard internal calibrations include:

- *Bias*: zero-second non-illuminated image
- *Dark*: non-illuminated images taken at longer exposure times to measure dark current in the CCD electronics
- *Flat field*: spectra taken with internal quartz halogen illumination for each HIRES configuration setting

- *Thorium-Argon (Th-Ar)*: spectra taken with the Th-Ar lamp in each HIRES configuration setting
- *Trace*: spectra taken with the D5 pinhole with internal quartz illumination to provide a trace spectrum for echelle order extraction. This purpose is often fulfilled with standard stars or the program stars if sufficiently bright.
- *Focus*: Th-Ar spectra taken with D5 pinhole for focusing purposes

Non-illuminated calibration images include short-exposure (i.e. generally less than 2s) or zero-length exposure bias images, and long exposure dark images. Table 3.1 lists keywords that may be used to identify bias and dark images. Keywords listed with more than a single possible value might only be used to verify an image type (for instance, if AUTOSHUT is F then the shutter did not open and the resulting image is a bias or dark; a similar discussion holds for other keywords in Table 3.1). Dark images are not frequently taken, since the CCD system has very low dark current that is inconsequential for all reasonable exposure times. Still, a dark image can be used as a system diagnostic at any time and should be part of a long-term instrument trend analysis.

Table 3.1: Internal calibration keywords: bias or dark image

Internal calibration identifier	Keyword	Value
Bias image, shutter	AUTOSHUT	F
Bias image, exposure length	TIME	Short (< 2) s
Dark image, shutter	AUTOSHUT	T or F
Dark image, exposure length	ELAPTIME	Any value
Bias or dark image	HATCLOS	closed or not closed

HIRES is equipped with internal calibration lamps that project halogen flat field and Thorium-Argon comparison sources onto the entrance slit. The flat field spectrum is used to correct scientific object spectra for pixel to pixel variation in CCD response, and in some cases to correct for instrumental wavelength response. An example of a flat field spectrum is shown in Figure 2.2. The Th-Ar spectrum provides emission lines at precise wavelengths, the positions of which are used to wavelength calibrate the science object spectra. An example a Th-Ar spectrum is shown in Figure 3.1. Table 3.2 lists keyword values that can be used to identify images as internal calibration spectra of certain types.

Table 3.2: HIRES internal calibration keywords

Internal calibration identifier	Keyword	Value
Flatfield spectrum	LAMPNAME	quartz, quartz1 or quartz2 (ascii)
	DECKNAME	Same as program object
Trace	DECKNAME	D5
	LAMPNAME	quartz, quartz1 or quartz2 (ascii)
Focus	DECKNAME	D5
	LAMPNAME	ThAr1 or ThAr2 (ascii)

Th-Ar spectrum	LAMPNAME	ThAr1 or ThAr2 (ascii)
Th-Ar spectrum ON	CATCUR1 or CATCUR2	25.0 (real, nominal, mA)
Comparison mirror in beam	LMIRRIN	in light path (ascii)

Note that LAMPNAME is a configurable keyword, so there is no guarantee that the values will match those in Table 3.2. For ThAr spectra, the lamp current must also be turned on for the spectrum to be valid.

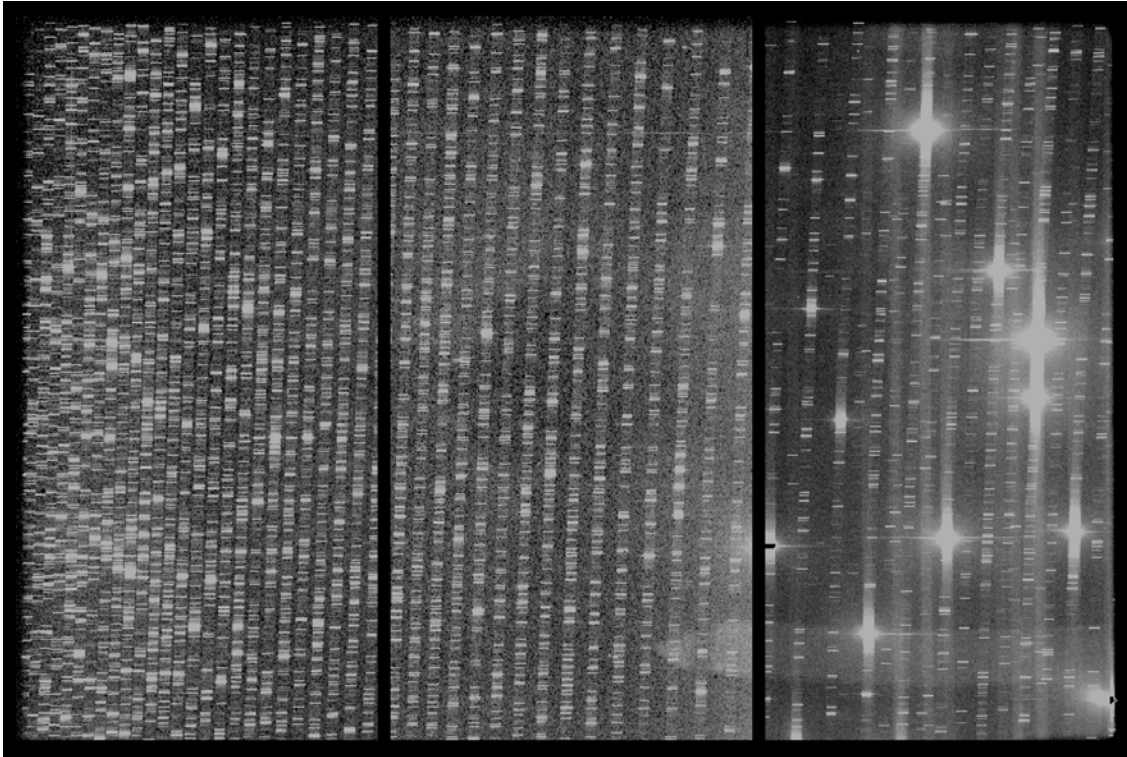


Figure 3.1: Hires Th-Ar comparison spectrum binned 2x1. Orientation as in Figs. 1.0 and 2.0

Other images used for data calibration include spectra taken of standard stars or the sky background. Standard stars fall into several categories, including flux standards, flat continuum stars for atmospheric telluric line removal, radial velocity standards, and other types. Bright stars are also used to provide a trace spectrum for echelle order extraction. Sky background or direct reflectance spectra are often taken in planetary programs to provide a solar spectrum for subtraction from the scientific object spectrum.

3.2 Program Object Images

The scientific versatility of Hires means that the instrument is used to observe a number of classes of objects by astronomers. These include but are not limited to the following:

- Point-source spectroscopy of faint objects (e.g. quasars and faint stars).

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- Point-source spectroscopy of bright stars.
- Extended-source spectroscopy of faint objects (e.g. galaxies, some planetary objects)
- Extended-source spectroscopy of bright objects (e.g. planetary objects, comets)
- Point-source velocity-calibrated spectroscopy of bright stars (e.g. planet-hunting with the use of the iodine cell).

Each observing program will be conducted in the manner determined by the PI. The resulting data will therefore be organized and calibrated in different ways. Two example program object spectra are shown in Figure 3.2 (extended object spectrum with a superimposed sky background) and Figure 3.3 (point source spectrum of a star).

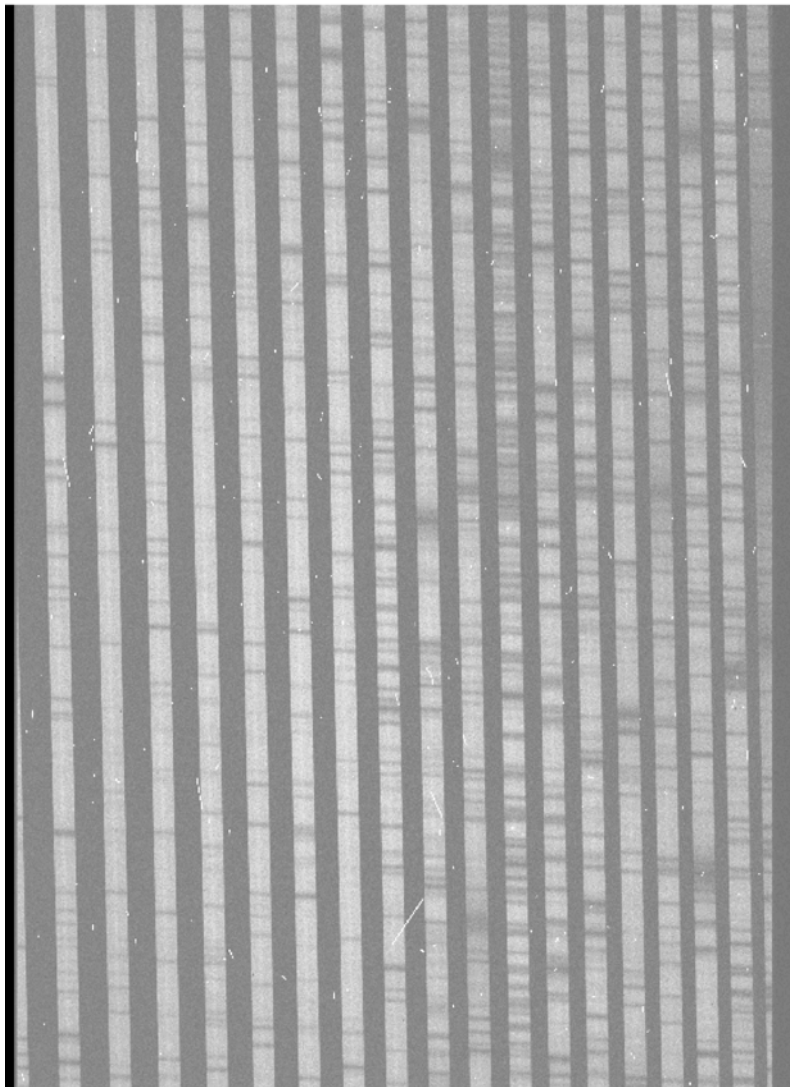


Figure 3.2: HIRES spectrum of an extended object. This is a portion of the green (middle) CCD of a comet with the reflected and absorbed sunlight from the earth's atmosphere. The dark lines superimposed on the bright continuum bands are primarily Fraunhofer absorption from specific elements in the Sun's atmosphere.

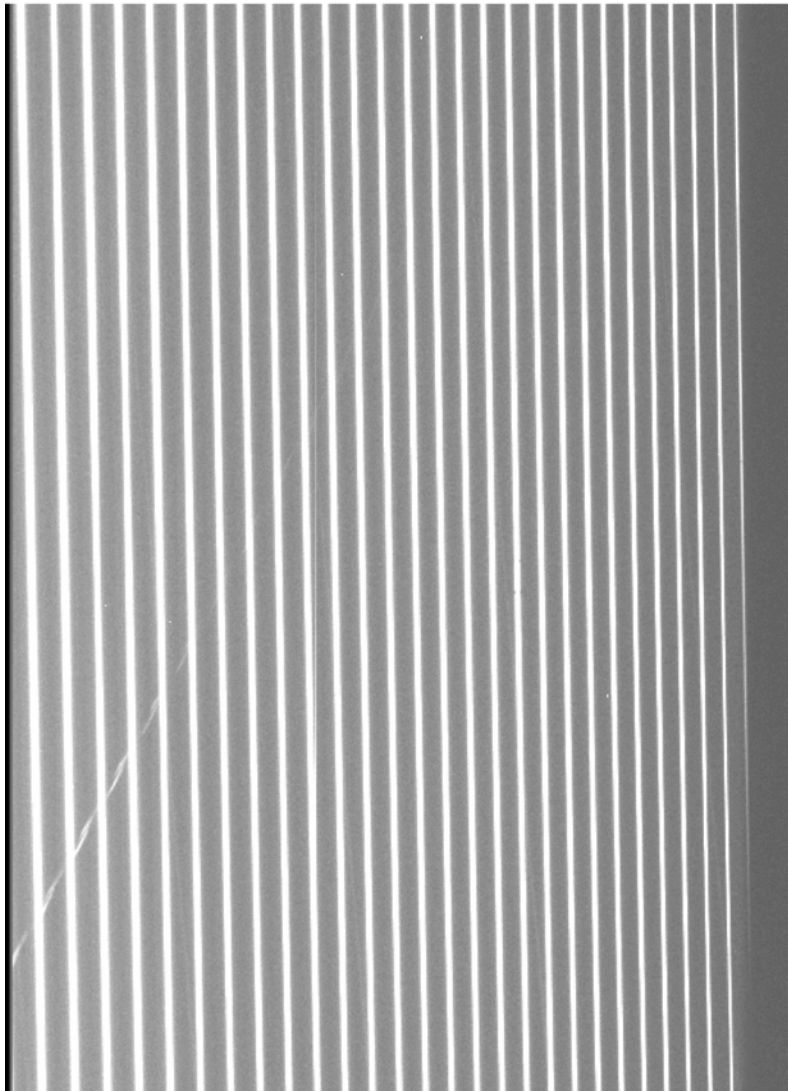


Figure 3.3: HIRES spectrum of a bright star. This is a portion of the blue CCD. Each spectral order is narrow, the width determined by the seeing and guiding of the telescope. The diagonal streak “meteor” can be seen toward the lower left. Wavelength increases from lower right to upper left.

The HIRES guider camera is used by the telescope observing assistant and the observer to identify objects and to point the telescope so that the proper point source or extended object appears on the spectrograph entrance slit. An example guider image is shown in Figure 3.4. Guider images are stored at WMKO on a different computer than the HIRES control computer. Frequently, guider images are taken and stored only for observatory engineering purposes. Observers have the option to choose and save selected guider images for their own use.

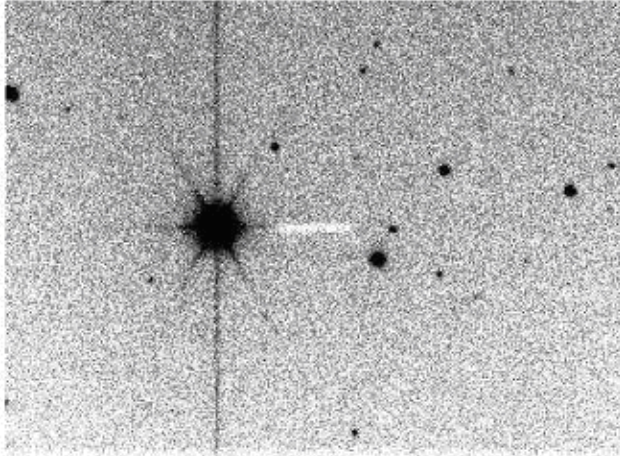


Figure 3.4: HIRES guider image of a star field. The image scale is inverted (black is bright). The HIRES entrance slit is faintly evident as a brighter horizontal rectangle in the center of the image. The signal from the bright star left of the slit has saturated the CCD, causing the charge to "bleed" in the vertical direction.

4.0 HIRES Data Set Definition for the Keck Observatory Archive

The HIRES dataset consists of a set of image files of several types. As discussed above, these image categories can be further subdivided as follows:

1. Calibration images
2. Scientific (program) object images

For the purposes of the archive, a HIRES *dataset* is defined as all spectra taken with the same instrument and CCD configurations. A simple method of linking science targets with the appropriate calibration files is to say that all calibrations taken on the same night as the science target and with the same configuration is part of that objects dataset. The basic set of calibration files consist of a number of flats, ThAr (arc lamp), bias and/or darks. A "trace" or "focus" spectrum taken through a pinhole may also be present. The calibration files can be distinguished from each other and from the science files by their "IMAGETYP" header keyword.

Association of a science object with calibration files is made in near real time as an archive query is sent. A calibration can be associated with a target by comparing certain keywords that define both the instrument and CCD configurations (see Table 4.1). A pair of science and calibration files is said to be associated if these keyword values are identical or matched, within the specified tolerances. For bias and darks, only the CCD configuration keywords need to be matched; for the rest of the calibration file types, both the instrument and CCD configurations are matched (see Table 4.2).

Table 4.1 Instrument and CCD Configuration Keywords

INSTRUMENT CONFIGURATION KEYWORDS	DESCRIPTION	UNIT	FORMAT	EXAMPLES	TOLERANCE
SLITWID	Slit width	mm	float	10.21383190	±0.005
SLITWIDT	Slit width projected on sky	arcsec	F10.8	0.861	±0.005
FIL1NAME	Filter #1	-	A8	KV370	
FIL2NAME	Filter #2	-	A8	clear	
COLLRED	Red collimator in?	-	A1	T/F	
COLLBLUE	Blue collimator in ?	-	A1	T/F	
ECHANGL	Echelle angle	deg	F9.8	0.01441866	±0.001
XDISPERS	Cross disperser type	-	A4	RED	
XDANGL	Cross disperser angle	deg	F9.8	0.32800001	±0.001
CCD CONFIGURATION KEYWORDS					
AMPMODE	Amplifier mode	-	char	SINGLE:B	
AMPLIST	Amplifier list	-	char	3,1,0,0	
BINNING	Binning	pix	I1,I1	2,1	
MOSMODE	Mosaic readout mode	-	char	B, G, R	
NVIDINP	No. of video inputs	-	I1	3	
PRECOL	Pre-column pixels	pix	I3	12	±0
POSTPIX	Post-column pixels	pix	I3	80	±0
CCDGAIN	CCD gain setting	-	char	low	
WINDOW	CCD window	-	A25	0,0,0,2048,2048	
CCDSPEED	CCD readout speed	-	char	fast	

Table 4.2 Keywords Comparison for Association

IMAGETYP		
Science Files	Calibration Files	
	<i>CCD Comparison Only</i>	<i>Both Instrument and CCD Comparison</i>
Object	Bias	Flatlamp
	Dark	Trace
		Arclamp
		Focus

The best set of calibrations is defined to be those taken on the same night as the science files or, if they're not available, those closest in time. Currently the archive user interface is constraint to automatically look for associated calibrations within +/- 3 days of the date of observations of the science targets. All calibration files that match with the science files according to the above prescription within the specified date range will be returned. An ascii file containing a listing of all the calibration files associated with each science file is also provided.

In future upgrades, the calibration association algorithm will look for matching calibration files taken only on the same night as the science files, moving out to neighboring nights only if a minimum number of files for each of the calibration file types has not been reached. If users

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desire to search for calibration files over more extended time periods, this option will also be implemented.

References:

HIRES User's Manual, <http://www2.keck.hawaii.edu/inst/hires/manual1.pdf>

Vogt et al. (1994), "HIRES: the High Resolution Echelle spectrometer on the Keck 10-m Telescope," S.P.I.E., 2198, 362.