Keck Telescope and Facility Instrument Guide

August 2002

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1 Introduction

The two 10-meter telescopes of the W. M. Keck Observatory (WMKO) are located near the summit of Mauna Kea on the island of Hawaii, in the state of Hawaii. Keck I was fully scheduled for astronomy in early 1994, and Keck II in October 1996. The two telescopes are separated by 85 meters, with Keck II roughly northeast of Keck I.

The observatory is operated by the California Association for Research in Astronomy in a partnership among the University of California, the California Institute of Technology, and NASA. These institutions and the University of Hawaii share observing time. The observatory headquarters is in Waimea (in the postal district Kamuela) in the northwestern portion of the island of Hawaii.

Teleconferencing links between each of the telescope control rooms and the respective remote operations rooms in Waimea provide excellent visual and audio communication between observers in Waimea and the observing assistants on the mountain. With the physical conditions in Waimea (especially the atmospheric pressure) much kinder to observers than those on the summit, observing from Waimea is substantially more efficient in most instances and is the choice of nearly all Keck observers. First time observers, however, may profit by visiting the summit to get a proper appreciation of the way the observatory functions and how the observing assistants operate.

A 45 Mb/s optical fiber data link connects the telescopes to the Waimea headquarters.

Observatory postal address: 65-1120 Mamalahoa Highway, Kamuela, HI 96743

Telephone: (808) 885-7887, Fax: (808) 885-4464

Public web site: www2.keck.hawaii.edu/ (currently mirrored at: astro.caltech.edu/mirror/keck/)

2 The Site

Observatory location:	longitude:	155° 28.4' W
	latitude:	19° 49.6' N
	altitude:	4123 meter
Median seeing:	about 0.5 arcsec FWHM in K-band	
Night temperatures:	within 2.5° +/- 4° C for about 90% of the time	
Median wind speed:	about 7 m/s (~14 mph)	

Allowable wind velocity with dome open: 50 mph (but velocity for closure may be varied depending on dust conditions and dome orientation)

Sky brightness:

U 23.2 mag/arcsec^2

B 23.0 mag/arcsec^2

V (excluding the bright OI line at 5577Å) 22.6 mag/arcsec^2

V 22-21.25 mag/arcsec^2 (various estimates that probably include the OI line)

R ~22 mag/arcsec^2

3 The Telescopes

3.1 Optics

3.1.1 The primary mirrors

The primary mirror comprises 36 hexagonal segments, each 1.8 m across the corners. The maximum diameter of the primary is 10.95 m and its focal length, 17.5 m. The telescope aperture area is equivalent to that with a circular aperture 9.96 m in diameter. The average optical performance of the segments (in combination with the f/15 secondary and the tertiary mirror) is such as to concentrate 80% of a star image within 0.4 arcsec diameter. The corresponding FWHM is about half as large.

The mirror segments are maintained in mutual alignment both in angle and in piston, using measurements of relative axial positions of neighboring segments, with capacitive sensors accurate to about 5 nm. With a freshly calibrated ACS, the stacked image is not significantly inferior to the average of the individual segment images; with a calibration a few weeks or more old, secondary mirror tilt and stacking imperfections sometimes contribute to image degradation. In most of the scientific observing modes, it is possible to measure the secondary tilt error and the ACS stacking imperfections and correct them without excessive loss of time during observing.

3.1.2 The f/15 secondary mirrors

The f/15 secondary mirror forms a Ritchey Chrétien system in conjunction with the primary mirror, giving zero coma. It may be used directly with the instrument mounted in the rear of the primary mirror support structure or with the tertiary flat for bent Cassegrain or Nasmyth foci.

3.1.3 The f/25 secondary mirror

An f/25 chopping secondary mirror, which forms a focus near the intersection of the telescope optical axis and the elevation axis, is used with the infrared instruments on Keck I. Its performance is listed in Table 1.

3.1.4 The f/40 secondary mirror

An f/40 chopping secondary mirror has been made for Keck II and is mounted in the Infrared Fast Steering Mechanism (IFSM). Its final focus is parfocal with the f/15 system; i.e., it feeds the conventional Cassegrain, bent Cassegrain, and Nasmyth foci, rather than forward Cassegrain. It differs from the Keck I f/25 chopping secondary in having a simpler drive, with more restricted ranges in both chopping throw and frequency.

The f/25 and f/40 secondary mirrors are undersized and have central holes so that they reflect no radiation to the detector from beyond the periphery of the primary mirror or from the primary mirror's central obstruction, for chop angles up to +/- 150 arcsec on the sky. The secondary mirror chopping mechanism is contained within an annulus behind the secondary mirror so that the detector sees direct skylight through the mirror's central hole and outside its external profile, apart from spider vanes supporting the chopping secondary assembly within the main secondary module.

Table 1. Features of infrared secondary mirrors.

Feature		Chopping Secondary	IFSM
Maximum amplitude	(arcsec on sky)	+/- 151	+/- 31
Maximum amplitude at 10Hz chop	(arcsec on sky)	+/- 16	+/- 2
Maximum amplitude at 50Hz chop	(arcsec on sky)	+/- 2	< 1

Note: The maximum amplitudes shown are conservative, allowing for the center of the chop being considerably offset in angle.

3.2 Details of Foci

Table 2 gives the main optical details of the alternative foci. The aberrations are expressed as rms diameter, meaning 2x rms radius of ray deviations from the image centroid at the test plane in which this rms is minimized.

Table 2. Main optical features of foci.

	f/15	f/25	f/40
Focal length (m)	149.6	249.7	395.0
Scale (mm/arcsec)	0.725	1.211	1.915
Field diameter (arcmin) (mm)	20 870	10 727	10 1138
Approx. radius of curvature of focal surface (m) (concave to secondary mirror)	2.14	0.82	0.85
Field radius (arcmin) / rms image diameter due to aberrations (arcsec)	5 / 0.09 10 / 0.36 (astigmatism)	2.5 / 0.19 5 / 0.41 (mainly coma)	2.5 / 0.21 5 / 0.42 (mainly coma)

3.2.1 Cassegrain focus

The Low Resolution Imaging Spectrograph (LRIS) can be mounted at this focus on Keck I and the Echellete Spectrograph and Imager (ESI) occupies the Cassegrain focus on Keck II.

3.2.2 Nasmyth/bent Cassegrain foci

With a (flat) tertiary mirror mounted on the elevation axis, the f/15 beam can be sent to either of two Nasmyth platforms (left and right) or to any of four bent Cassegrain focal stations. The High Resolution Echelle Spectrograph (HIRES) is on the right Nasmyth platform of Keck I, while the left Nasmyth platform is occupied by the Keck I adaptive optics (AO) system. On Keck II, the Near Infrared Spectrometer (NIRSPEC) and the Deep Extragalactic Imager and Multi-Object Spectrograph (DEIMOS) are available on the right Nasmyth platform, and the Keck II AO facility occupies the left Nasmyth platform. NIRSPEC and its internal slit-viewing camera (SCAM) also serve as AO science instruments for the Keck II AO system, along with a permanent AO camera and spectrograph, NIRC2, which was commissioned in late 2001. Prospective applicants should check the WMKO web site for the latest information.

3.2.3 Forward Cassegrain focus

Two infrared instruments, the Near Infrared Camera (NIRC) and the Long Wavelength Spectrometer (LWS), use the f/25 chopping secondary on Keck I. These instruments are mounted at the forward end of the Forward Cassegrain Module (FCM), which carries an offset CCD guider and provides instrument rotation.

3.2.4 f/40 Cassegrain/Nasmyth foci

Currently there are no facility instruments planned for the f/40 foci. There is, however, a bent Cassegrain port with rotator and guider, available for mounting visitor instruments on Keck II. Two mid-IR visiting instruments, MIRLIN and OSCIR, have been used at this port.

3.3 Telescope Control

3.3.1 Telescope drive details

The telescopes are on alt-azimuth mountings, with friction drive around both axes.

Slewing rates:	azimuth:	1.3 deg/s	acceleration: 0.05 deg/s^2
	elevation:	0.5 deg/s	acceleration: 0.03 deg/s^2
Zenith blind spot:	0.5 degree radius		

Telescope Tracking Limits:

Keck I

Over azimuth range 5.3° to 146.2°:	Elevation range :	33.3° to 88.9°
for other azimuths:	Elevation range :	0° to 18° (vignetted)
		18° to 88.9° (unvignetted)

Keck II

Over azimuth range 185.3° to 332.8°:	Elevation range :	36.8° to 89.5°
for other azimuths:	Elevation range :	0° to 18° (vignetted)
		18° to 89.5° (unvignetted)

See figure 1.

Pointing accuracy: ~4 arcsec rms

Closed-loop tracking: 0.08 arcsec rms

Open-loop tracking: not fully characterized, but ~0.1 arcsec/min

Open-loop offsetting: 0.1 arcsec over several arcsec

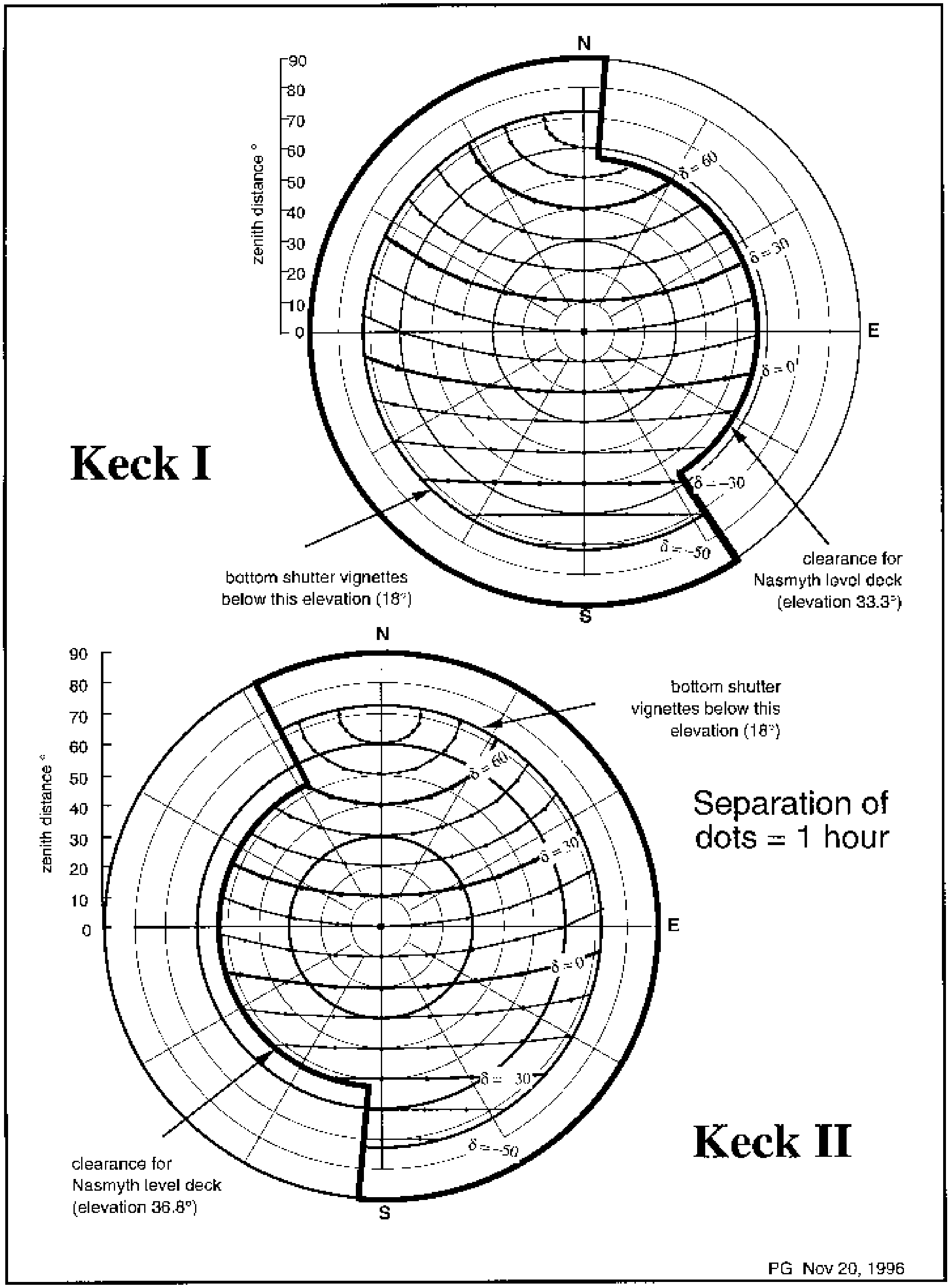

Figure1. Keck telescope drive limits.

3.3.2 Focus control

The telescope focus is controlled by pistoning the secondary mirror. Changes in focus due to changing elevation and temperature of the steel tube structure (and some other effects when necessary) have been calibrated and are applied as corrections to the raw measurement of the secondary piston position to derive what we refer to as "telfocus." Normally, the system is set to maintain telfocus constant with changing telescope attitude and time, so optimum focus should be maintained on the science detector. Unfortunately, occasional unexplained shifts in focus of 0.1 mm or more (referred to the secondary motion) still occur, so it is advisable to recheck the focus periodically and whenever unexpected image degradation is noticed.

The most informative and accurate way of checking focus (along with the secondary mirror alignment and the ACS performance) is with the routine known as MAlign (for Mirror Alignment). MAlign works with NIRC and LRIS on Keck I and ESI and NIRSPEC on Keck II.

4 The Instruments

4.1 HIRES - High Resolution Echelle Spectrometer

Principal Investigator: Steve Vogt (UCO/Lick Observatory)

Original Reference: Vogt, S. S., Steve L. Allen, Bruce C. Bigelow, L. Bresee, B. Brown, T. Cantrall, Albert Conrad, M. Couture, C. Delaney, Harland W. Epps, Darrie Hilyard, David F. Hilyard, E. Horn, Neal Jern, D. Kanto, Michael J. Keane, Robert I. Kibrick, James W. Lewis, Jack Osborne, G. H. Pardeilhan, T. Pfister, T. Ricketts, Lloyd B. Robinson, Richard J. Stover, D. Tucker, J. Ward, Ming Zhi Wei. "HIRES: the high-resolution echelle spectrometer on the Keck 10-m Telescope," pp. 362-375, 1994, S.P.I.E., 2198, 362.

HIRES is an in-plane echelle spectrograph with grating cross-dispersion. It resides permanently at the f/15 right Nasmyth focus of the Keck I telescope, enclosed in a light-tight and thermally stabilizing clean room. HIRES is designed to go faint (to V = 20.0), with a large nominal throughput (resolution-slit width product of 39,000 arcsec). The spectral coverage extends to the atmospheric UV cutoff, utilizing the red-optimized cross-disperser in 2nd order, or the blue-optimized cross-disperser in first order. Observers are required to specify which cross-disperser they need on their proposal cover sheets. Changing between cross-dispersers is a lengthy daytime task, so deviations from the cross-disperser designated on the cover sheet are strongly discouraged.

HIRES is operable at any time, with comparison source optics that mimic the telescope pupil. The position of the cross-dispersed echelle spectrum on the CCD is controlled by tilt adjustments of the echelle and cross-disperser mosaics. An echelle format simulator graphically displays the order and wavelength coverage of specific settings. The HIRES image rotator was commissioned in late 1996 and is now available for general use.

4.1.1 HIRES instrument specifications

Location	Right Nasmyth Keck I
Scale	0.725 mm/arcsec
Echelle	12" x 48" mosaic, 52.68 gr/mm, 70.5° blaze
Cross Dispersers	red: 16" x 24" mosaic, 250 gr/mm, 5600 Å
	blue: 16" x 24" mosaic, 400 gr/mm, 3800 Å
Collimator mirrors	12" diameter; blue (enhanced Al) and red (enhanced Ag)
Camera	f/1.0 catadioptric, 22 µm rms diameter images
Camera-collimator angle	10.0°
Detector	Tektronix 2048 x 2048, 24 µm pixels
Readout electronics	Leach-type DSP programmable
Readout mode	Single or dual-amplifier
CCD readout noise	5 - 6e^-
CCD dark current	<10 e^-/pixel/hour
Spectral range	0.30 - 1.1 µm
Spectral resolution	To 67,200 (0.074 Å = 2 pixel at 5000 Å)
Spatial resolution	0.191 arcsec/pixel
Slit projection	0.575 arcsec = 2 pixel
Spectral coverage	0.3 - 0.45 µm (2nd order cross disperser (CD))
	0.25 - 0.5 µm (2nd order CD)
	0.38 - 0.69 µm (1st order CD, no gaps)
	0.7 - 1.0 µm (1st order CD, two exposures, small gaps)
Order separation	8 arcsec at 0.3 µm (2nd order CD)
	21 arcsec 0.5 µm
	4 arcsec 0.3 µm (1st order CD)
	11 arcsec 0.5 µm
	21 arcsec 0.7 µm
	42 arcsec 1.0 µm
Slit dimensions	Decker: 2, 3, 4 and 6 pixel projected slit width x 3.5-28 arcsec; 0.12 arcsec pinhole; long slit: adjustable width, to 70 arcsec length
Filters	Two 12-position wheels accept 2" round or square filters
	13 order-blocking filters; 4 30-Å bandpass @ 5893, 6199, 6300, and 6563 Å
Guider	Fixed slit-viewing Photometrics CCD 45 x 60 arcsec FOV, 6.66 pixels/arcsec; to V = 22.0 at 8 sec exposure; ND and bandpass filters in two wheels
	Modes: off-slit rotation, on-slit, dispersion compensation
Image de-rotation	Provides constant position angle or maintains atmospheric dispersion along the slit.
Calibration sources	Halogen, ThAr hollow cathode, Iodine absorption cell (generally available from August 1, 1997), Edser-Butler Fabry-Perot; ND and bandpass filters in one wheel

4.1.2 User interface

Control electronics	Vx Works-based serial communication; parallel stage control
Computer	Sun UltraSparc 10, Openwindows toolkit
Image display	Figdisp with GUI
GUIs	Motif and DataViews
Simulators	Echelle format and signal-to-noise ratio, both exportable
Data reduction	IRAF, IDL, custom packages

4.1.3 Additional information

Further documentation for HIRES is available on the WMKO web site at http://www2.keck.hawaii.edu/realpublic/inst/hires/hires.html.

4.2 LRIS - Low Resolution Imaging Spectrometer

Principal Investigators: J.B. Oke, J.L. Cohen, and J.K McCarthy (California Institute of Technology)

Original Reference: Oke, J.B., Cohen, J.G., Carr, M., Cromer, J., Dingizian, A., Harris, F.H., Labrecque, S., Lucinio, R., Schall, W., Epps, H., and Miller, J., 1995, PASP, 107, 375 http://adsbit.harvard.edu/cgi-bin/nph-iarticle query?1995PASP..107..3750.

LRIS is an imaging spectrometer which operates at the f/15 Cassegrain focus of the Keck I telescope. Designed to work on very faint objects to the limiting optical magnitudes of the telescope, it can acquire bandpass-photometric images at high spatial resolution, and obtain low spectral resolution spectra also at high spatial resolution. The instrument mode is completely configurable from a remote workstation.

As an imaging device, LRIS can view 6×8 arcmin in the red beam, in four available bandpasses, or with custom filters. As a spectrograph, LRIS can function in long-slit or multi-slit modes. User-supplied coordinates, or those derived from LRIS images, are processed for input into a plate slit-milling machine. The instrument is also equipped with a polarimeter module which can be installed (if requested in advance of the run) for taking spectropolarimetry.

LRIS has completed a major upgrade to add a second, UV/blue optimized beam to the existing red beam of the instrument. This system employs dichroic beamsplitters to enable the simultaneous use of the two cameras for imaging in two passbands or taking spectra over two wavelength ranges. As of May 2002, the status of the upgrade is that all of the optics, mechanisms and the two science-grade CCDs have been installed. We have commissioned the blue side of the instrument and it is available for science. The main characteristics include:

1) **CCDs**: 2 2K×4K Marconi CCDs, 15 micron pixel size. Very high sensitivity in the blue (60-70% @3500, 90-95% @4000A, 85-90% between 4000 and 6000 A, >80% till 6500A). Readout time is 42 seconds. Pixel scale is 0.135"/pix. Noise ~ 2.5 ADU, gain ~1.6 e-/ADU.

2) **Geometry**: the CCDs are rotated 90 degrees with respect to the previous configuration (rotation is clockwise on the figdisp display). The gap between them runs along the direction of the bar on the slitmask (i.e., along the direction of dispersion in a spectrum). The gap is 100+/- 2 pixels wide corresponding to 13.5" on sky. The bar on the slitmask is 9.5" on sky, and it is centered within the gap. Two extra arcsec are now lost on each side of the bar. This may have consequences on the slitmask design: you may lose part of the slits which are close to the bar.

3) Longslit observations are affected because the center of the slit falls in the gap. A new pointing origin called "slitb" has been defined: it will place the object 30" from the inner edge (30" from the gap) of the right hand chip, the one with higher QE. The object is visible close to the left edge of the slit viewing guider camera.

4) **Spectral coverage** is 25% more because we have more pixels; we cover the full LRIS field along the spatial direction (all 8'; the red side is only 7.3').

5) The images are rotated 90 degrees CW with respect to the red CCD. Slitmask alignment is affected by the presence and the geometry of the gap. A new set of IRAF scripts is available for slitmask alignment on the blue and shell scripts for telescope moves. The total prescan area is 204 pixels (four 51 pixel wide stripes), the overscan 320 (80×4).

6) Below 4000 Å, the CCDs uniformity gets worse and a brick wall pattern becomes clearly visible. More care with flat fielding is required. If you plan to use the 1200 grism, it is recommended that you take a series of flats during the afternoon (with the internal lamp – dome lamps will not provide enough UV light).

7) **Image quality**: the blue camera, with the coma-correcting first camera element now in its nominal setting, and with a flat chip for the first time, achieves pinhole images of 0.23" through its useful wavelength range. Thus, if the telescope and camera are well-focused, it should be possible to obtain very good images in the blue under good seeing conditions.

Other additions to LRIS since last period:

1. Addition of the new Short Pass 580 filter (sp580) in the blue side. It has ~96% transmission above 565 nm. The transmission averages around 90% in the 400-565 nm range and falls to 50% at 320nm.The filter transmission curve has some “fringes” in it throughout the entire range, where the transmission falls down to 70%. Please consult the LRIS web pages to check if the filter transmission is suitable for your science. The filter is meant to eliminate all the ghosts in the blue side, which are generated by the second order dispersed light coming from the red side. Even if not suitable for your science, using this filter certainly makes arc images easier to reduce.
2. Replacement of the old “V_BAD” filter with a new one in the blue side. The old filter was producing “double” images because of delamination. The new filter has a 540-nm central wavelength (transmission T~77%), a bandwidth of ~90 nm. Please check the filter curves and specs in the LRIS web pages.

4.2.1 LRIS instrument specifications

Location	Cassegrain
Focal plane scale	0.725 mm/arcsec
Collimator	2004 mm FL, off-axis paraboloid, 147 mm beam diameter
Camera	304 mm FL f/1.3, all-refracting
Camera-collimator angle	44.1°
Detectors	Red side: Tektronix 2K×2K, 24 µm pixels Blue side: 2 2K×4K E2V CCDs, 15 µm pixels
Readout electronics	Leach-type DSP programmable
Readout mode	Single or dual amplifier
Readout noise	Red side: 6 -7e^{-}/pixel Blue side: 6×8 arcmin
Wavelength range	Red side: 0.38 - 1.1 µm Blue side: 320-900. QE is 60-70% @3500, 90-95% @4000A, 85-90% between 4000 and 6000 A, >80% till 6500A
Guiders	Offset (movable): 82 × 60 arcsec FOV, 82 arcsec x 6 arcmin available, 0.213 arcsec/pixel; v, clear filters; to V = 23.0 at 20 sec exposure Slit-viewing (fixed): 92 × 69 arcsec FOV, 0.239 arcsec/pixel; B, R, I, clear filters Modes: position angle, vertical angle

Imaging mode

Field of View	Red side: 6×8 arcmin rectangular Blue side: 6×8 arcmin rectangular
Plate Scale	Red side: 0.215 arcsec/pixel Blue side: 0.135 arcsec/pixel
Bandpass Filters	Red side: B, V, R, I, Z (RG850) Blue side: u', B, V
Sensitivity	Red side: 235,000 e^{-}/s integrated flux at V = 15.0 (R-band)
Throughput	Blue side zeropoints u' = 27.28; G: 28.38

Spectrometer mode

Spectral range	0.190 – 0.757 µm (300/500)
Spectral resolution	5.46 Å (FWHM with 300/5000) to 0.98 Å (1200/3400)
Spectral coverage	568 nm (300/5000) to 100 nm (1200/3400)
Slit projection	0.5 arcsec 2-pixel at 600 gr/mm (6200 Å setting)
Long slits	0.7, 1.0, 1.4, and 8.7 arcsec widths; all 3 arcmin long
Slitmask plates	4×8 arcmin field; up to 30 - 40 objects; slits milled on-site; 0.7 - 1.4 arcsec wide
Order blocking	GG495, OG570 filters

Grating complement (red side):

gr/mm	blaze (Å)	Å/pixel	$\Delta\lambda$(Å)	η (instrument)
150	7500	4.80	9800	
300	5000	2.54	5300	0.34 (6000 Å)
400	8500	1.92	3950	
600	5000	1.28	2650	
600	7500	1.28	2600	0.40 (6500 Å)
600	10,000	1.28	2600	
831	8200	0.93	1900	
900	5500	0.85	1740	
1200	7500	0.65	1320	0.36 (7200 Å)

Grism complement (blue side):

gr/mm	blaze (Å)	Å/pixel	$\Delta\lambda$(Å)	η (instrument)
300	5000	1.387	5678	
400	3400	1.071	4384	
600	4000	0.609	2496	
1200	3400	0.242	992	

Dichroic complement: 4600, 5000, 5580, and 6800 Å beamsplitters

Calibration sources: Hg, Ne, Ar, Xe, Zn, Cd, Halogen internal lamps; dome illuminated separately

Polarimetry

Configuration	Installed behind slit (daytime operation)
Field of View	35 x 35 arcsec
Modes	Imaging or spectroscopic
Polarization states	Linear or circular

User interface

Control Electronics	Motor control: Solaris-based, serial communication; serial (red side) and parallel (blue side) stage control
	CCD control: VxWorks-based system
Computer	Sun Ultrasparc 10, Openwindows toolkit
Image display	Figdisp with GUI
GUIs	Motif and Data Views
Data reduction	IRAF, IDL, Figaro, Vista, custom slitmask alignment and display software

4.2.3 Additional information

Further documentation on LRIS is available on the WMKO web site at http://www2.keck.hawaii.edu/realpublic/inst/lris/lris.html.

4.3 NIRC - Near Infrared Camera

Principal Investigators: Keith Matthews, Tom Soifer (California Institute of Technology)

Original Reference: Matthews, K. and Soifer, B.T., 1994, Infrared Astronomy with Arrays: the Next Generation, I. McLean ed. (Dordrecht: Kluwer Academic Publishers), p. 239.

NIRC is an instrument designed to produce both infrared images and low-resolution spectra in the 1 to 5 µm spectral range, although in practice the performance of the NIRC readout electronics imposes severe limitations on observing in the 3 - 5 µm range. The NIRC dewar and electronics are mounted in the rotating infrared instrument frame at the f/25 forward Cassegrain focus of the telescope. The converging light from the secondary mirror strikes an off-axis, gold-coated tertiary mirror which is mounted on the side of the dewar, then passes through a vacuum window. A mask with slits and an occulting pointer (for coronographic imaging) can be deployed prior to the light striking a gold-coated parabolic field mirror which collimates light to a gold fold mirror. An image of the infrared secondary mirror is then formed on a pupil mask. Just after the pupil mask, two tandem filter wheels intercept the collimated light. The filter wheels also hold grisms for spectroscopy, and an assortment of narrow- and broad-band filters. The camera lens, which is a barium fluoride, lithium fluoride achromat, focuses the collimated light coming through the filter wheels on the detector. Re-imaging optics (outside the dewar) can be inserted to provide about 7x magnification. This mode is used for speckle imaging.

NIRC was commissioned in March 1993 as the first instrument on the telescope. The camera is normally used in both imaging and spectroscopic modes out to 3.0 µm. Use of NIRC in the 3 - 5 µm range is severely limited by the performance characteristics of the fast timing patterns. The only way to obtain readout times fast enough to avoid saturation is to read out only a very small window on the detector. In M-band the usable window is so small as to make observing extended sources impossible.

4.3.1 NIRC instrument specifications

Wavelength	0.8 - 5.3 µm	
Plate Scale	0.15 arcsec/pixel (0.02 arcsec/pixel with reimager)	
Detector	256 x 256 InSb Hughes SBRC	
	30 µm pixels (38.4 arcsec x 38.4 arcsec field)	
	4-channel parallel readout	
	16-bit ADC, 500 KHz	
	12-bit ADC, 2 MHz	
Filters (bandpass µm)	JH (1.00 - 1.60)	Z (0.954 -1.1105)

	J (1.105 - 1.397)	H (1.491 -1.824)
	K'(1.955 - 2.292)	KS (1.99 - 2.32)
	K (2.00 - 2.427)	HK (1.402 - 2.532)
	KW (1.952 - 2.546)	UV22 (0.2 -2.7)
	LS (2.467 - 3.490)	L' (3.521 - 4.141)
	KL (2.146 - 4.149)	LW (2.747 -4.237)
	M (4.404 - 5.032)	LM (2.944 - 4.946)
	MW (4.344 - 5.7)	HE I (1.0761 - 1.0897)
	Pγ (1.0878 - 1.0982)	OII (1.2308 - 1.2413)
	Pβ (1.2750 - 1.2896)	Fe II (1.6383 - 1.6559)
	Cont. Bα (3.96815 - 4.01645)	Bα (4.0193 - 4.0717)
	H2 1-0 (2.1132 - 2.1367)	Bγ(2.1535 - 2.1759)
	H2 2-1 (2.2366 - 2.2605)	CO 2-0 (2.2836 - 2.3110)
	Cont. K (2.2331 - 2.2862)	CS PAH (3.03215 - 3.13285)
	PAH (3.2785 - 3.3415)	CL PAH (3.3761 - 3.4495)
Grisms	60 g/mm (4.22, 2.11, 1.42, 1.13, 0.09, 0.75)	
	120 g/mm (2.11, 1.13, 0.75)	
	150 g/mm (1.71 1st order, 0.92 2nd order, 0.61 3rd order)	
Slits	1.5, 2.5, 3.5, 4.5, 8.5, 16.5 pixels wide	
Window	CaF_2	
Dewar size	13-inch octagon x 51 inch	
LN_2 tank	40 liter	
LHe tank	15 liter	
Hold time	3.5 days LN_2, LHe	
Sensitivity	20.4 mag, 1 σ in 1 sec in 1 x 1 arcsec (at 2.2 μm) or 22.3 mag, 10 σ in 1 hour	

4.3.2 Additional information

Further documentation on NIRC is available on the WMKO web site at http://www2.keck.hawaii.edu/realpublic/inst/nirc/nirc.html.

4.4 LWS - Long Wavelength Spectrometer

Principal Investigator: Barbara Jones, University of California at San Diego

LWS is a facility instrument that produces diffraction-limited images, low-resolution spectra, and moderate resolution spectra, over the mid-infrared range of 8-25 microns. The LWS detector is a 128x128 Boeing Si:As BIB moderate flux array. The instrument has met its design goals in the areas of image quality, sensitivity, spectral coverage, spectral resolution, and operability. LWS is fully commissioned and available for regularly scheduled science observing.

Please check the web site for more detailed information and the latest news.
http://www2.keck.hawaii.edu/realpublic/inst/lws/lws.html

The LWS dewar is an uplooker, i.e., it looks directly at the telescope secondary with no tertiary mirror. A rotating grating turret contains the low- and high-resolution gratings and a mirror for direct imaging. A plate scale of 0.080 arcsec/pixel was selected to provide adequate sampling of the 0.25 arcsec FWHM of the 10-micron diffraction pattern. Gold-coated mirrors are used throughout for high performance (1% loss per surface, 10 reflections). A 16-position filter wheel provides imaging filters and blocking filters for spectroscopy. An aperture wheel provides slits for spectroscopy. All the optical components beyond the dewar window are cooled to liquid helium temperature except the detector, which is maintained at 8.52 +/- 0.02 ^{o}K.

The instrument is controlled remotely using a workstation with a graphical user interface (gui). The gui is comprised of several windows that control different aspects of the instrument and telescope configuration. The gui is a higher level software that lies above a keyword interface. The keyword architecture is a Keck standard that allows the user to interrogate and manipulate the instrument (and telescope) from several interfaces including scripts (macros) and the command line. The image display tool, dubbed Quickview, is IDL based. Quickview allows the user flexibility in image buffer control and display with realtime assessment of data. Quickview includes tools for initial data analysis in both imaging and spectroscopy modes.

4.4.1 LWS instrument specifications

Wavelength	3 - 25 microns
Plate scale	0.08" / pixel
Detector	128 x 128 Si:As BIB array, moderate flux
	4-channel, Boeing
	75-micron pixels
Detector temperature control	8.52 +/- 0.02^{o}K
Electronics	custom preamplifier, level shifter with 4-channel parallel coadders on peck bus
	12-bit ADC
Filters	16-position filter wheel includes (bandwidths below are in microns)
	L (3.5 - 4.15)
	M (4.4 - 5.0)
	8.0 (7.5 - 8.2)
	8.9 (8.4 - 9.2)
	9.9 (9.4 - 10.2)
	10.7 (10.0 - 11.4)
	Si C (10.5 - 12.9)
	11.7 (11.2 - 12.2)
	12.5 (12.0 – 13.0)
	Nwide (8.1 - 13.0) (not usable for imaging)
	17.65 (17.3 – 18.2)
	17.9 (16.9 – 18.9) (not recommended)
	18.75 (18.3 – 19.2)

	Spec10 long pass > 6.94
	Spec20 long pass > 13.71
Apertures	open
	long slit 3.0 pixels wide
	long slit 6.0 pixels wide
Gratings	8 g/mm, 10-micron blaze, res = 100 (LRES)
	50 g/mm, 20-micron blaze, res = 1000 (HRES)
Window	Hydroscopic KBr, AR coated ZnSe that moves out of path for 20-micron operations
Calibration	Chopping sector wheel equipped with mirrored and mat black paddles
Performance	Imaging FWHM of 0.28 arcseconds best at 11.7 µm (instantaneous)
	Imaging FWHM of 0.35 arcseconds typical at 11.7 µm (over extended period)
Imaging Sensitivity	Performance for imaging a point source is that a flux of
	17 mJy gives SNR = 1, for t = ls at 11.7 microns, SiC filter, 2.4-micron bandwidth
	0.10 JY, SNR = 1, for t = ls, 17.65 microns, 1.0-micron bandwidth
Low Resolution	Performance for spectra of a point source is that a flux of
Spectroscopic Sensitivity	0.15 JY, SNR = 1, for t = ls, @11.7 microns, per resolution element (3pix or 0.25"slit)
High Resolution	TBD
Spectroscopic Sensitivity	

4.4.2 Additional Information

Original Reference: "The Keck Long-Wavelength Spectrometer," Jones, B., Puetter, R.C., 1993, Proc. SPIE, 1946, Infrared Detectors and Instrumentation, 610.

Further information on LWS is available on the WMKO web site at http://www2.keck.hawaii.edu/realpublic/inst/lws/lws.html.

4.5 f/25 Guider

This camera is designed to be a fixed-position offset guider for the IR f/25 focus and is used for NIRC and LWS. The camera is a Photometrics frame transfer CCD.

Field of View	46.1 x 61.4 arcsec
useful pixels	288 x 384
plate scale	0.160 arcsec/pixel
sky annulus from NIRC	4.4 to 5.4 arcmin radius
sky annulus from LWS	6.7 to 7.7 arcmin radius

4.6 NIRSPEC - The Near Infrared Echelle Spectrograph

Principal Investigator: Ian McLean (UCLA)

Reference:

The Design and Development of NIRSPEC: A Near-Infrared Echelle Spectrograph for the Keck II Telescope by Ian S. McLean et al. SPIE vol. 3354, 1998, pp. 566-578.

The Near Infrared Spectrometer (NIRSPEC), a cryogenic cross-dispersed echelle spectrograph, features spectroscopy over the 0.96-5.5 micron range at resolutions of R 2000 or 25000. The HgCdTe slit-viewing camera provides additional capability to image fields in a 46"-square field from 1-2.5 microns. The software interface includes planning tools for users to prepare observational setups and exposure sequences.

4.6.1 NIRSPEC instrument specifications

Location	RNAS, Keck-2, f/15 input beam
Detectors	Slit-viewing (SCAM): Rockwell HgCdTe, 0.18"/pixel, read noise = 10 e^-, Linear limit = 120000 e^-, 46" square field, 0.95-2.5 microns wavelength range Spectrograph: ALADDIN InSb 1024x1024, 27 micron pixels, dark current = 0.2 e^-/s/pixel, read noise = ~40 e^- RMS, single-read mode Linear limit = 100000 e^-, 0.95-5.5 microns wavelength range

Filter Bandpasses

Name	Wavelength Range (microns)
Nirspec-1	0.947-1.121
Nirspec-2	1.089-1.293
Nirspec-3	1.143-1.375
Nirspec-4	1.241-1.593
Nirspec-5	1.143-1.808
Nirspec-6	1.558-2.315
Nirspec-7	1.839-2.630
Br-Gamma	2.155-2.175
CO	2.228-2.305
K	1.996-2.382
K-Prime	1.950-2.295
L-Prime	3.420-4.120
M-Prime	4.570-4.810
KL	2.134-4.228
HeI	1.078-1.088
Pa-Beta	1.276-1.289
H2	2.110-2.129
FeII	1.639-1.654

	M-Wide	4.420-5.530
Spectroscopy	Low resolution: R 2000 (150 km/s), 3-pixel slit (0.43") High resolution: R 25000 (3-pixel slit (0.43"))	
Slit Complement	0.144"x12 0.288"x12 0.432"x12 0.576"x12 0.720"x12 0.288"x24 0.432"x24 0.576"x24 0.720"x24 42x0.380" (low res) 42x0.570" (low res) 42x0.760" (low res)	
Guider	1024x1024 PXL, R-band, annular diameter 1-3.5', 7.5 arcmin^2 coverage. Guiding also available on SCAM.	
Optics	Spectrograph optics all reflecting, diamond-machined, post-polished, Al/Ni-Al substrates, silver or gold coated.	
Cryogenics	Full vacuum enclosure, CCR continuous cooling to 55 K (30 K ALADDIN). All cryogenic mechanisms, including image derotator to fix sky PA on slit.	
Electronics	Transputer-based architecture.	
User Interface	DataViews (control) and IDL (quicklook, image rotator control, and echelle format simu lator/scripter).	
Performance	SCAM image quality FWHM 0.3-0.55" typical. SCAM J-band zero point: 24.7 mag @ 1 DN/s. Other sensitivity TBD	

Additional Information:

WWW sites:

http://www2.keck.hawaii.edu/realpublic/inst/nirspec/nirspec.html

http://www.astro.ucla.edu/~irlab/nirspec/

4.7 ESI - Echellette Spectrograph and Imager

P.I.: J. S. Miller, M. Bolte, R. Guhathakurta, D. Zaritsky (UCO/Lick Observatory)

The ESI instrument is a versatile, multi-mode spectrograph and imager, with high throughput one of its most important goals. There are two distinct spectroscopic modes: a medium-resolution echellette mode with prism cross dispersion; and a high-throughput mode using prism dispersion only. The echellette mode covers the full wavelength range of the future Keck II silvered mirrors (3900 to 11,000 Å) in a single exposure with a velocity resolution of ~10–15 km/sec/pixel. The low-resolution, prism-only mode provides the same spectral range and high throughput. ESI also provides an imaging mode with a field of view of 3.0 arc-minutes. An Epps refracting camera and a single 2K x 4K detector are used for all three modes.

The ESI collimator is an off-axis paraboloid, similar to the collimator in LRIS. A single 2K x 4K Lincoln Labs CCD with 15 micron pixels is used with a Leach-2 CCD controller. A single, all-refracting camera, is used for all three operating modes. There is a 1Kx1K PXL acquisition/ guide TV camera that views part of the slit plus a stationary, offset mirror. Three 5-position filter-wheels are provided in the science beam: one in the focal plane containing slits, and two beneath that providing either a mask (for the echellette slits, which are all on a single slit plate) or filters. Another wheel carries filters for the guide/acquisition camera. At any one time, a single echellette grating is available, fixed in position and in rotation. Changing gratings is a manual operation and will not be done during the night. Only one grating is presently available. A flat mirror bypasses the grating for switching to the prism-only (low-dispersion) mode. A second flat mirror bypasses both the prisms and the grating to provide the imaging mode.

4.7.1 ESI instrument specifications

General specifications

Location	Keck II Cassegrain (f/15)
Focal plane scale	0.725 mm/arcsec
Scale at detector	0.15 arcsec/pixel
Wavelength range	0.39–1.1 microns
Detector	MIT-LL 2048x4096 CCD, 15 micron pixels
CCD sensitivity	QE of 10% (at 0.32 µm), 61% (0.4 µm), 82% (0.5 µm), 80% (0.6 µm), 77% (0.7 µm), 69% (0.8 µm), 45% (0.9 µm), 11% (1.0 µm)
Readout electronics	Leach 2 DSP programmable
Readout modes	Single or dual amplifier; slow, normal, and fast modes
Readout times	39 sec (dual-amp, normal speed) 70 sec (simgle amp, normal speed)
Readout noise	2.5 electrons/pixel (normal readout speed)
Grating	175 lines/mm, 32.3° blaze angle
Cross dispersion	Two prisms, first used in double-pass mode.

Slit/filter wheels	Three, only first (slit wheel) in focal plane. Five positions in each wheel.
Wavelength calibration lamps	Ne, Xe, HgNe, CuAr, quartz
Guider	Slit viewing with offset field 1024x1024 Photometrics PXL CCD Total FOV 3x3 arcmin. 0.18 arcsec/pixel 50x50 mm filters, none provided initially
Echellette mode	
Wavelength range	0.39–1.1 microns
Spectral resolution	15 km/sec/pixel (R = 20000/pixel)
Slit length	20 arcsec
Slit widths	0.3, 0.5, 0.75, 1.0, 1.25, 6 arcsec (all on same slit plate, selectable using mask in second wheel)
Order blocking filters	None
Low-dispersion mode	
Wavelength range	0.39–1.1 microns
Spectral resolution	R=6000 (0.39 microns) to R=1000 (1.1 microns)
Slit length	8 arcmin
Slit widths	0.5, 0.75, 1, 1.25, 6 arcsec (each on a separate slit plate)
Order blocking filters	None provided initially
Slitmasks	Not available initially
Imaging mode	
Field of view	2x8 arcmin full field 2.1x3.5 arcmin (for 93x154 mm filters)
Scale	0.15 arcsec/pixel
Filters	B, V, R, I (93x154 mm; 2.1x3.5 arcmin FOV) holders for two 100x100 mm filters (2.3x2.3 arcmin) holders for three 50x50 mm filters (1.1x1.1arcmin)
Sensitivity	~280,000 e^-/s integrated flux at V = 15.0 (V-Band)

4.7.2 User Interface

Control electronics	Intelligent Galil controllers, parallel stage control
Computer	Sun Ultra 2, OpenWindows
Image display	FIGDISP with tcl/tk GUI
Control GUI	Dashboard (tcl/tk-based)

Data reduction	IRAF, IDL, Vista, custom echelle reduction software

4.7.3 Additional information

Further documentation on ESI may be found at http://www2.keck.hawaii.edu/realpublic/inst/esi/esi.html. This Web page will be kept up to date as information from commissioning runs becomes available, and can be expected to contain more recent information than the current document.

4.8 DEIMOS - DEep Imaging Multi-Object Spectrograph

P.I.: S. M. Faber (UCO/Lick Observatory)

Literature reference: not yet available

DEIMOS is a general-purpose, faint-object, multi-slit, visible-wavelength imaging spectrograph residing on the Nasmyth platform of the Keck II telescope. DEIMOS features wide spectral coverage (up to 5000 Å per exposure), high spectral resolution (down to ~1 Å), high throughput, and relatively wide field of view (81.5 $arcmin^2$ field). Conceived as a dual-beam instrument, it has been built with one camera and offers three observing modes: direct imaging, long-slit, and multi-slit spectroscopy using custom slitmasks. Commissioning began in June 2002, and is expected to continue though the end of Semester 2002B, with shared-risk science observing occurring concurrently.

DEIMOS features a sophisticated closed-loop internal flexure compensation system which maintains alignment of the image to an accuracy of less than 1 px in both imaging and spectroscopic configurations. The instrument is completely configurable and operable from a remote workstation.

For the first year of operation, multi-object slitmasks will be custom milled at Lick Observatory and shipped to Keck. Observers with astrometric coordinates for their list of targets can use IRAF-based software, supplied by the instrument team, to design custom slitmasks. Slitmask design files must be delivered to Lick Observatory no less than two weeks prior to your observing run in order to allow time for milling the masks, shipping them to Keck, and installing them in the instrument. Please contact instrument support personnel at WMKO to coordinate slitmask observing programs.

4.8.1 DEIMOS Instrument Specifications

Location	Right Nasmyth platform, Keck II telescope; removable from focus
Layout	Two cameras fed from common collimator (Only one currently constructed)
Rotator	740° rotation
User access	Slit masks, all gratings and all filters

Guiding system	One guider; ~10 sq arcmin FOV; slit-viewing and offset modes are both available
Spectrograph flexure control (internal)	Two-coordinate beam-steering with closed-loop feedback
Flexure	Goal is 0.25 px rms motion over typical integration (with flexure control system on, 2px rms open loop)
Slit masks	Capacity of 11 in cassette; cylindrical radius of curvature matched to focal plane curvature
Slitlet options	Slitlets of arbitrary size and orientation
Dispersive elements	Capacity of 2 in spectrograph
Imaging option	Silvered flat mirror replaces grating
Filters	6.5×6.5 in glass filters; 7 slots available; assorted "clear," broadband, and order blocking
Collimator focal length	86.50 in
Camera focal length	15.00 in
Beam diameter	6.33 in for 10.95 m primary; 5.79 in for 10.02 m primary
Monochromatic f/ratio	f/2.358 for 11.00 m primary; f/2.586 for 10.02 m primary
Polychromatic f/ratio	f/1.29
Scale at detector	0.00759 arcsec/µm; 0.119 arcsec per 15µm px
CCD detector array	8192×8192 px (15 µm px); 2×4 mosaic of 2K×4K CCDs
Readout electronics	SDSU Leach 2 system, customized for fast readout
Readout mode	Imaging: single or dual amplifier Spectroscopy: dual amplifier only
Readout noise	2.3-3.3 e-
Image format	Multi-HDU FITS (NOAO Mosaic format)
Image size	74 MB (imaging, uncompressed); 142 MB (spectroscopy, uncompressed)
Angular field radius of camera	11.40°
Camera glass transmission	97% for lambda > 5200 Å; 88% at 3900 Å; 93% at 4400 Å
Total camera throughput	85% at lambda > 5200 Å;

	77% at 3900 Å (including coatings and transmission)

Imaging Mode

Field shape	Rectangular with 2 lopped-off corners; sliver out of long side
Outer dimensions of rectangular field	16.7 arcmin×5.0 arcmin
Area lost to CCD mosaic gaps	0.4 arcmin×5.0 arcmin
CCD pixel scale	0.119 arcsec per px (15µm px)
Wavelength range (imaging)	4100 Å - 11,000 Å
Standard filters	BVRIZ
Throughput at 6000 Å	40% (including telescope)
Image size (including telescope aberrations)	B band (0.5 arcsec seeing): 0.56 arcsec FWHM V-->I bands: 0.54 arcsec FWHM
Expected count rate	800 e- per sec in V band at 21.0 mag
Mode changes	30 sec changeover between imaging and spectroscopy

Spectroscopy Mode

Total slit length	16.7 arcmin
Usable slit length	16.3 arcmin
Total number of slitlets	85 10-arcsec slitlets with 1.5 arcsec gaps
CCD detector scale	0.119 arcsec per px (15µm px)
Wavelength range (spectra)	4100 Å -- 11,000 Å
Order blocking filters	GG400, GG455, GG495, OG550
Slit widths	User selectable by choice of mask standard 1.0 arcsec longslit mask also available
Design slit widths	1.0 arcsec nominal
Current gratings (all 6×8 in)	600 l/mm (7500 Å blaze) 830 l/mm (gold coated); 900 l/mm (5500 Å blaze); 1200 l/mm (7500 Å blaze, gold coated);
Number of grating slots	2 slots available
Corresponding dispersions	0.65 Å/px, 0.47 Å/px, 0.44 Å/px, and 0.33 Å/px

Spectral lengths (8000 px)	5300 Å, 3840 Å, 3530 Å, and 2630 Å
FWHM resolutions	3.5 Å, 2.5 Å, 2.1 Å, and 1.1-1.6 Å for 0.75 asec slit
Throughput at 6000 Å	29% (including telescope)
Count rate at 6000 Å	1.0 e- per sec at V = 21.0
S/N on faint stellar objects in one hour	5:1 for V = 24.0; 12:1 for V = 23.0; 21:1 for V = 22.0
Calibration sources	Hg, Ne, Ar, Kr, Xe, Cd, Zn, Quartz halogen internal lamps; dome illuminated separately

NOTE: All throughput numbers are predicted, not yet confirmed.

4.8.2 User Interface

Control Electronics	Motor control: Solaris-based, parallel stage control
CCD control	VxWorks-based system
Computers	User host: Sun Ultrasparc 4 Instrument host: Sun Ultrasparc 10
Image display	Science mosaic: ds9 (customized) FCS mosaic: FIGDISP
Data reduction software	IDL-based pipeline supplied; IRAF reduction via MSCRED package
Slitmask alignment software	IRAF-based

4.8.3 Additional Information

Further information and updates are available on the DEIMOS Home Page: http://www2.keck.hawaii.edu/inst/deimos/.

4.9 Science Instruments for Use with Adaptive Optics

Principal Investigator (Keck AO System): P. Wizinowich, W. M. Keck Observatory

Original Reference: P. Wizinowich, D.S. Acton, T. Gregory, P. Stomski, J. An, K. Avicola, J. Brase, H. Friedman, D. Gavel, C. Max. "Status of the W.M. Keck Observatory Adaptive Optics Facility," SPIE Proc. 3353, 568-578 (1998).

The Natural Guide Star (NGS) Adaptive Optics (AO) facility is available on the Keck II telescope. NIRC2, the second-generation Near Infrared Camera, and NIRSPEC, the Near

Infrared Spectrograph, are currently available as the science instruments.

The AO facility, along with the science instruments that accompany it, is located at the telescope's f/15 focus on the left Nasmyth platform in a light tight and thermally stabilized enclosure. The role of the AO system is to correct for the wavefront distortion introduced by atmospheric turbulence. A fast Shack-Hartmann wavefront sensor camera is used to sense the distortion and a 349-actuator deformable mirror is used to correct the distortion. Nearly diffraction-limited FWHM images are delivered to the science instrument over the 1 to 2.6-micron range. The resultant Strehl ratio and FWHM are a function of the seeing (spatial and temporal scales) and the guide object's magnitude, off-axis distance, and size (if non-stellar).

The output of the AO system is identical to that of the telescope with the same f/# and with the pupil at the same distance in front of the focal plane. NIRC2 is designed to take full advantage of this natural AO focus, with selectable image scales of 10, 20, and 40 milli-arcseconds per pixel. When NIRSPEC is used as the science instrument, a magnification of 10.6 is provided to give a plate scale of 0.0168 arcseconds per pixel on NIRSPEC's slit-viewing camera (SCAM) (see below). The AO system also provides field (or pupil) de-rotation with a K-mirror rotator and a 2-arcmin-diameter field of view acquisition camera.

Future major planned upgrades include a laser guide star facility, which will dramatically increase the sky coverage with AO.

4.9.1 AO instrument specifications

Location	Left Nasmyth Keck II at the f/15 focus
AO Optical Path	The AO bench science path optics consist of: a K-mirror to provide field or pupil de-rotation, an off-axis parabola (OAP) to collimate the f/15 beam & re-image the telescope primary mirror onto the deformable mirror, a 349-actuator deformable mirror with 7x7 mm actuator spacing corresponding to 56.25 cm on the primary, a 2nd OAP to reproduce the telescope's f/# and pupil location with respect to the focal plane, and an IR transmissive dichroic to transmit light from 1 to 2.7 µm wavelength.
Natural Guide Object	V magnitude < 13.5 Separation from science object < 30 arcsec Diameter < 2.5 arcsec
Performance	Performance will degrade with NGS magnitude & somewhat with off-axis distance. Typical current values (Strehl ratio and FWHM) for a 9th mag on-axis NGS are: 15% & 35 milliarcsec in J-band 35% & 40 milliarcsec in H-band 50% & 50 milliarcsec in K-band
Wavefront sensor	The wavefront sensor consists of: a pair of field steering mirrors to select the off-axis NGS a field stop (selectable apertures of 1.2, 2.0 & 4.8 arcsec diameter) pupil reimaging optics (to reimage the DM on the lenslet array) a lenslet array (selectable 200x200 µm lenslets of f = 2.0, 5.0 & 7.9 mm)

	reducer optics (from 200 to 63 µm spacing)
Wavefront sensor camera	Adaptive Optics Associates camera MIT/LL 64x64 pixel CCD, 21 µm pixels, 6-7 e-/pixel readout noise Frame rate selectable between 80 and 670 Hz
Deformable mirror	Xinetics 349 PZT/PMN actuators, on a square array with 7 mm spacing
Subapertures	56.25 cm square subapertures on the telescope primary mirror map directly to the inter-actuator spacing on the deformable mirror, to 200 µm spacing on the lenslet array, & to 2x2 pixels on the wavefront sensor
Acquisition Camera	Photometrics PXL camera, 1024x1024 pixels, 0.134 arcsec/pixels

4.9.2 NIRSPAO – NIRSPEC with AO

NIRSPEC is designed to move on rails between the direct f/15 focus on the Keck II right Nasmyth platform to a position at the output of the AO system on the left Nasmyth platform.

AO Optical Feed to NIRSPEC

NIRSPEC and its slit-viewing camera, SCAM, do not normally have the appropriate plate scale to take proper advantage of AO correction. SCAM has 0.18 arcsec pixels, whereas, we would really like to have 17 milli-arcsec (mas) pixels to Nyquist sample the diffraction-limited H-band images. Similarly, the minimum width NIRSPEC slit is 0.14 arcsec.

The AO system currently outputs an f/15 beam (same f/# and pupil location as the telescopes') to the NIRC2 location where the KCAM dewar and external fore optics are located. A set of three fold mirrors and a new set of fore optics, similar to those used for KCAM, have been implemented to feed the f/15 AO-corrected beam to NIRSPEC. These fore optics maintain the image and pupil locations while producing the needed factor of 10.6 in magnification. A pupil stop corresponding to the new reduced pupil diameter has already been installed in NIRSPEC.

In addition to the three telescope mirrors in the beam path to NIRSPEC at the direct f/15 focus, the AO system introduces 10 additional reflections and transmission through three optics (a dichroic and two achromats). The throughput through the AO optics to NIRSPEC was expected to be 60 to 65%, but in practice has been found to be significantly less, largely due to higher slit losses resulting from the plate scale change. The emissivity is increased by a corresponding amount.

Filters and Wavelength Coverage

Since the smaller AO pupil mask is mounted in one of the two NIRSPEC filter wheels, only the filters in the other wheel are available with AO. Seven of these filters are custom spectroscopic filters designed to cover the spectral range from 0.95 to 2.61 microns wavelength. The remaining four filters are K, K', CO and Brackett gamma. Thus, NIRSPEC behind AO can only be used in the wavelength range from 0.95 to 2.61 microns; NIRSPEC cannot be used at longer wavelengths behind the AO system.

Predicted Imaging Performance

The SCAM plate scale with the reimaging optics is 16.8 mas/pixel, giving a field of view of about 4 arcseconds. Sensitivities and background levels are given in the following table:

Band	Zeropoint	Background
J	22.97	15.2
H	23.55	13.6
K-prime	22.80	11.03
K	22.57	10.25

The zeropoint is the source magnitude that yields 1 DN/sec on the SCAM detector. The background level is in magnitudes/square-arcsecond.

For imaging programs, NIRC2 provides higher throughput, wider field of view, more filters, and broader wavelength coverage.

Predicted Spectroscopic Performance

The AO-produced image size is not well matched to the NIRSPEC slit width, resulting in higher slit losses than seen on NIRSPEC without AO. Despite the reduction in pupil size, the spectroscopic resolution is unchanged.

In NIRSPEC high-resolution mode the plate scale will be 13 mas/pixel. Five slit widths are available corresponding to 1, 2, 3, 4 and 5 pixels. Two slit lengths are available: 1.12 arcsec for all 5 slit widths or 2.24 arcsec for all but the 1-pixel slit width. The spectral resolution with the 3-pixel slit width is 27000.

In NIRSPEC low-resolution mode the plate scale will be 18.5 mas/pixel. Three slit widths are available corresponding to 2, 3 and 4 pixels. The slit length is 3.93 arcsec. The spectral resolution with the 2-pixel slit width is 2000. NIRC2 in its spectroscopic mode provides superior throughput at comparable resolutions of 2000-4000.

NIRC2 provides superior performance at imaging and low-resolution spectroscopy. Prospective observers should request the NIRSPEC+AO combination only for programs that require both high spatial and spectral resolution.

4.9.3 NIRC2

NIRC2 is the near-infrared instrument designed to take full advantage of the adaptive optics on the Keck II telescope. At its heart is an Aladdin-3 InSb 1024x1024 pixel detector, which is sensitive from 1 to 5 microns. NIRC2 provides three selectable cameras to cover the range in image sizes and provide critically sampled images over the entire bandwidth. Two filter wheels with 18 positions each provide a variety of filters, while a focal plane mechanism provides slits and occulting spots for grism spectroscopy or for coronography. A dedicated slide carries grisms for spectroscopy. Six selectable pupil masks are available to reduce background noise sources; four of these rotate in concert with the telescope pupil and one is specific to spectroscopy. NIRC2 is positioned behind the AO bench on the Left Nasmyth Platform of Keck II. NIRC2 data acquisition scripts perform the software interface needed for handshaking with the AO control loops. The instrument was delivered to Hawaii in the spring of 2001, seeing first light in the summer of 2001. NIRC2 has been fully commissioned only in its imaging mode.

Spectroscopic and coronographic modes have been successfully tested but are not yet fully characterized. For Semester 2003A, these modes are available for shared-risk science proposals.

Users should be aware that the Medium field camera exhibits detectable variations in focus across its field of view. Science programs that require high image quality should plan on using either the Narrow or Wide field cameras.

4.9.3.1 NIRC2 specifications

Location	Keck II Adaptive Optics Facility F/15 Left Nasmyth Focus Fixed gravity Vector
Detector	Aladdin-3 InSb 1024x1024 27 micron Pixels 4 e^- / DN Gain Read Noise 43 e^- per read 60 e^- per CDS read 15 e^- for MCDS with 16 reads 0.1 e^- / DN Dark Current 60,000 e^- (14,000 DN) Linear Range 0.95 – 5.5 micron Detective Bandwidth QE 80% at 1.7 microns (manufacturer data)

Filters

NAME	central (mu)	bandpass	transmission
J	1.25	1.17-1.33	85.2
H	1.63	1.48-1.78	84.8
Ks	2.15	1.99-2.30	91.8
Kp	2.12	1.95-2.30	92.6
K	2.20	2.03-2.36	90.4
BrGamma	2.187	2.172-2.202	65.0
Kcont	2.290	2.275-2.305	67.0
Hcont	1.585	1.575-1.595	64.0
FeII	1.650	1.638-1.663	70.0
NB2.108	2.108	N/A	N/A
Lp	3.78	3.43-4.13	88.8
Ms	4.67	4.55-4.79	83.8

Optics	Cameras Narrow: 0.01"/pix, 10" FOV Medium: 0.02"/pix, 20" FOV Wide: 0.04"/pix, 40" FOV All reflecting, gold-coated Clean room manufactured and assembled Maintained at 50 K
Spectroscopy	Not commissioned as of semester 2002A 2 Grisms: resolution of 5000 at J-K With 2-pixel slit Slits: 10, 20, 30, 40, 60, 80, 120, and 160 milliarcsec
Coronography	Not commissioned as of semester 2002A

	circular: 100, 150, 200, 300, 400, 600, 800, 1000, 1500, 2000 milliarcsec

Pupil Masks	6 pupil masks available
	Circumscribed, non-rotating
	    No central obscuration
	Inscribed circle, rotating
	    Circular + spider obscuration
	Large Hexagonal, rotating
	    Hex + spider obscuration
	Medium Hexagonal, rotating
	    Hex + spider obscuration
	Small Hexagonal, rotating
	    Hex + spider obscuration

Cryogenics	CCR-cooled 2 Cold Heads with speed control 50 K optics 30 K detector Vacuum pump auto - back up system Full vacuum enclosure 11 External motors, vacuum feed through
Electronics	Transputer-based, detector / data system "Smart Motor" mechanisms control "Lake shore" cryogenic control
Host computer	Sun Sparc Ultra 60, Solaris 5.7
User Interface	Command Line Interface (CLI) CSH scripts Configuration status display QuickLook image display, IDL AO tools and AO interface control
Performance	J-H Strehl ratio (with AO) 10-20% typical K Strehl ratio of 30-40% typical L-M Strehl ratio of 70-80% typical J zero point, 23.5 mag @ 0.2 Strehl J sky mag, 14.9 mag/(arcsec ^2)

Additional Information: http://www2.keck.hawaii.edu/realpublic/inst/nirc2.

4.9.4 Additional Information

Further documentation for AO is available on the WMKO web site at http://www2.keck.hawaii.edu/realpublic/inst/ao/ao.html.

Special attention should be paid to the results for the science objects that have already been observed with the AO system to understand the scientific capabilities of the AO system.

5 Contacts

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