

Performance of the W.M. Keck Observatory Natural Guide Star Adaptive Optic Facility: the first year at the telescope

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ABSTRACT

First light for the Keck II Natural Guide Star (NGS) Adaptive Optics (AO) facility was on the night of February 4, 1999. On the first attempt at closing the AO loops the image full-width-at-half-maximum (FWHM) went from 0.6 to 0.04 arcsec at H-band (1.65 μm wavelength), with a Strehl ratio of 25%. The AO system became an officially scheduled Keck science facility in August 1999; 30 science nights are scheduled in the first half of 2000. The primary purpose of this paper is to present results from this first year at the telescope.

Keywords: Keck, adaptive optics

1. INTRODUCTION

This paper is organized in the following sequence. We first provide a brief overview of the AO system and the associated science instruments. We then present some results from our science verification program and discuss how we currently observe with the AO system. In closing we discuss the near-term future for Keck AO. Additional technical details can be found in earlier SPIE proceedings¹ and in other papers at this conference.²⁻⁵ The first two refereed science papers using the Keck AO facility have been published^{6,7} and several others are in preparation.

2. SYSTEM OVERVIEW

The NGS AO facility is located on the left Nasmyth platform of the Keck II telescope at the f/15 focus. The entire facility is enclosed in the thermally insulated enclosure shown in Figure 1. The enclosure is divided into two rooms, one for the AO bench and science instruments and the other for the electronics racks. The electronics room contains an air-to-glycol heat exchanger to remove heat from the telescope.

Figure 2 is a schematic of the optics bench. The optics bench components are listed in Tables 1 to 4 along with their functions and some details. Figures 3 and 4 are photographs of the science path and wavefront sensor path components, respectively. The same identification numbers are used in the figures and tables. Figure 4 also shows a wavefront sensor camera image illustrating the Shack-Hartmann quad cells illuminated by the irregularly shaped Keck pupil.

The NGS AO facility consists of multiple subsystems that communicate over an ethernet connection using EPICS (Experimental Physics and Industrial Control System). These subsystems include the optics bench subsystem, wavefront controller subsystem, supervisory controller subsystem and user interface. With the exception of the user interface and acquisition camera servers, which run on Sun/Unix machines, all of the subsystem computers are mounted in two VME crates. There are two electronics racks for the optics bench subsystem, one for the wavefront controller and one for the deformable mirror.

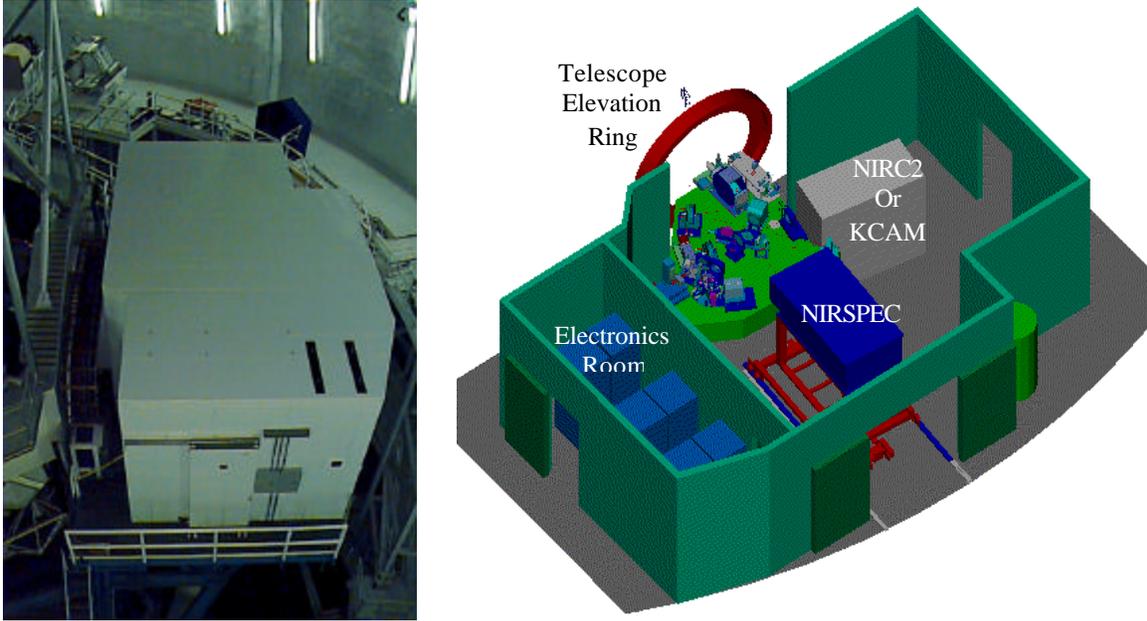


Figure 1. Left: The AO enclosure on the left Nasmyth platform of the Keck II telescope. Right: A schematic view of the AO enclosure with its roof removed.

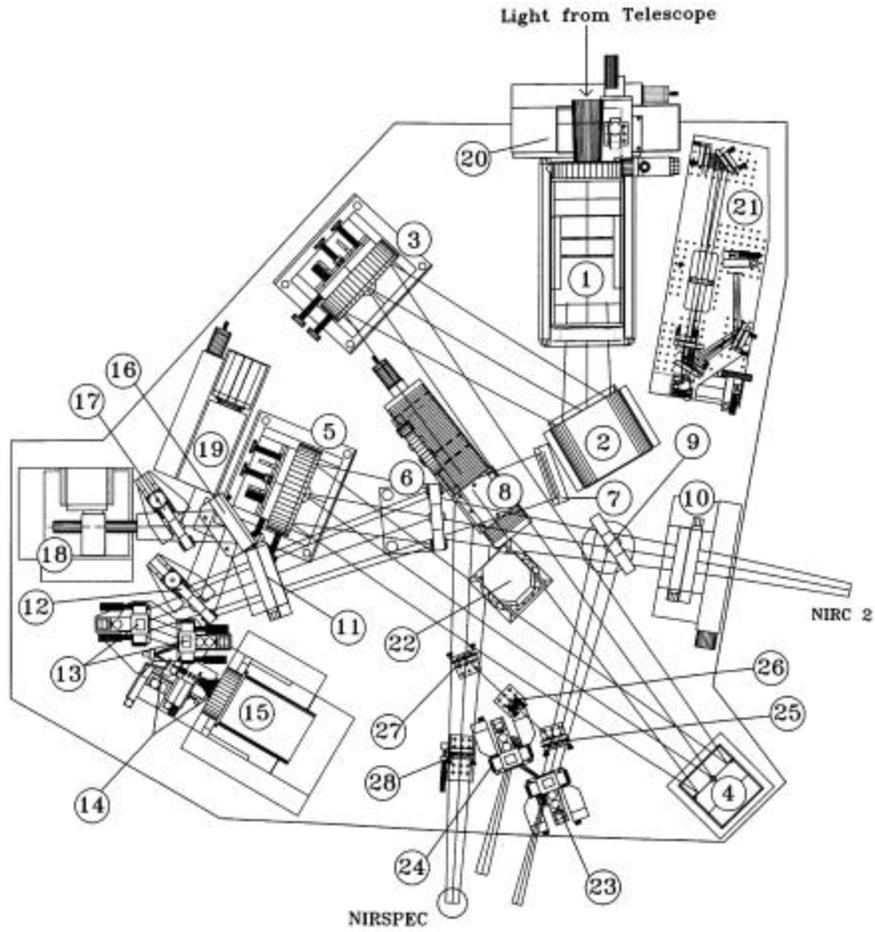


Figure 2. Aerial view of the AO optics bench.

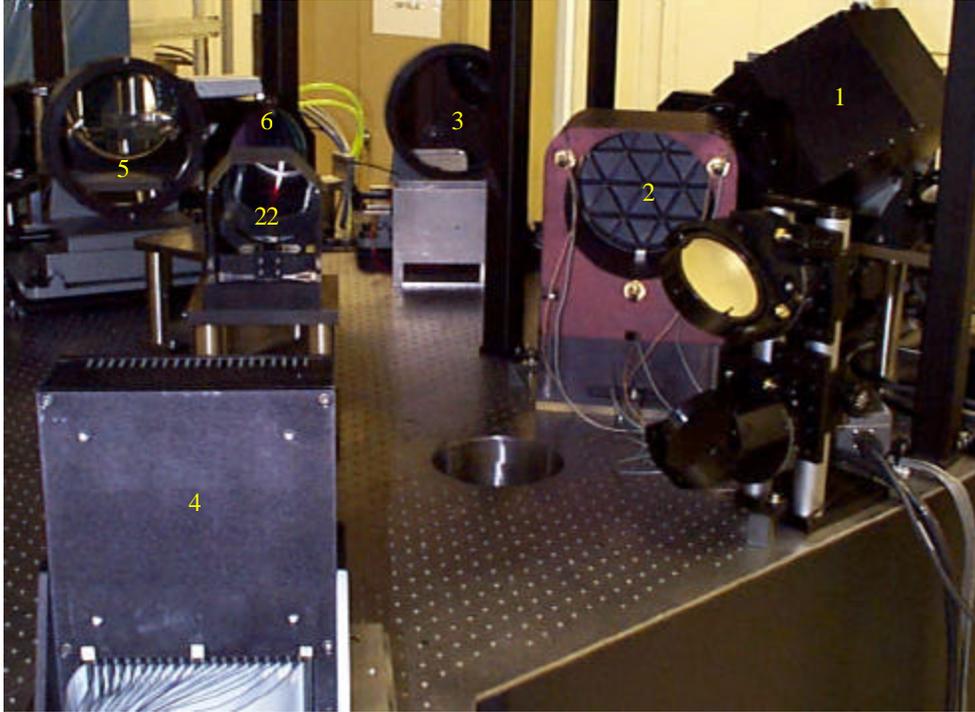


Figure 3. Science path components on the optics bench.

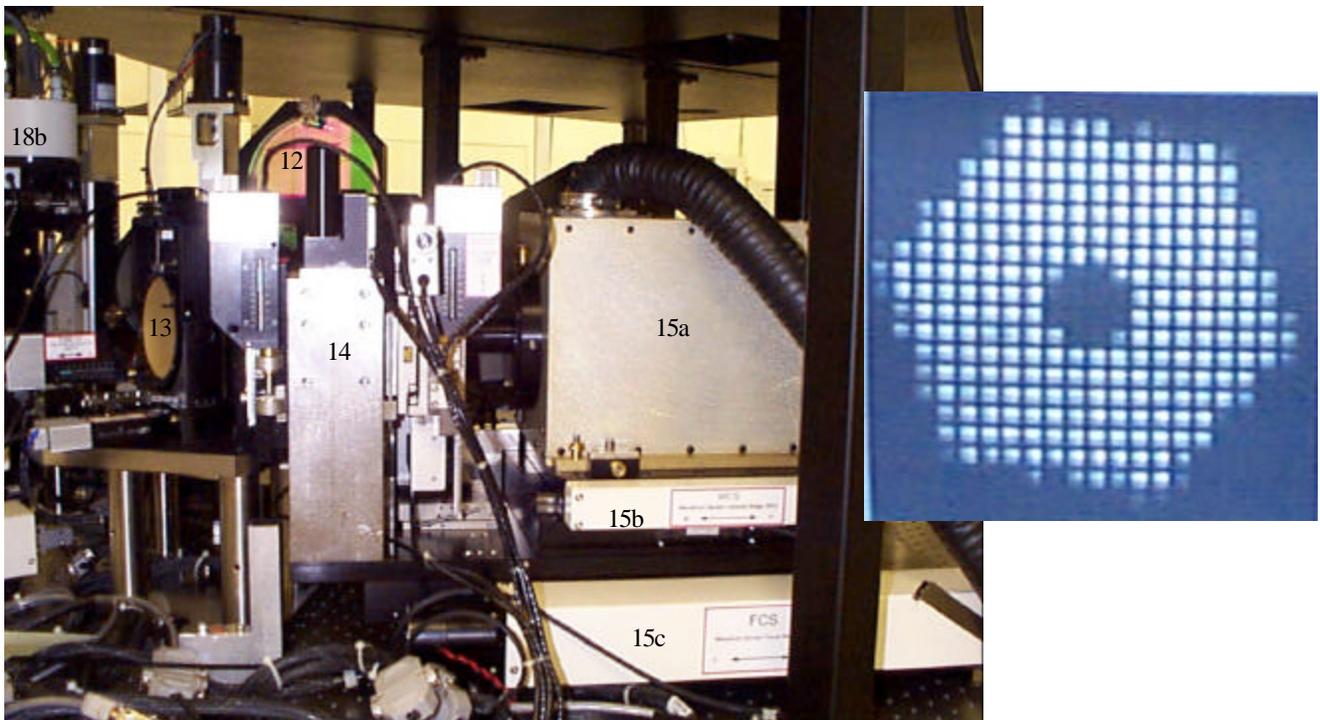


Figure 4. Left: Wavefront sensor components. Right: Wavefront sensor camera video display showing the subapertures illuminated by the irregularly shaped Keck primary mirror.

Table 1: Science Path Components

Component	Function	Details
1. Image rotator	Field rotation correction	Custom K-mirror
2. Tip/tilt mirror	Fast tip/tilt correction	200 mm SiC mirror in a LLNL custom mount
3. Off-axis parabola(OAP)	Collimate & reimaged primary mirror onto DM	F=1.77m, d=0.25m SORL OAP & Unertl mount
4. Deformable Mirror (DM)	High order correction	Xinetics 349-actuator, 7 mm actuator spacing corresponding to 56 cm on the primary mirror
5. Off-axis parabola	Converge the light with the same focal ratio & pupil location as the telescope's	Identical to 1 st OAP
6. Dichroic beamsplitter	Transmit the IR light & reflect the visible light	Barr coating on fused silica, transmits 1-2.7 μ m (plan to install 1-5 μ m Barr coating on ZnS)
7. Cold source	Reduce thermal background seen in reflection off back of dichroic	No design.
8,9. Science fold mirrors	Insert to fold beam to instruments as needed.	Mirror 8 is motorized, 9 is manual & kinematic
10. IR atmospheric dispersion corrector	Correct for dispersion across J to K science bands	All parts in-house, but not implemented yet
23,24. Interferometer field selector mirrors	On-axis star passes through 23. The pair of mirrors is steered to select an off-axis star.	Modified NRC 100mm diameter gimbal mounts with 850f actuators & Renishaw encoders
25,27. NIRSPEC folds	Relay beam from mirror 9 to NIRSPEC axis	50 mm mirrors
26,28. NIRSPEC optics	Provide a magnification of 10.6 without moving the NIRSPEC image or pupil planes	2 Melles Griot achromatic doublets

Table 2: Wavefront Sensor Path Components

Component	Function	Details
11. Visible atmospheric dispersion corrector	Correct for dispersion across sensing bands	Only design exists
12. Sodium notch filter / beamsplitter	Reflect either 4% of the light or all but the sodium wavelength light	2 fused silica substrates. Filter - Barr narrow band transmission coating
13. Field selector mirrors	Position a star on wavefront sensor axis while maintaining DM-to-lenslet registration	Same as 23, ~60x60 arcsec field
14a. Field stop	Prevent light contaminating adjacent quadrants	4 field stops & a single mode fiber on a stage
14b. Pupil relay optics	Image DM onto lenslet array. Singlet moves to maintain pupil size versus LGS distance	Achromatic doublet & motorized singlet. Lenslet corners registered with DM actuators
14c. Lenslet array	Divide the pupil into a number of subapertures & produce an image for each subaperture	Shack-Hartmann sensor with 3 different focal length AOA lenslets on 200 μ m spacing
14d. Filter stage	ND & color filters for bright stars	6 ND filters on a stage
14e. Reducer optics	Relay lenslet focal plane onto CCD while reducing the image spacing from 200 to 63 μ m	A singlet & 2 custom achromatic doublets mounted to the front of the camera
15a. Camera	Produce the signal for quad cell centroiding each of the 240 subapertures	AOA camera, MIT/LL 64x64 pixel CCD, 6-7e- read-noise, 0.8ms readout.
15b. Camera stage	Focus camera for each lenslet	Translation stage
15c. WFS Focus stage	Focus versus field position & LGS distance for all post-field stop components	The translation stage moves by ~250 mm between a NGS & a LGS at zenith.

Table 3: Auxiliary Sensing Path Components

Component	Function	Details
16. Fold mirror	Fold the light	
17. Fold / beamsplitter	Reflect 10% or all light to acquisition camera	Fused silica splitter with broad reflection coating
18a. Tip/tilt (TT) sensor	Tip/tilt sensing on a NGS in LGS mode	4 fiber fed APDs
18b. Low bandwidth wavefront (LBWF) sensor	Wavefront sensor calibration in LGS mode	Shack-Hartmann with Photometrics CCD camera
18c. XYZ-stage	Position a star on TT & LBWF sensors	3-axis translation stage with 2 arcmin field
19a. Camera optics	Provide a 2 arcmin field with 0.134"/pixel	Field lens plus Nikor re-imaging lens
19b. Camera	Provide images for acquisition	1024x1024 pixel Photometrics CCD camera

Table 4: Alignment, Calibration and Diagnostics Components

Component	Function	Details
20,21. White light source	Provide a source for alignment, calibration & diagnostic purposes	Rack mounted lamp + ND & color filter wheels. Multi & single mode fibers to items 20 & 21
20. ACD stage	Select between starlight, a fiber, the pupil simulator, or (future) calibration lamps	1-axis stage for selection. 2 additional axes to position fiber in telescope focal plane
21. Pupil simulator	Used to simulate telescope pupil & f/#	Fiber source collimated through a pupil mask
22. DM Interferometer (located under bench)	Setting the DM shape & qualitative monitoring of the DM shape	WYKO phase shifting interferometer located under bench; fed by mirror 22

3. SCIENCE INSTRUMENTS

Science instruments can be positioned at two locations next to the AO bench as shown in Figure 1. The properties of the existing and planned science instruments are summarized in Table 5. The only science instrument available during the first year of engineering and observing was K(eck)CAM. KCAM was placed on a focus stage on a 2x4 foot optical bench at the AO output.

A significant advance in the scientific capability was made in February 2000 when the Near InfraRed echelle SPECTrometer (NIRSPEC) was moved behind the AO system. NIRSPEC had been commissioned in 1999, at the right Nasmyth direct f/15 focus of the telescope. In order to take advantage of the angular resolution of the AO system a pair of achromatic lenses, and 3 fold mirrors, were implemented on the AO bench; the re-imaging optics maintain the image and pupil plane locations while providing a magnification of 10.6. NIRSPEC (after installation of a smaller pupil plane mask) was moved to the left Nasmyth platform at the output of these optics for a single very successful night of engineering on February 14, 2000.

A near-infrared camera, NIRC2, should be delivered in late 2000. The first interferometer fringes with the Keck telescopes, which will require an AO system on the Keck I telescope as well, are expected to occur in early 2001.

We have tried one quick experiment with a high-resolution plate scale on our AO acquisition camera, ACAM. That experiment clearly demonstrated that visible science imaging should be pursued since we achieved a Strehl of about 6% and a FWHM of 0.022 arcsec in a 10 ms exposure at 850 nm. We hope to implement an optics stage in front of this camera that will allow us to switch between the two plate scales needed for science and acquisition.

Table 5. Science Instruments

Name	Date of 1 st AO Light	Detector (# pixels & type)	Plate Scale (arcsec/pixel)	Spectral Resolution	Notes
KCAM (UCLA)	Feb., 1999	256x256 NICMOS3 (HgCdTe)	0.017	N/a	Focus stage; 12-position external filter wheel; J,H,K' internal filters
NIRSPEC ⁸ (UCLA)	Feb., 2000 for spectra	1024x1024 InSb	0.0185 low R 0.013 high R	Low=2000 High=27000	10.6 magnification provided by 2 achromats on AO bench
	Apr., 2000 for imaging	256x256 PICNIC for slit viewing	0.017	N/a	
NIRC2 (Caltech)	Dec., 2000	1024x1024 InSb	0.01, 0.02 & 0.04	~5000 with grisms	Designed for AO system
Interferometer ⁹ (JPL, CARA)	Jan., 2001	Hawaii			AO on both Kecks
AO Acquisition Camera	Apr., 1999	1024x1024 CCD Photometrics PXL	0.0075 in high resolution mode	N/a	Only tried once, normal=0.134"/pix

4. SCIENCE VERIFICATION PROGRAM

A major part of our commissioning effort was to perform a science verification program, in collaboration with members of our AO Science Team. The purpose was to determine and demonstrate the effectiveness of the AO system on various types of science targets and to ensure that the required techniques and tools were in place. A research note⁶ has been published describing the results of this program on three types of science targets: solar system, galactic and extragalactic.

All of the imaging observations described below were performed with our engineering science camera, KCAM. The spectroscopy result is from the first engineering night with NIRSPEC behind the AO system.

Solar System:

The system performs extremely well on solar system objects where the object itself is used as the guide star. We have observed planets (Neptune, Uranus, Pluto-Charon), satellites of planets (Titan, Io) and asteroids (Vesta, Eugenia). The performance on Neptune was excellent, 0.044 arcsec FWHM, even though Neptune is 2.3 arcsec in diameter. The maximum wavefront sensor field of view is 4.8 arcsec, so even Uranus with a 4-arcsec diameter could be used to close the loop although the correction was poorer. (We also closed the loop on a couple of Uranus' satellites while imaging Uranus and the correction might actually be better in this case.) We observed Vesta continuously over one rotation period (5.5 hours) in several mineral bands and produced a movie of it rotating.

The image of Io shown in Figure 5 is an excellent demonstration of the capabilities of AO since images from the Galileo spacecraft can be used as a reference. The Keck AO image, taken in November 1999, is a color composite (blue, green, red) of J (1.25 μm), H (1.65 μm) and K' (2.1 μm) images so that hot features show up red. Every feature seen in the AO infrared image has a counterpart in the Galileo visible image. In addition, a volcanic eruption on the limb of Io can be seen in the Keck image (some warm lava flows are also potentially seen as red in a color version of this image).

Galactic:

The galactic center (GC) is a challenging AO science target from our latitude since it is low in the sky (elevation $\sim 40^\circ$) and the closest star (14th visual magnitude) bright enough to close the AO loops is located 31 arcsec from the GC. Similar resolutions have previously been obtained with speckle observations at Keck. However, because of the higher AO Strehl, twice as many stars can be seen in a 90-sec AO integration than in the previous speckle observations.

The AO system has been particularly effective in identifying previously unknown binary stars. Within the first hour of the first official AO science night in August 1999, the very cool dwarf Gliese 569B was found to consist of two stars separated by 0.10 arcsec.⁷ Figure 6 is a H-band, 30-sec integration, image of this binary.

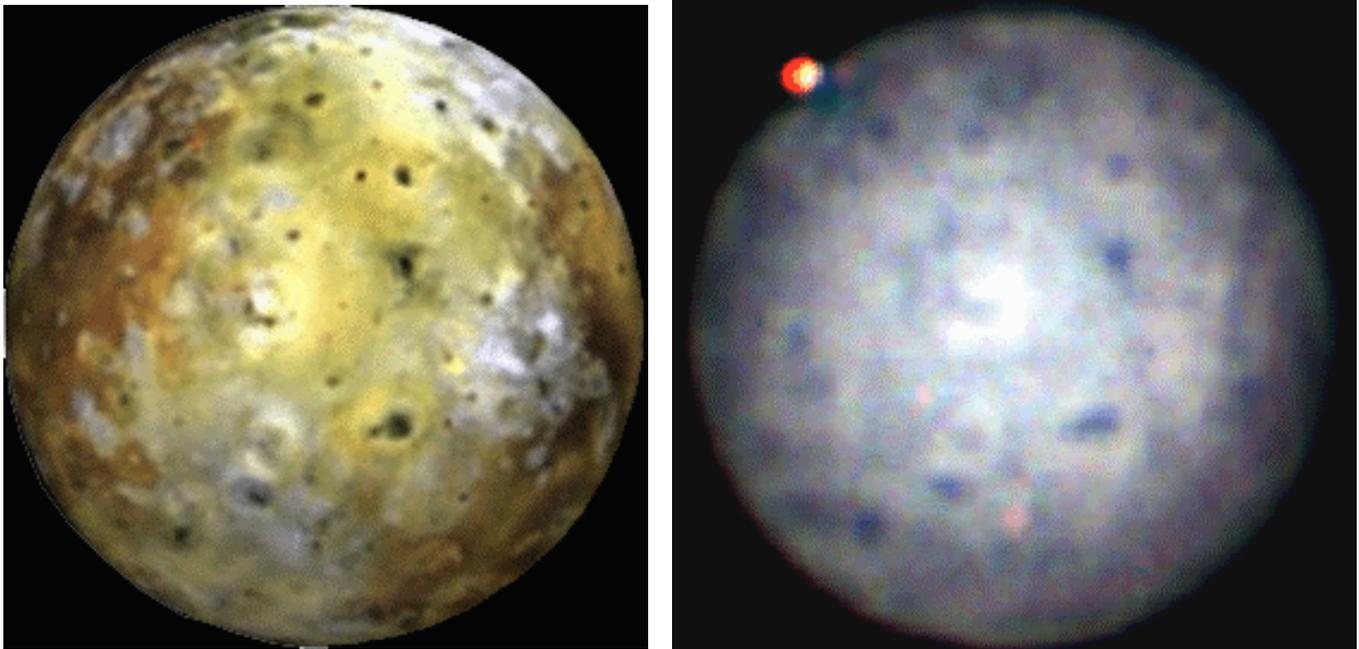


Figure 5. Left: Galileo spacecraft visible image of Io (NASA). Right: Keck AO J,H,K' composite image of Io with a volcanic eruption on the limb.

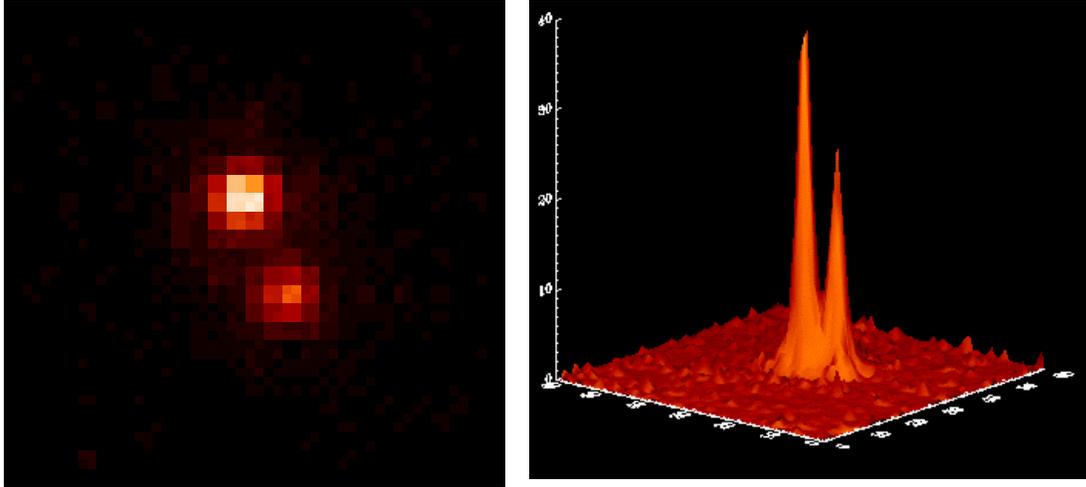


Figure 6. Left: Keck AO H-band image of GL569B. The stars have a 0.10 arcsec separation. Right: Intensity plot.

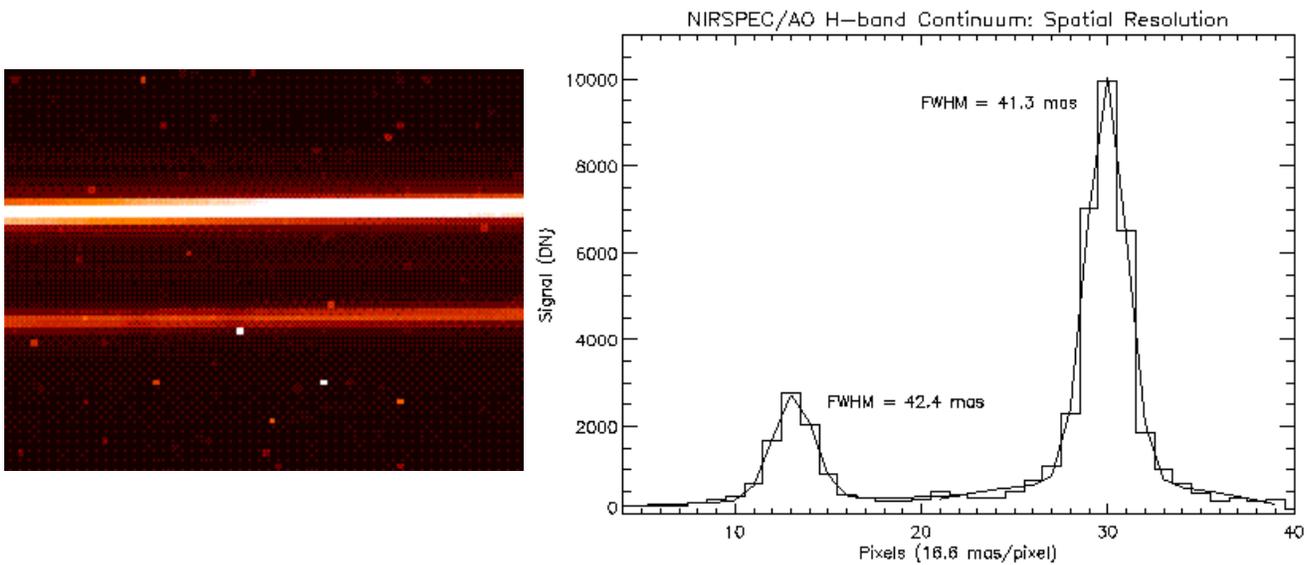


Figure 7. Left: Portion of the NIRSPEC/AO R=14600 H-band continuum spectra (no sky subtraction) for two stars (HR3210) separated by 0.28 arcsec along the 0.068 arcsec wide slit. Right: Vertical cut through the two spectra showing the stars with a Gaussian fit superposed to reveal an angular resolution of FWHM = 0.042 arcsec.

Extragalactic:

We have observed a few Seyfert galaxies where the core of the galaxy was used to close the AO loops. Two of these galaxies are discussed elsewhere in this conference.¹⁰ Clearly there is some real high resolution information in these images, but there is also a concern that there could be some AO-introduced artifacts in these images. These objects are extended and fuzzy at the visible wavefront sensor wavelength and, therefore, there is no clean core on which to lock the AO loops.

Another approach to observing galaxies is to use bright nearby stars to close the AO loops. This approach has been successfully used to observe a number of faint field galaxies.¹⁰ The general approach is to lock the loops on the bright star and then perform a blind offset to the galaxy, since 5- to 15-minute integrations are required before the galaxy can be seen. In general, a star at a similar distance from the NGS is also observed for deconvolution purposes.

Spectroscopy:

Spectra of a number of objects were obtained with NIRSPEC, on the night of February 14, 2000. The spectra of a binary with approximately 0.070-arcsec separation were clearly spatially separated. The most interesting object of the evening was

a Seyfert galaxy, NGC4151, for which we obtained R=14700 Hband continua spectra with a signal-to-noise ratio per pixel of 22 in a 10-minute exposure through the 0.068 arcsec slit. A raw H-band spectra for two stars separated by 0.28 arcsec is shown in Figure 7.

5. PERFORMANCE CHARACTERIZATION

So far, the emphasis has been on improving the AO system and demonstrating its scientific capabilities. A careful characterization process has, therefore, not yet taken place. In particular, there are still some problems, most notably telescope vibrations, that we would like to reduce prior to embarking on a significant characterization process. The following comments are, therefore, more qualitative in general than quantitative.

Although the initial results are quite impressive, the AO system has not yet met its design requirements.^{11,12} The design error budget predicted a H-band Strehl ratio of 68% for an infinitely bright star under median seeing conditions. The best H-band Strehl ratios we have seen are 45 to 50%. These best images, with a FWHM of 36 to 40 milli-arcsec, are also broader than the diffraction-limit of 34 milli-arcsec at H.

There has been a characterization of the wavefront controller tip/tilt and deformable mirror loop bandwidth as reported elsewhere in this conference.⁵ The maximum frame rate currently allowed by the wavefront controller computation and communication speed is 670 Hz, and the minimum is 60 Hz.

The galactic center observations have demonstrated AO performance under three relatively difficult conditions: a faint guide star (V=14), a large NGS to science object separation (31 arcsec), and a small elevation angle (40°). We performed galactic center observations on four different nights, and the results were quite variable as shown in Figure 8. The FWHM varied from as good as 0.050 arcsec to as poor as 0.25 arcsec in the K'-band, while the Strehl ratio correspondingly varied from 20% to a few percent.

Figure 9 provides some data on the size of the isoplanatic angle. To obtain this data we alternated between measurements of the off-axis star and the NGS, and then normalized the off-axis measurements by dividing by the Strehl and FWHM measurements for the on-axis NGS. The telescope elevation for these observations is given in the legend. We are modifying our field steering mirrors to provide a 2-arcmin diameter field to take advantage of the good off-axis correction.

The AO loops are able to close, and get reasonable performance, as long as there are about 20 counts per subaperture. The wavelength band for the wavefront sensor is quite broad, 0.5 to 1.0 μm, so the NGS color is important. In general, however, this corresponds to about a 14th visual magnitude star. Figure 10 shows some Strehl and FWHM data versus subaperture counts. The figure legend gives the telescope elevation and the wavefront sensor bandwidth for these observations.

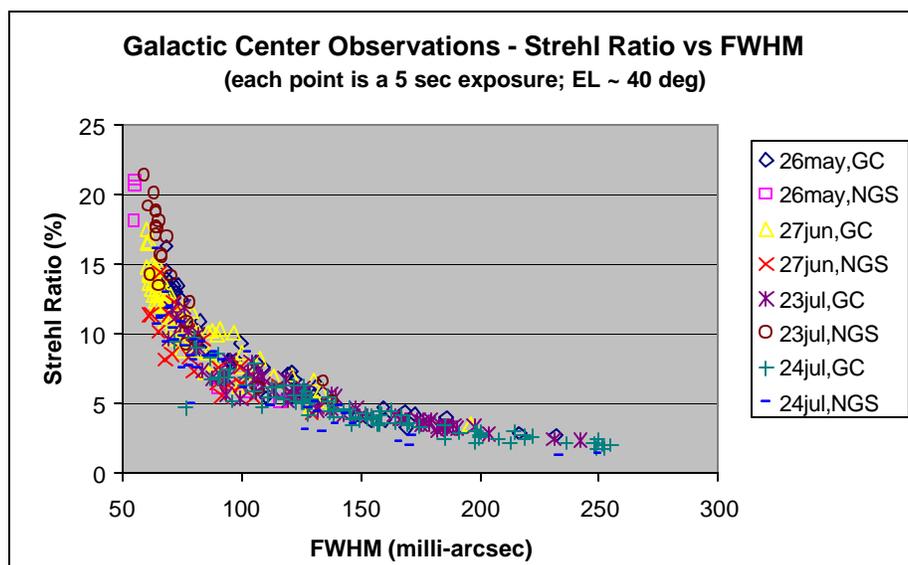


Figure 8. Measured AO performance on the Galactic Center (GC) and associated NGS.

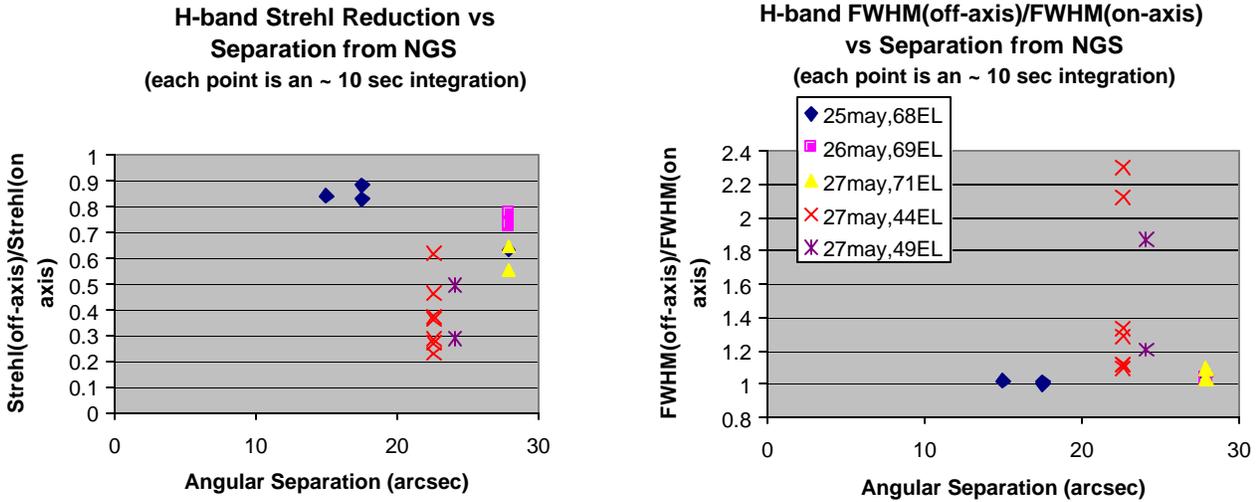


Figure 9. Measured AO performance versus separation from the NGS. Left: Strehl ratio. Right: FWHM. The plots have been normalized by the performance on the NGS. The legend gives the date and elevation of the observation.

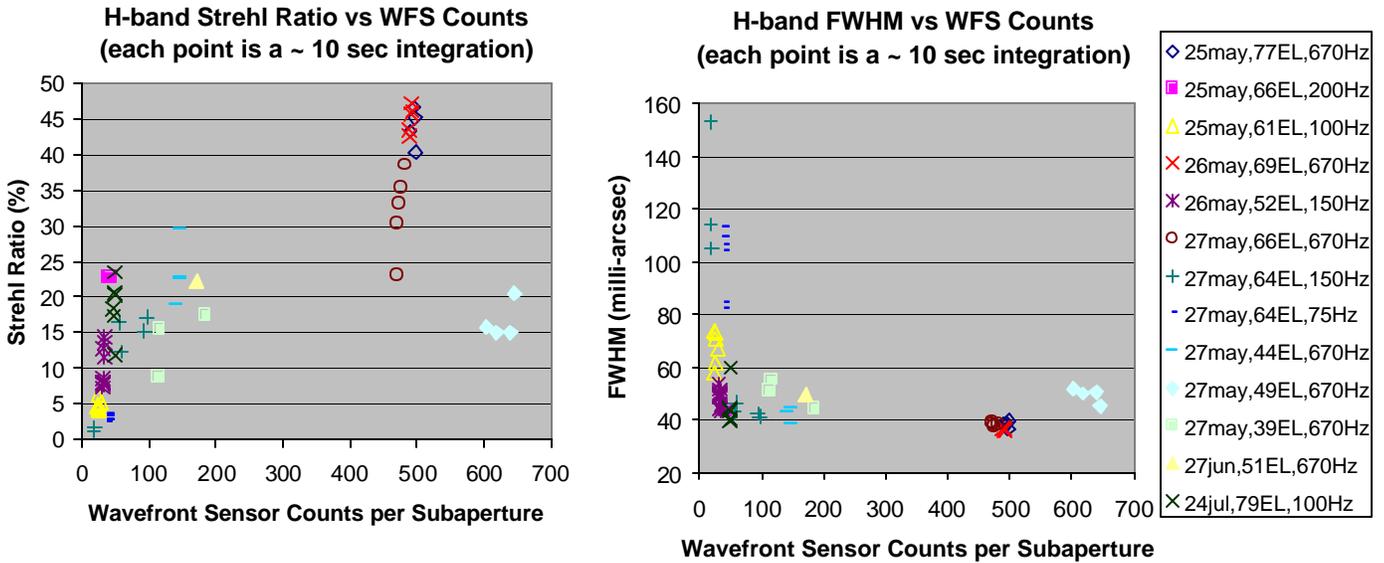


Figure 10. Measured AO performance versus the average number of counts per wavefront sensor subaperture. The legend, sorted by date of observation, also provides the elevation and wavefront sensor frame rate for the observation.

Most of the Keck AO observations to date have been at wavelengths between 1 and 2.5 μm . A single experiment was performed at a significantly shorter wavelength using our acquisition camera with a modified plate scale of 0.0075 arcsec/pixel. A 10-ms exposure of a 4.5 magnitude star using a 10 nm wide, 850 nm wavelength filter had a FWHM of 0.022 arcsec and a Strehl ratio of 6%. This is believed to be the highest resolution in the visible/near IR regime ever obtained via direct imaging.

6. OBSERVING WITH THE AO FACILITY

Ever since our fourth engineering night, all AO observing has been performed remotely from the Keck offices in Waimea. This is considerably more comfortable than working at the 4000 m summit and speaks highly of the system reliability that we have experienced. An AO operator is still required, because of the remaining complexities of the system, although we are moving toward a model where AO operation can be performed by a combination of the astronomer and observing assistant (i.e., telescope operator).

Typically, the AO operator spends about 2 hours in the afternoon setting up and calibrating the system remotely. Some of the more interesting calibrations are described elsewhere in these proceedings.² The procedures (a step-by-step set of instructions for performing AO operations) and the user interface tools are all launched from the Web-based User Interface (WUI). These procedures are written in html and the tools that are required to perform the procedure are launched by a mouse click on the highlighted item in the procedure. Figure 11 shows the top level WUI screen, a procedure and a screen launched from the procedure. The top-level user interface screens are created from a set of standard Java applets. A set of IDL tools is used for calibrating the system. Additional engineering level tools can be launched as needed, including a Tcl/Tk tool for initializing the optics bench motion control devices and the EPICS display screens for each device. The non-Java engineering tools are presented to the user by means of Common Gateway Interface like “servlets,” executing as part of the Web server. Since this is a web-based UI, a good deal of additional AO documentation is available, including the public Keck instrument page at <http://www2.keck.hawaii.edu:3636/realpublic/inst/>.

The typical observing sequence on a new target is as follows. The observing assistant slews the telescope and AO image rotator as requested, and acquires the target on the AO acquisition camera. The AO operator then closes the tip/tilt loop to center the object. The deformable mirror loop can be closed at this point, however, the optimal correction requires waiting for a new control matrix to be loaded for the current pupil orientation. New control matrices are automatically calculated and loaded on-the-fly as a function of which wavefront sensor sub-apertures are illuminated. The pupil rotation compensation software package, necessitated by the irregularly shaped and rotating Keck pupil, is described elsewhere in these proceedings.³ As appropriate, the AO operator also adjusts the frame rate (including taking a new wavefront sensor sky), tip/tilt loop gain and deformable mirror loop gain. Ultimately, we hope to have an automated approach to gain adjustment.⁴

There are a number of graphical displays and alarms to monitor the performance of the AO system. The most useful monitoring tool has turned out to be a video display of the interferometer fringes from the interferometer looking at the deformable mirror. This display gives you a feel for the spatial and temporal characteristics of the turbulence, gives you feedback on adjusting parameters, immediately shows waffle if it is present, and lets you see when the loops are closed. There is also a video display of the wavefront sensor output, although the auto-scaled user interface display is much more useful on faint sources.

The astronomer operates the science camera and can use a hand-paddle on his computer screen, or scripts, to move the image on the science camera. New images are automatically displayed and processing can be performed with a Quick Look and Data Reduction Pipeline tool.¹³ A hand-paddle request automatically opens the AO loops (tip/tilt and deformable mirror, if they are closed), moves the telescope to the desired location, moves the field steering mirrors to reacquire the NGS, and re-closes the loops. Currently, with KCAM, exposures cannot be automated so the astronomer must watch for the loops to close before pushing a computer key to start another exposure. With future science instruments, such as NIRSPEC, the next exposure and even a series of exposures and telescope moves could be obtained without any user intervention via the use of scripts.

The level of automation noted in the previous paragraph is provided by the Supervisory Control (SC) subsystem. The SC communicates with each of the AO subsystems and the telescope to perform these coordination tasks. Two other examples are tip/tilt and focus offloading. These offloading loops are left on all night and offloads, from the tip/tilt mirror to the telescope pointing, and from the deformable mirror (focus) to the telescope secondary mirror piston, are automatically performed.

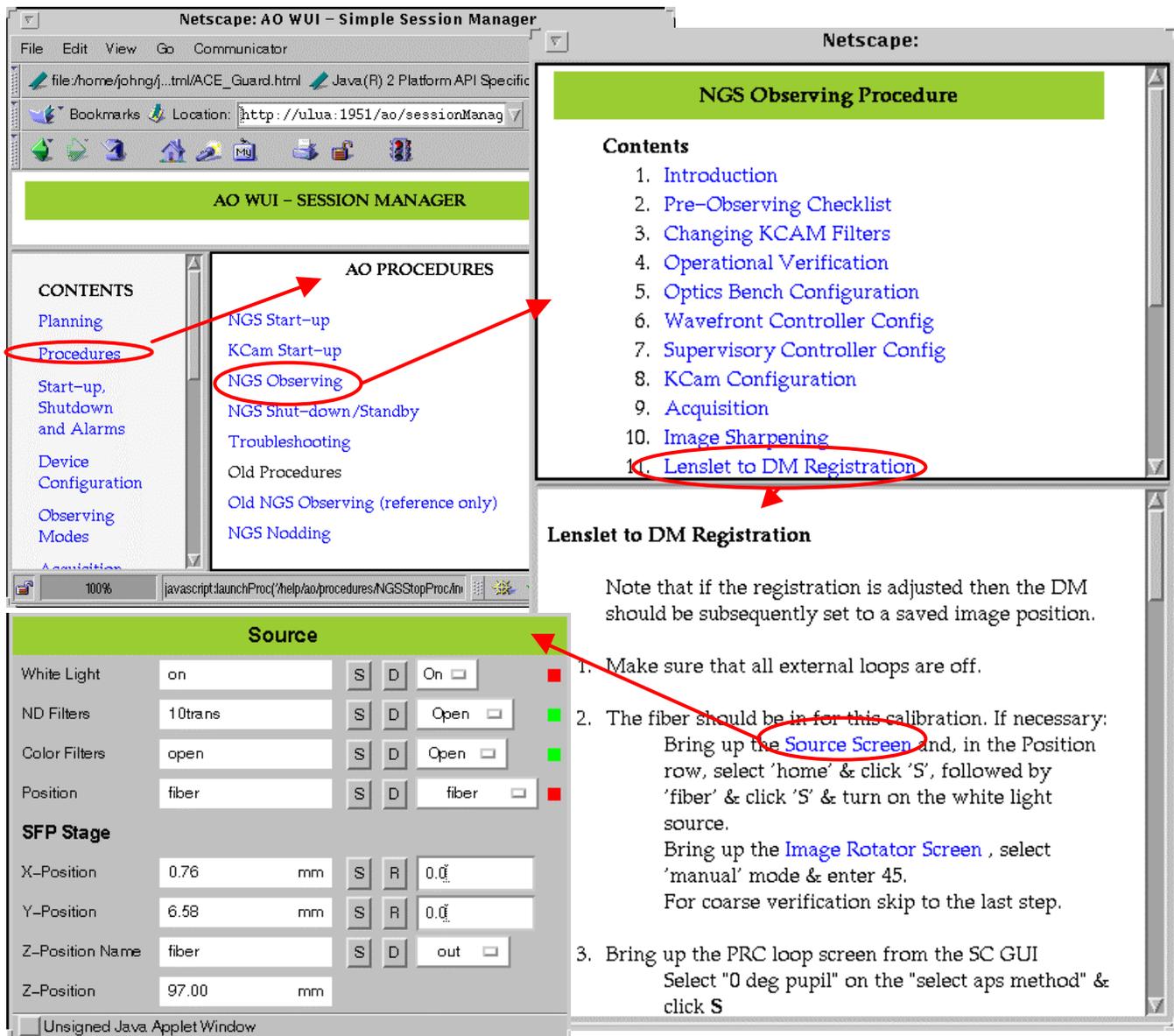


Figure 11. Parts of the Web-based user (WUI) interface. Clicking on an item in the left “Contents” column of the WUI (top-left) brings up a list of items in the right column. In the illustrated case, clicking on “NGS Observing” brings up the NGS Observing Procedures page (right). The top half of the page is the Contents and the bottom half of the page is the selected procedure. The tools needed to perform the procedure can be popped up via a mouse click as illustrated by the Java screen (bottom left).

7. ONGOING EFFORTS

We are proceeding along several parallel paths at the moment. The two main projects are the completion of the LLNL-supplied sodium wavelength laser system in a lab at Keck headquarters, and the build-up of the Keck I telescope NGS AO facility for the Keck Interferometer. Other ongoing projects include performance improvements to and characterization of the Keck II AO system, operational improvements to the Keck II AO system, characterization and amelioration of telescope vibrations, and integration with future science instruments (NIRSPEC at the moment). The next one to two years should see significant improvements in the scientific capability of the Keck AO facilities.

8. ACKNOWLEDGEMENTS

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