Keck Adaptive Optics Note 263

Adaptive Optics Developments at Keck Observatory

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ABSTRACT

The purpose of this paper is to report on new adaptive optics (AO) developments at the W. M. Keck Observatory since the 2002 SPIE meeting.[1] These developments include continued improvements to the natural guide star (NGS) facilities, first light for our laser guide star (LGS) system and the commencement of several new Keck AO initiatives.

Keywords: Adaptive optics, Keck, Laser Guide Star

1. INTRODUCTION

In 2002, a Keck AO Working Group (AOWG) was formed to develop short- and long-term goals for Keck AO. Over the past two years the group has emphasized continued optimization of the NGS AO systems and the integration of the Keck II LGS AO system as our top priorities. The result has been significant NGS performance and operational improvements, and successful on-sky LGS AO demonstrations, as discussed in sections 2 and 3, respectively, below. In order to keep Keck AO competitive in the mid-term, the AOWG has recommended an upgrade of the existing AO wavefront controller systems (section 4) and the implementation of a laser on the Keck I telescope (section 5). Finally, the AOWG's highest priority long-term goal is to develop a next-generation high Strehl system with a stable and well-characterized PSF that extends into the visible (section 6). The AOWG has also been supportive of the concept of implementing the Extreme AO Planet Imager (XAOPI), being developed by the Center for Adaptive Optics, behind one of the Keck AO systems.

Table 1 provides a chronological list of the major AO milestones to date at Keck Observatory.

Table 1: Major Keck AO milestones.

Date	Telescope	Milestone
Feb-99	K2	AO 1st light with KCAM
Aug-99	K2	AO/KCAM available for science
Feb-00	K2	NIRSPEC 1st light with AO
Aug-00	K2	AO/NIRSPEC available for science
Dec-00	K1	AO 1st light with KCAM
Mar-01	K1&2	Interferometer 1st light with both AO systems
Aug-01	K2	NIRC2 1st light with AO
Sep-01	K2	AO/NIRC2 available for science
Dec-01	K2	1st laser projection
Jul-03	K1&2	Interferometer 1st published science
Sep-03	K2	LGS AO 1st light with NIRC2
Jun-04	K2	LGS 1st engineering science demonstration

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2. NATURAL GUIDE STAR OPERATIONS AND PERFORMANCE

A total of 47 refereed science papers have been accepted for publication using Keck NGS AO results (27 since the 2002 SPIE meeting). Three papers were published in 2000, 5 in 2001, 17 in 2002, 14 in 2003, and 8 so far in 2004. The mix of these papers is 13 planetary, 26 galactic and 7 extra-galactic. The above information is displayed graphically in Fig. 1. A bibliography of refereed AO science papers, from Keck and other observatories, is maintained at http://www2.keck.hawaii.edu/optics/ao/biblio/.

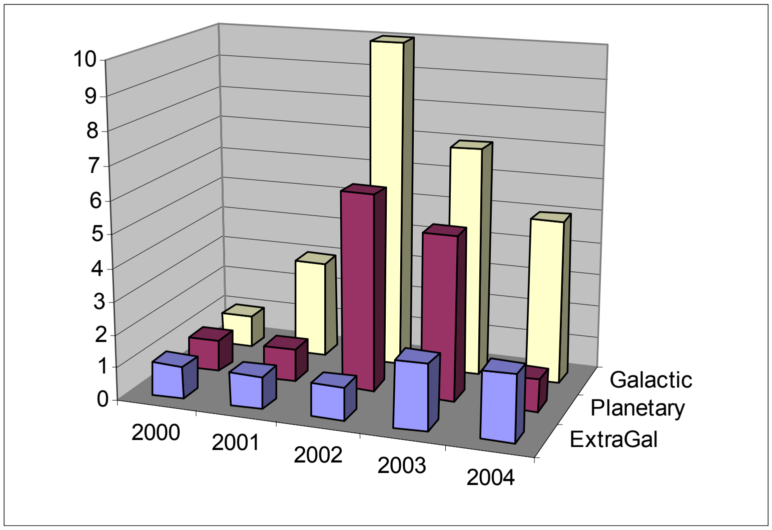

Fig. 1. Histogram of Keck AO refereed science papers by type and year.

The current AO science instruments include NIRC2 and NIRSPEC on Keck II, and the Interferometer[2] that combines Keck I and II. OSIRIS, an OH-suppression IR integral field spectrograph, will begin commissioning with the Keck II AO system in late 2004.

Altogether there has been a total of 260 NGS AO science nights through the end of January, 2004. This has included 133 nights with NIRC2, 96 with NIRSPEC, 30 with KCAM (our initial engineering science camera) and 5 with the interferometer. Using the 47 papers noted above this works out to a publication rate of roughly 5 nights per paper, a statistic that compares well with other instruments at the Observatory.

Current AO usage is reflected in the following numbers for the period from February 2004 through January 2005. This period contains a total of 115 scheduled AO science and engineering nights, representing a third of the Keck II observing time. The usage includes 48.5 NIRC2, 7 NIRSPEC, 26.5 Interferometer, 24.5 LGS and 8.5 OSIRIS nights.

A long list of operational improvements has been made to the Keck I and II NGS AO systems since the 2002 SPIE meeting, including: conversion of the AO enclosures into clean rooms, placing the AO electronics on UPS, upgrades of the AO host computers, a port of the wavefront controller command processor from Solaris/SPARC to EPICS/PowerPC, implementation of opto-mechanical configuration management, implementation of a new operator's user interface, improvements to the on-line Web-based AO system checkout and troubleshooting documentation, recoating and realignment of the Keck I and II image rotators, implementation of higher resolution and larger range field steering mirrors, installation of new servo amplifiers without turn-on transients, and the implementation of chopping with the AO tip/tilt mirror to support the nuller mode of the Keck Interferometer.

The characterization and optimization of NGS AO performance has been a high priority since the 2002 SPIE meeting, and the results have been excellent.[3,4] The characterization effort has included studies of wavefront sensor spot size, optimal focusing of the wavefront sensor camera, system interaction matrices, tip/tilt residuals, control loop parameters, centroid origins and how they are affected by SNR, centroid gains and how they are affected by spot size, subaperture selection, reconstruction matrix, CCD noise, flat fielding, etc. Performance improvements have been demonstrated with the implementation of optimized calibration routines, a better system matrix and tip/tilt and deformable mirror gains, smarter reconstruction matrices (Bayesian), a fix to the interaction matrix generation code, CCD flat-fielding, centroid origin scaling for extended objects or bad seeing, etc. In particular, the new IDL-generated reconstruction matrices are much faster (5 sec on the new AO host computer) and have been responsible for a 10% Strehl increase. A semi-online tool has been implemented to provide r_0 and L_0 from the wavefront sensor data.[5]

The current imaging performance can be seen in Fig. 2. The overall rms wavefront error in the bright NGS case is approximately 260 nm. The division of this error budget is briefly described in the following sentences. Image sharpening on the AO fiber source achieves a Strehl of 0.76 in H-band on NIRC2, corresponding to a 130-nm rms wavefront error. The fitting error is 120 nm. The tip/tilt bandwidth error is 100 nm and the higher order bandwidth error is 90 nm, due to the maximum frame rate of 670 Hz and time lag in processing. The telescope is believed to be responsible for ~ 100 nm while various noise terms contribute ~ 50 nm. The rss of the above contributors is 250 nm.

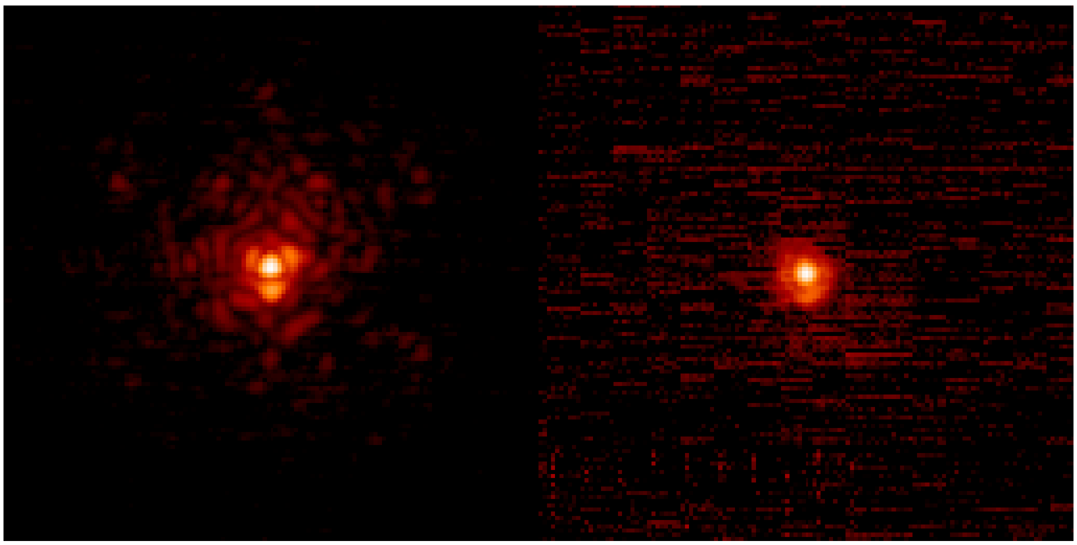

Fig. 2. Left: Bright NGS (V=7.5) case, the H-band Strehl ratio is 0.38 with a FWHM of 36.5 milli-arcsec, in this 15-sec integration on NIRC2. Right: Faint NGS (V=13.3, R=12.0) case, the H-band Strehl is 0.23 with a FWHM of 41 mas, in this 20-sec NIRC2 integration. In both cases, the H-band seeing was 0.45 arcsec.

3. LASER GUIDE STAR DEVELOPMENT

The LGS AO system achieved first light in September 2003. Two of the first light images are shown in Figs. 3 and 4. Since first light, continued development and on-sky testing has gradually increased the systems capabilities, performance and reliability. Since this is the first LGS AO system on an 8-10 m telescope there has also been a good deal of learning about the appropriate observing techniques and control algorithms.

The major components of the LGS AO system are represented schematically in Fig. 5 and have been described in an earlier paper[6]. All of the functionality illustrated in this Figure is currently in place for the Keck LGS AO system. The NGS and LGS light collected by the telescope are reflected off the tip/tilt mirror (TTM), the deformable mirror (DM) and the IR transmissive dichroic. The infrared light is transmitted to the science camera. The sodium wavelength light is transmitted through a sodium transmissive dichroic to the wavefront sensor (WFS), while the visible light is reflected off this dichroic to the tip/tilt sensor (STRAP) and the low-bandwidth wavefront sensor (LBWFS). STRAP and the LBWFS are mounted on an x,y,z translation stage in order to acquire an off-axis NGS (see Fig. 6). STRAP is a quadrant avalanche photodiode unit manufactured by Microgate. STRAP's output is used to drive the TTM, which in turn offloads to telescope pointing. The LBWFS lenslets are registered to the DM actuators in an identical pattern to the WFS lenslets, but with 16x16 pixels per subaperture instead of 2x2. The WFS is mounted on a translation stage to keep it conjugate to the sodium layer as a function of zenith angle (at the zenith the WFS is positioned ~ 250 mm from the NGS focus corresponding to 90 km). Any focus error measured with the LBWFS (which is conjugate to the science instrument focus) is used to re-position the WFS stage to zero the LBWFS focus. Errors in the position of the individual centroids on the LBWFS are used to adjust the centroid offsets used for the WFS in the wavefront controller (WFC). We have recently begun testing of LGS-specific reconstructors based on the orientation of the laser with respect to the WFS (note that the images are more elongated as you move to subapertures farther from the off-axis laser projector) and the laser spot size and elongation. The LGS reconstructor is updated on the fly as the pupil rotates, as is done for our NGS reconstructors. The WFC makes use of all these inputs in controlling the DM. Power on the DM is offloaded to the piston of the telescope's secondary mirror. The average tip/tilt measured on the WFS is used to control a fast tip/tilt mirror just prior to the laser projector to minimize the WFS tip/tilt residuals. The laser TTM is offloaded to a pointing mirror within the laser projector that is also used for some elevation-dependent compensations. More details on the WFS focus corrections and laser pointing can be found in the paper by D. Summers et al.[7]

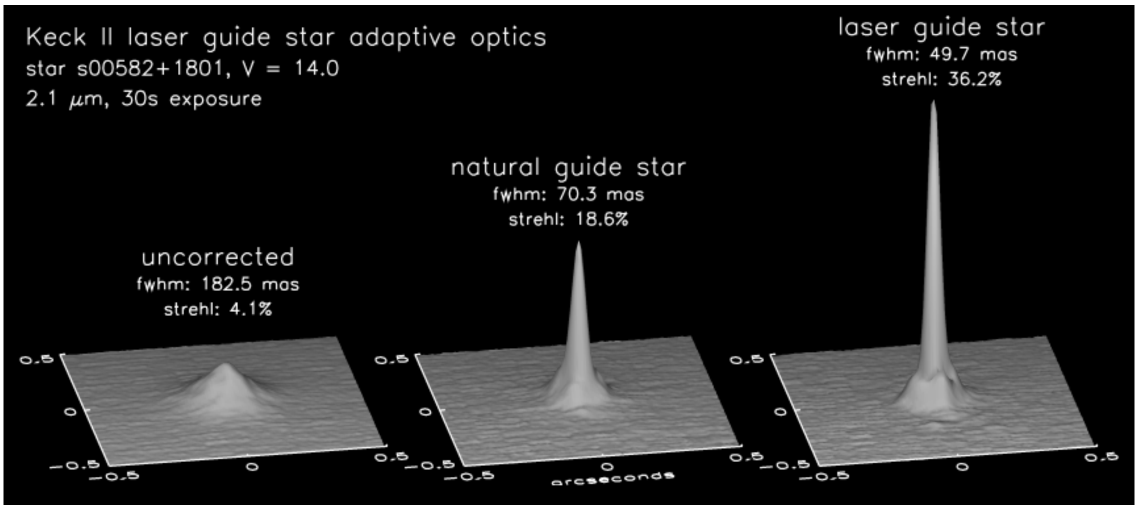

Fig. 3. LGS AO first light image compared to uncorrected and NGS AO images on the same NGS. The seeing during this first light demonstration was exceptionally good as seen in the uncorrected image.

Fig. 4. LGS AO first light image of HK T Tauri component A at bottom right and component B at top left. The separation between these two components is 2.4 arcsec. Component B is believed to lie in the dark lane of a circumstellar disk. Component A (V=15) was used to lock the LGS tip/tilt and low-bandwidth loops. This image is a color composite of 30-, 40-, and 72-sec exposures at H, K' and L' (blue, green and red, respectively, in this display).

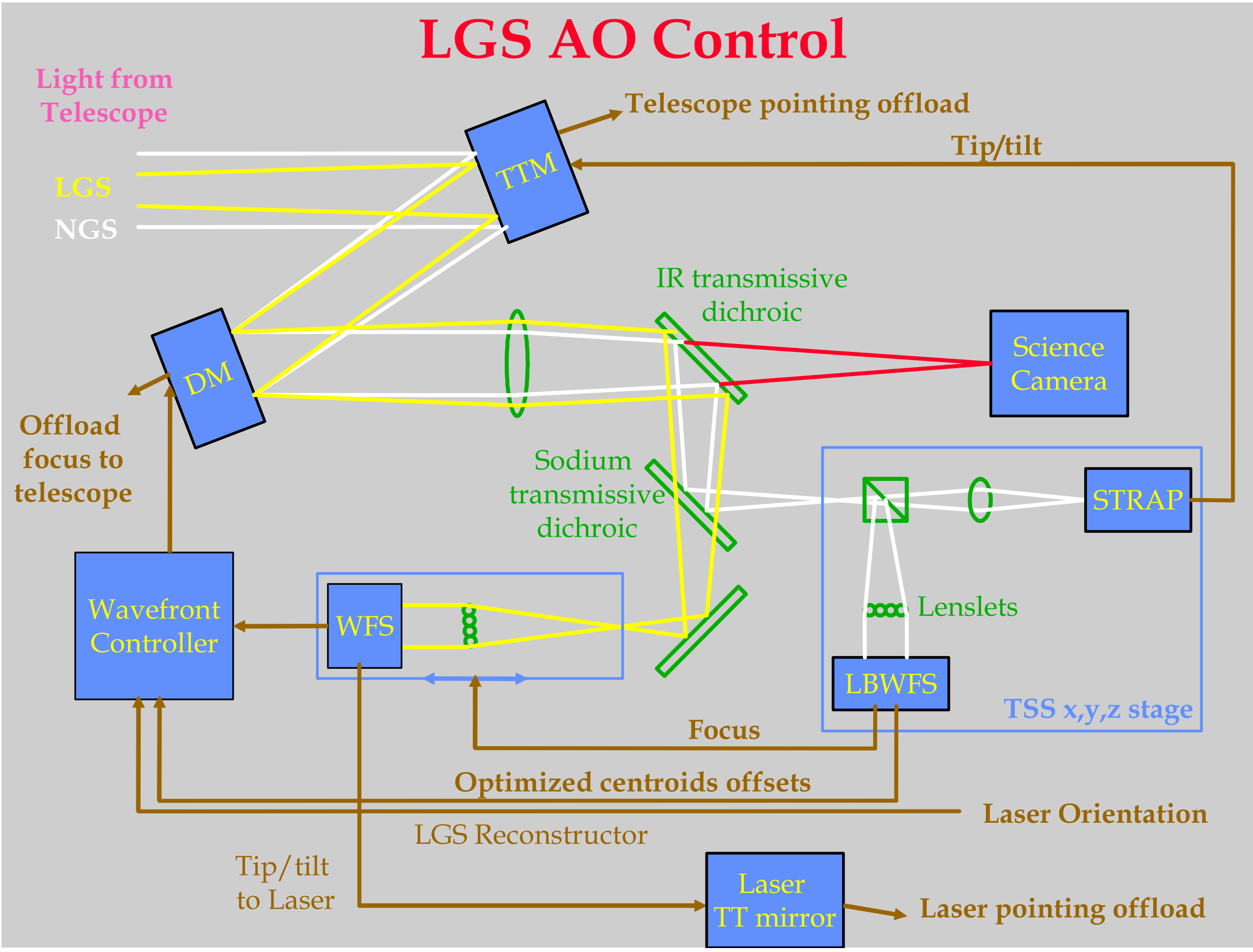

Fig. 5. LGS AO system components.

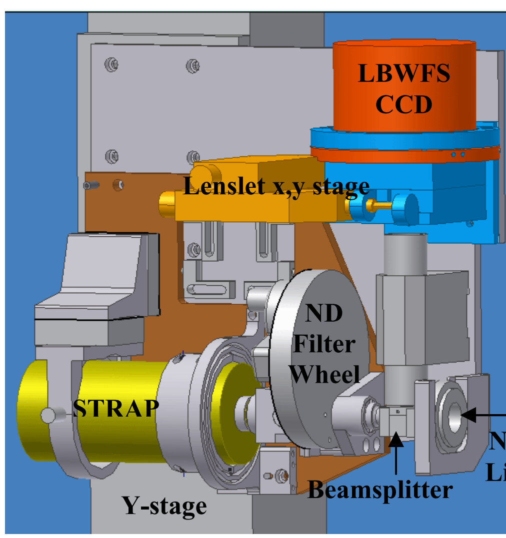

Fig. 6. CAD drawing of the STRAP tip/tilt sensor and LBWFS sensor.

The laser itself has progressed significantly since the 2002 SPIE meeting. The laser was first projected in late 2001 in collaboration with a team from Lawrence Livermore National Laboratory. After a 10-month hiatus, we began projecting the laser again in the fall of 2002, after hiring our own laser expert. The laser is now operating reliably, with one exception, for our observing runs, and the preparation time has been reduced. On the day of a run we turn the laser on at approximately 1:00 pm and by 3:00-4:00 pm are pumping the dye amplifiers and doing the final alignment; everything is ready for observing before 6:00 pm. When the laser is first projected, it is immediately seen on the AO acquisition camera and a mirror in the laser projection telescope is used to remotely center the LGS on the wavefront sensor. The laser is monitored remotely during the night by a laser expert from the summit control room. This role has been demonstrated from the headquarters control room, and we plan to transition this role to headquarters as we gain more confidence (note that all the other LGS AO operation roles are performed from headquarters). Getting adequate power to the amplifier, and the amplifier pumping efficiency, have both improved. The major problem we are currently dealing with is frequent burning of the dye amplifier cell. This has occasionally required a nighttime realignment and has also required us to change out the amplifier between runs. We are currently operating at lower powers (12-14W) in order to minimize dye amplifier burns and plan to increase the dye flow rate, which we believe contributes to this burning. Other ongoing minor failures include flashlamp replacements, power supply diode failures and YAG misalignments. The laser spot quality both pre- and post-projection is quite repeatable. The implementation of a power-in-the-bucket camera and the IDL tool, shown in Fig. 7, has proved very useful for optimizing the laser beam quality.

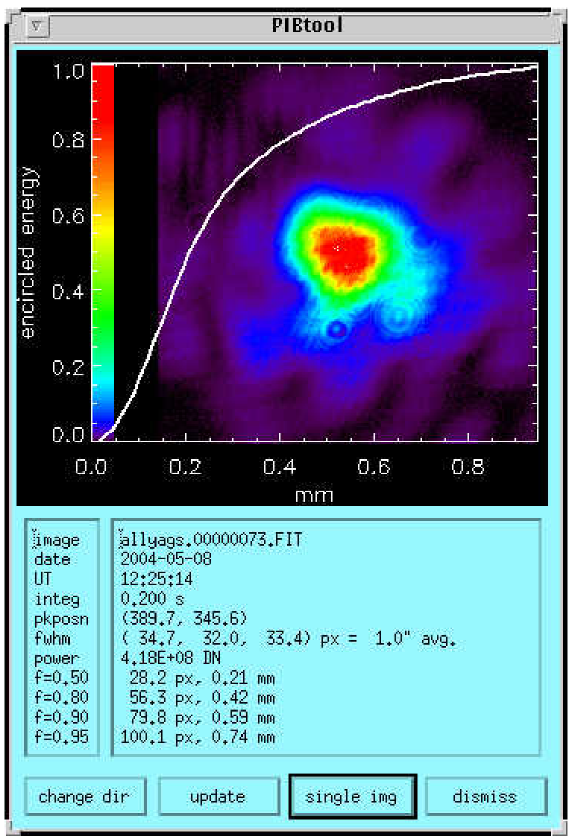

Figure 7. Laser power-in-the-bucket tool for measuring and monitoring laser beam quality.

Acquisition of a new target in LGS AO is somewhat complex, due to the requirement that two properties of the Na layer must be determined before science integrations can begin. One is the altitude of the sodium layer; the other is the effect of the layer's structure and thickness on the wavefront measured by the WFS. Both of these are determined iteratively by observing the wavefront of a natural guide star with the LBWFS while locked on the LGS with the WFS. Since LBWFS integrations are necessarily long when using a faint TT references, the initial determination of these properties is more efficiently done on a bright star prior to acquisition of the science target. The current acquisition sequence is described elsewhere in these proceedings.[8]

All targets must be pre-screened by the U.S. Space Command, with possible laser black-out periods. The laser may not be projected in the direction of any target that has not been pre-approved. Brief interruptions in observing could also occur due to the presence of aircraft. Two aircraft spotters are always outside during any laser projection. Neither of these has been an issue over the last 1 to 2 years. The laser is automatically shuttered by our Laser Traffic Control System in the event of our laser beam intersecting the field of view of other telescopes on Mauna Kea.

Figure 8 shows an acquisition camera image of the LGS with the 36 segments of the telescope unstacked. The images can clearly be seen to increase in elongation as the distance from the laser projector increases. The segment images closest to the projector can have FWHM of as small as 1", while the best stacked images are typically 1.5" FWHM. The average sodium altitude, the structure of the sodium layer and its density can all be observed to change through the night.

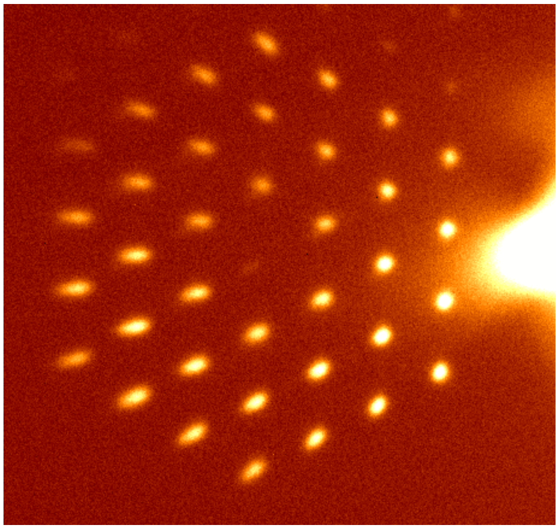

Fig. 8. LGS image with the Keck segments unstacked. The laser projector is on the right side of the telescope in this image; the side from which the Rayleigh-scattered light can just be seen. The individual segment images are elongated toward the projector. The segment image closest to the projector has a FWHM of 1.2 arcsec, while that of the furthest segment is 1.3x3.0 arcsec.

The planned milestones for completion of the LGS AO system, revised in March 2004, are listed in Table 2. The first light milestone was achieved in September 2003, and the first engineering science demonstration was achieved in June 2004. With respect to the earlier, September 2002 version of this milestone calendar, the achieved date was on schedule for the first light milestone and was 3 months behind schedule for the first engineering science.

Table 2. Planned LGS AO milestones.

LGS	Date	Description	Actual
1	03Q4	1st corrected images on NIRC2 w/ laser	9/18/03
2	Jul/04	2nd level performance/operability criteria met	
3	Sept/04	1st engineering science	6/10/04
4	Nov/04	1st shared risk science (scheduled for 11/2/04)	
5	Jan/05	Readiness review for non-shared risk science	
6	Aug/05	3rd level performance/operability criteria met	
7	Sept/05	1st non-shared risk science	
8	Jan/06	Operations handover requirements review	
9	Sept/06	Operations handover readiness review	
10	?	1st queue scheduled science observing	

We chose a planetary nebula, the Egg Nebula, for our first engineering science demonstration.[8] The resultant image is shown in Figure 9. Despite the poor seeing at the time of this observation, the correction in this image is comparable to or better than the HST/NICMOS images we have seen. All of the functionality illustrated in Figure 5 was utilized to make these observations.

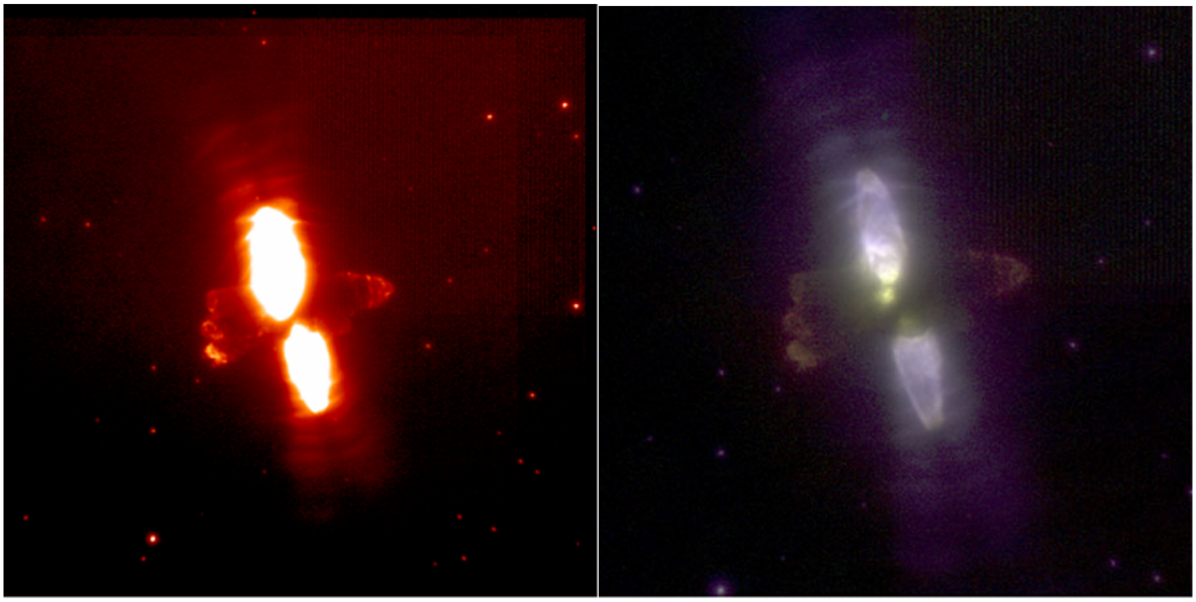

Fig. 9. LGS AO first engineering science demonstration image of the Egg Nebula. The laser was projected at the nebula. The R = 14 magnitude NGS used for tip/tilt and low bandwidth sensing was located 25 arcsec off-axis. The image on the left is the sum of twelve 30 second integrations at Kp. It has been saturated in this display to provide a better view of the structure. The image on the right is a color composite of a total of 18 minutes of integration, where blue is H-band, green is an H2 filter, and red is a combination of Kp and Lp-bands. The field of view in both of these images is 36x36 arcsec. The seeing was ~ 0.8 arcsec in K-band.

We are currently working on meeting a set of 12 performance and operability criteria established shortly after achieving our first light milestone. These criteria and their status are summarized in the following bullets. The first 8 criteria have already been met and the next two are very close to being satisfied. The last two will be a challenge to achieve prior to the end of July 2004 date for this milestone.

- ✓ K-band Strehl ≥ 0.2 for an R ≥ 15 magnitude NGS in a 30 sec integration. Demonstrated 0.23 for R = 16.1.
- ✓ K-band Strehl ≥ 0.1 for an R ≥ 17 NGS. Demonstrated 0.13 for R = 17.2.
- ✓ Off-axis science for a target ≥ 20 arcsec from the NGS. Demonstrated for 25 arcsec off-axis.
- ✓ Off-axis functionality for a target ≥ 30 arcsec from the NGS. Demonstrated for 35 arcsec off-axis.
- ✓ LGS software release in a controlled version.
- ✓ Demonstrating LGS correction for elevation angles from at least 50° to 85°.
- ✓ Nodding (moving the science object and LGS on the science camera) in less than 20 sec.
- ✓ Demonstrating nodding over a 5”x5” field.
- Demonstrating 10 milli-arcsec positioning accuracy. 11 mas has been demonstrated in daytime testing with a repeatability of 5 mas.
- Operating the LGS AO system with 3 AO experts and 1 laser expert. Currently 4 AO experts and 1 laser expert are still needed. All the LGS functions are performed from headquarters. During our most recent observing run the laser was also operated from headquarters, with a laser expert on the summit for emergencies.
- K-band Strehl ≥ 0.2 for an R ≥ 17 magnitude NGS.
- Corrected images on the science camera ≤ 5 minutes after slewing to a new target. Currently achieving 10 to 15 min.

The above criteria are only intermediate performance and operability criteria. On the August 2004 timescale we will be identifying a set of third-level criteria to be completed by August 2005. The LGS system is designed to observe any object within 60" of natural guide stars as faint as V=18, opening up roughly 70% of the sky to AO corrected observations.

The LGS AO system has been advertised to be available for five shared-risk science nights in the latter part of 2004; these nights have already been assigned by the Caltech, University of California and University of Hawaii time allocation committees. A Web page has been set up at http://www2.keck.hawaii.edu/optics/lgsao/ to support observation planning. We plan to continue in a shared-risk mode through the first half of 2005, with the goal of shifting to general observing availability in the latter part of 2005.

4. NEW WAVEFRONT CONTROLLER DEVELOPMENT

A proposal to the W. M. Keck Foundation to support the implementation of newer wavefront controllers and sensors was funded in January 2004. Our existing wavefront controllers (Mercury array processors with i860s) and cameras (MIT/LL 64x64 pixel CCDs in AOA cameras) make use of early 1990s technology. Our proposal was based on the success of using newer processors (DSP boards) and cameras (EEV39 in SciMeasure cameras) in the Palomar AO system.[9] We have, therefore, teamed with the JPL group that implemented the Palomar upgrade in this Keck development effort.

Figure 9 shows the current AO system performance and the predicted performance with the implementation of the new wavefront controller and sensor. This improvement is due to significant reductions in both the bandwidth and measurement errors. The small (~10%) improvement for bright guide stars is due to bandwidth error reductions while the significant improvement for faint guide stars (~130% at 13th magnitude) is due to the reduction of both read noise and dark current with the new detectors.

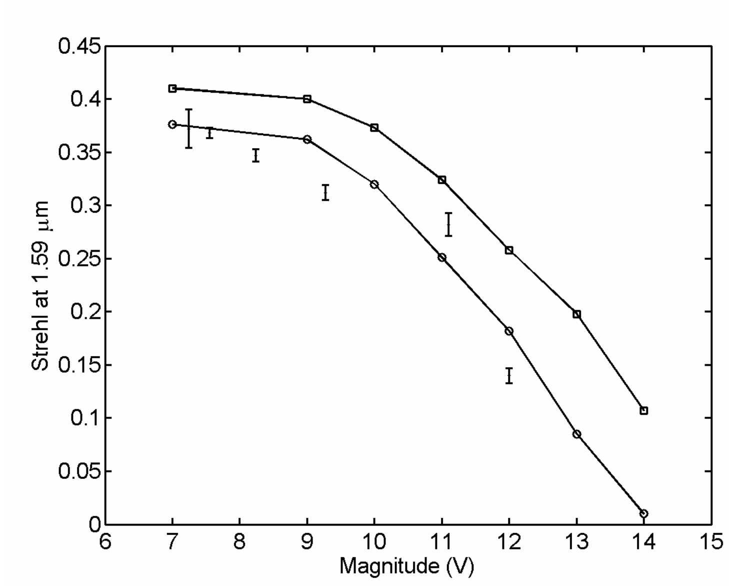

Fig. 10. Strehl ratio versus brightness of guide star. The points with error bars are measurements with the current Keck II NGS AO system. The solid lines are computer simulations. The lower line represents the performance of the current system, and the upper line represents the predicted performance with the new wavefront controller and sensor.

Our existing wavefront controller has very little spare capacity and limited telemetry capability, features that are very important to system optimization. The new system will have plenty of extra capacity, and the telemetry and diagnostics, to allow the implementation of the on-line optimization and performance measurement tools that we have already identified and to handle future technical developments.

We have been laying the ground work to start on this project, including putting a JPL contract in place and preparing a software requirements document, and will officially begin the project in June 2004. We plan to complete the PDR and CDR by early 2005. Three identical development systems will be built up, with two located at Keck and one at JPL. After a readiness review, we intend to begin integration and test of the Keck I system in early 2006, followed by the Keck II system a few months later. The overall project should be complete by early 2007.

5. NEW LASER

Sodium wavelength laser technology has advanced considerably in the last few years. The NSF is in the process of providing funding to develop a solid-state sodium wavelength laser to be implemented at Keck Observatory. The purpose of this proposal, part of a larger NSF-funded laser development program led by B. Ellerbroek, with co-investigators R. Fugate, J. Nelson and P. Wizinowich, is to use the procurement of a Keck laser as the mechanism to develop a commercial facility-class product for the astronomical community. We expect to distribute a request for proposal for this laser in late 2004. The announcement of opportunity and draft requirements will soon be posted on the Gemini and Keck Observatory Web sites.

The demand for AO observing makes it very attractive to mount this laser on Keck I. This would also provide a welcome redistribution of observing demand between Keck II and Keck I, by allowing us to move one of the high-demand AO instruments (likely OSIRIS) to Keck I.

6. NEXT-GENERATION KECK ADAPTIVE OPTICS

The Keck AOWG strategic plan report of November 2002 stated that: "Our primary recommendation is for the development of the first next-generation high-performance general-use AO system, which would deliver stable high Strehl ratio infrared images in moderate field-of-view areas throughout the sky." Further details from this report included: "Such a system is envisioned to be one which would deliver extremely high infrared Strehl ratios, high stability, near-complete sky coverage, a good knowledge of the delivered PSF, and the ability to observe at high resolution into the visible (albeit with lower Strehl ratios)." The AOWG dubbed this system KPAO for Keck Precision Adaptive Optics.

The KPAO concept was driven by a number of preliminary science cases proposed by members of the AOWG including monitoring global changes on Pluto, understanding low mass stars in binaries and clusters, and understanding star formation in quasar host galaxies.

We will begin working on a conceptual design for KPAO in FY05. Some modest efforts to date have gone into producing a technical requirements and constraints document[10], and to investigating the feasibility of the proposed error budgets. Two error budget cases are being evaluated: 120 nm and 180 nm rms residual wavefront error delivered to the science instrument focal plane. The key inputs we have so far found necessary to achieve these error budgets are summarized in Table 4; the current Keck LGS AO parameters are included for comparison.

Table 4. Key design parameters for KPAO compared to current Keck AO.

Parameter	Keck I/II	KPAO (180 nm)	KPAO (120 nm)
Number of actuators	349	~500	~2000
Subaperture size on primary	56.2 cm	40 cm	20 cm
Number of LGS spots	0/1	5	9
Laser Power	10 W	5x 5W/LGS	9x 20W/LGS (+ uplink AO)
CCD frame rate	672	1000 Hz (400)	1000 Hz (650)
CCD read noise	7e-	3e-	3e-

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REFERENCES

1. P. Wizinowich et al., “Adaptive optics developments at Keck Observatory,” in *Adaptive Optical System Technologies II*, P. L. Wizinowich and D. Bonaccini, eds., SPIE Proc. 4839, 9-20, 2003.
2. M. M. Colavita, P. L. Wizinowich, R. L. Akeson, “Keck Interferometer status and plans,” in *New Frontiers in Stellar Interferometry,* SPIE Proc. 5491, 2004.
3. M. A. van Dam, D. Le Mignant and B. A. Macintosh, “Performance of the Keck Observatory Adaptive Optics System,” to appear in *Applied Optics*, 2004.
4. M. van Dam, D. Le Mignant and B. Macintosh, “Characterization of adaptive optics at Keck Observatory: part II,” in *Advancements in Adaptive Optics,* SPIE Proc. 5490, 2004.
5. M. Schöck, D. Le Mignant, G. A. Chanan, P. L. Wizinowich M. van Dam, “Atmospheric turbulence characterization with the Keck adaptive optics systems. I. Open-loop data, *Applied Optics*, **42,** 3705-3720, 2003.
6. A. Contos et al., "Laser guide star adaptive optics at Keck Observatory," in *Adaptive Optical System Technologies II*, P. L. Wizinowich and D. Bonaccini, eds., SPIE Proc. 4839, 370-380, 2003.
7. D. Summers et al., “Focus and pointing adjustments necessary for laser guide star adaptive optics at the W.M. Keck Observatory,” in *Advancements in Adaptive Optics,* SPIE Proc. 5490, 2004.
8. A. Bouchez et al., Keck laser guide star adaptive optics: science verification results, SPIE Proc. 5490, 2004.
9. T. Truong et al., “Real-time wavefront processors for the next generation of adaptive optics systems: a design and analysis,” in *Adaptive Optical System Technologies II*, P. L. Wizinowich and D. Bonaccini, eds., SPIE Proc. 4839, 911-922, 2003.
10. P. Wizinowich, R. Dekany, M. Troy, G. Chanan, C. Neyman, “Keck Precision Adaptive Optics: Technical Requirements and Constraints,” Keck Adaptive Optics Note 237, 2003.