LGS AO at W. M. Keck Observatory: routine operations and remaining challenges

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ABSTRACT

The Laser Guide Star Adaptive Optics (LGS AO) at the W.M. Keck Observatory is the first system of its kind being used to conduct routine science on a ten-meter telescope. In 2005, more than fifty nights of LGSAO science and engineering were carried out using the NIRC2 and OSIRIS science instruments. In this paper, we report on the typical performance and operations of its LGS AO-specific sub-systems (laser, tip-tilt sensor, low-bandwidth wavefront sensor) as well as the overall scientific performance and observing efficiency. We conclude the paper by describing our main performance limitations and present possible developments to overcome them.

Keywords: Telescope operations, laser guide star, adaptive optics.

1. INTRODUCTION

Laser guide star adaptive optics (LGS AO) is a very promising technical solution to correct the optical distortions introduced by the atmospheric turbulence and improves the sky-coverage for diffraction-limited astronomical observations. Since 1995, 23 astronomical refereed papers have been published based on LGS AO data [1]. The challenges faced during the integration of the first generation of LGS AO systems may well illustrate the difficulty to combine complicated technologies such as AO and lasers for routine science operations; e.g., Lick Observatory LGS AO system has been in operation since 1996 [2] and underwent various upgrade phases [3].

The LGS AO system on the Keck II telescope at the W.M. Keck Observatory was designed from the start to be an LGS system. Yet, the Keck II AO saw first light in NGS AO mode, [4] and was characterized and optimized, [5] while the Keck laser was being developed and integrated. [6] The Keck II LGS AO system is the first installed on an 8-10-m telescope. An overview of the system is given in Wizinowich et al. (2006) [7]. The performance characterization is described in van Dam et al. (2006) [8] and the LGS AO operations are detailed in Le Mignant et al. (2006) [9].

Keck started to offer LGS AO instruments to its user community in shared-risk mode in November 2004 (5 nights in 2004B). The LGS AO engineering team supported thirteen nights in 2005A, and thirty nights in 2005B in shared-risk mode. In parallel, we began transitioning the LGS AO operations to the observing support group. This group is now supporting 50 nights for 2006A. The Keck II LGS AO has already produced 13 refereed science papers as of May 2006 in a wide variety of subject areas. [1]

In Section 1, we give some background information on the Keck Observatory operations with particular attention to the AO operations. The performance of the different sub-systems required for the Keck LGS AO operations are presented in Section 2. Section 3 provides an overview of the critical steps for the operations and support activities for an LGS AO observing night, focusing on the operations tools that we have developed. The overall performance and efficiency of the systems are presented in Section 4, and we conclude the paper by discussing the lessons learned and possible upgrade paths.

1.1 Observing Support at W. M. Keck Observatory

Science operations at Keck Observatory are performed in “classic” mode: astronomers come to Waimea, Hawaii in order to actively gather observations for their project. Usually each night of observing is given to one, or at most two separate observing projects. Observing is “remote” from the Waimea headquarters building, providing a more congenial atmosphere for observers than the rather-harsh conditions at the 14,000 foot summit of Mauna Kea.

Observers are supported by a Support Astronomer (SA) who provides information and guidance on using the instrument and on observing techniques, and an Observing Assistant (OA) who operates the telescope and provides observing advice.

1.2 NGS AO observing support

The Natural Guide Star AO systems are installed on each of the left Nasmyth platforms of the Keck telescopes and feed NIRC2, OSIRIS and NIRSPEC on Keck II and the Keck Interferometer [10]. NGS AO science operations accounts for about 45% of all science nights on Keck II. During these nights, the AO system is operated by the OA. LGS AO operations require a substantial increase in support personnel, including a second Observing Assistant operating the LGS AO software, a laser operations technician and a support astronomer, all of them for the entire night.

Figure 1 illustrates the scientific output of the Keck AO systems. As of May 2006, 85 astronomy papers based on data taken with the Keck NGS AO instruments have been published in refereed astronomical journals [11]: 76 using either KCAM, NIRSCPEC or NIRC2 and 9 with the Keck Interferometer. The distribution of the papers in the area of planetary, Galactic and extragalactic sciences is 30% / 50% / 20%. The requirements on the brightness and separation (from the science target) of the AO guide star are mainly responsible for the relative poverty of extragalactic papers.

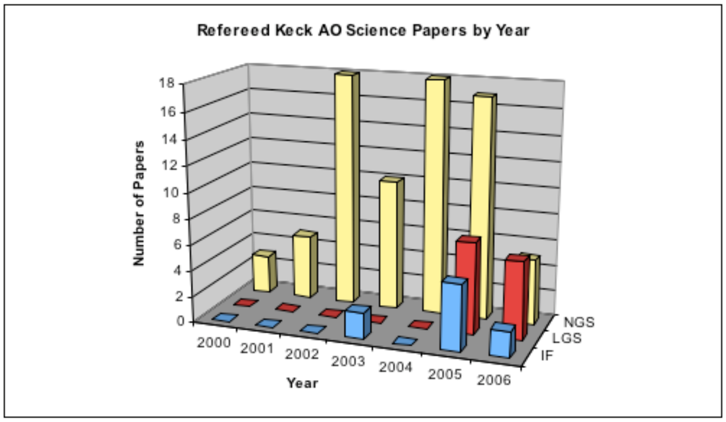


Figure 1: Histogram of refereed Keck AO science papers by year.

The user-level AO operations software was built in IDL, while some GUI tools were developed in Java in the early days of AO integration. The IDL operation software includes a number of automated sequences for system calibrations performed either for preventive maintenance or for observing; for night time setup and end-of-night scripts to interface with the telescope and the instrument in use; for acquiring and optimizing on a target, based on a well-calibrated look-up table for the AO parameters; and for monitoring the system health, detecting any fault and launching automated recovery scripts.

The system is calibrated by the SA before a run for each instrument: 1) registration of the wavefront sensor (WFS) lenslets to the deformable mirror (DM) and 2) measuring and recording the WFS centroid origins that compensate for the non-common path aberrations. The OAs who operate the telescope from the summit for any science night are the designated AO operator. The automated setup takes from 45 sec to 2 min once the telescope is pointed at the target with the target centered on the WFS. The AO acquisition scripts have also been upgraded to minimize the setup time during interferometer observing sequences.

The Keck AO systems’ performance has been described in Ref. [5]. The system produces diffraction-limited images for AO guide stars as faint as R=13.5-mag. The typical Strehl ratio for a star brighter than R=10.0-mag is 0.5 in the K band. The main time overhead during NGS AO science is associated with target acquisition; telescope/AO/instrument handshakes during dithering scripts; science instrument overhead and observing strategies. NGS AO open shutter time may vary from 70% for faint object spectroscopy to 20 - 30% for thermal infrared imaging.

2. LGS AO SUB-SYSTEMS PERFORMANCE

2.1 The LGS AO sub-systems

References [7-8] provide an extensive overview of the Keck II LGS AO sub-systems and their performance. For easier readability of the present paper, we show in Figure 2 the schematic representation of the AO systems for NGS AO (left) and LGS AO (right). The main sub-systems include the laser guide star and diagnostics tools, their associated safety systems, the Laser Traffic Control System (LTCS), and the laser beam steering optics; the STRAP unit for tip-tilt sensing on faint AO guide star; the low bandwidth wavefront sensor (LBWFS) for focus and image sharpening on the AO guide star; and the WFS focus manager.

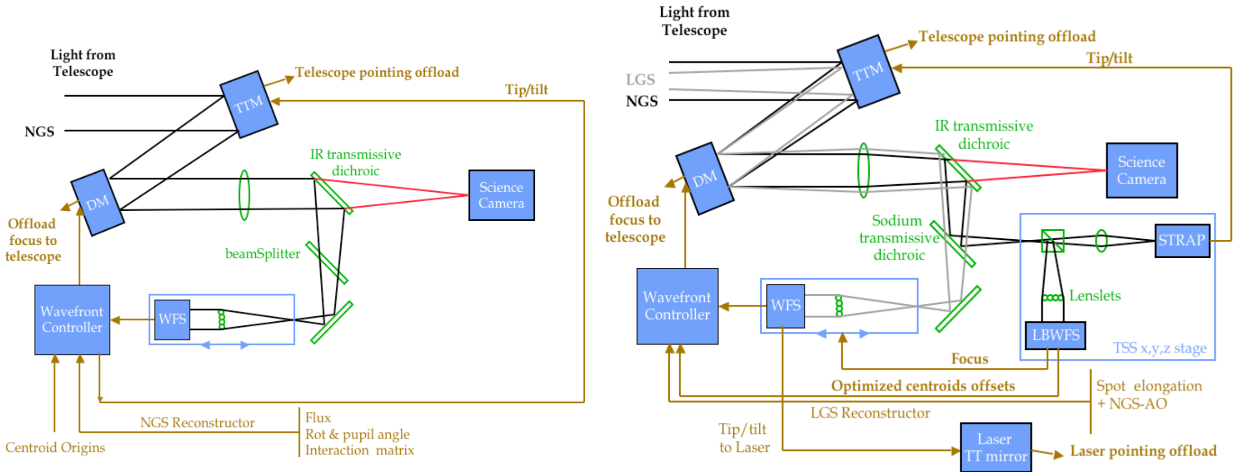


Figure 2: Schematics of the AO systems in NGS AO and LGS AO configuration. The LGS AO main additions are the LBWFS, STRAP, TSS and UTT (see text)

2.2 The laser guide star and its control optics

The Keck II LGS was fabricated by Lawrence Livermore National Laboratory (LLNL) and was delivered to Keck Observatory in 2000, further engineered by both LLNL and Keck Observatory and then integrated with the telescope in 2001. [6-7] A laser room on the Keck II dome floor houses 6 Nd-YAG lasers and a dye master oscillator (DMO). The DMO is tuned to the center of the Na D2 wavelength and provides the seed light to a table on the side of the telescope. The table includes two amplification stages fed through multi-mode fibers by the YAG lasers, and several alignment and diagnostic tools. The final output of the dye laser is sent to the sky through a projection telescope. The laser is typically operated at an output power of 10 to 14W, generating on most nights, an equivalent V=9-10-mag star (or ~175 to 70 photons s^{-1} cm $^{-2}$), at zenith, depending on sodium density. The laser performance characterization effort has been given a lower priority than working on laser reliability and operations. The averaged numbers for the laser performance are summarized in Table 1.

Period	Power	Na return			Altitude	Thickness
		ph. S^{-1}.cm	WFS counts	$V_{eq.}$-mag		
Oct – Apr	12±2 W	**120-200**	100 cts @ 600Hz	9.5-8.5	~ 88 km	7-13 km
May – Sep	12±2 W	**40-100**	110 cts @ 250Hz	9.7-10.7	~ 86 km	7-13 km

Table 1: Averaged performance numbers for the Keck II laser and Na return. Note that we have not noted a substantial change in Na layer thickness.

The laser system requires a warm-up time of 1-2 hours before all laser sub-systems have fully stabilized. This warm-up period is primarily driven by the Nd-YAG lasers and the DMO. After this warm-up period, some minor adjustment and optimization of the various laser subsystems is usually required. Ideally, once the system is stabilized and optimized, operator input is minimal. Once the laser is on sky, the most common problem facing the operator is instability in the Nd-YAG lasers. Most instabilities can be fixed without interfering with observations. Prior to an LGS laser run 1-2 days are spent checking the system, and fixing any apparent problems.

The most common critical failures of the laser system that can interfere with LGS observations are:

1) Serious persistent instabilities of one or more of the YAGs
2) Failure of the Nd-YAG power supply or flash lamp
3) Burning of the pre-amplifier dye cell
4) Burning of the amplifier dye cell

The impact to observing of these failures varies. Typically failures that fall into categories 1-3 can be fixed in under an hour, but an amplifier dye cell burn usually means the end of LGS observations for the night. Fortunately, amplifier burns are very rare (only one burn in the past 16 months). There are many diagnostics available that allow the operator to diagnose (and possibly prevent) nearly all of the more common problems that could interfere with observing. Other factors can also impact observing with the laser such as: frosting of the laser launch telescope's output lens due to sudden high humidity, electronics failures, and mechanical failure.

2.3 Steering and pointing the laser

LGS steering is achieved through the use of two separate mirrors and an interface to the wavefront sensing control system. A fast laser Uplink Tip/Tilt (UTT) steering mirror receives commands from real-time UTT pointing software using LGS centroid information from the fast WFS. UTT offloading for maintenance of fast steering mirror dynamic range is accomplished as one of several slow pointing mirror functions. The UTT software has a built in capability to overlay a high frequency dither pattern on UTT during operations in order to estimate the centroid gain variations caused by the laser guide star spot elongation. We do not, however, use this capability routinely because the performance of UTT, even without dithering, can be a limiting factor in the wavefront correction we attain. Typical values for the RMS residual tip-tilt error, which depend on the seeing and the elevation, vary between 50 and 150 milliarcsec along each axis. There are two reasons why this performance is so poor in comparison with downlink tip-tilt. First, the diameter of the launch telescope (0.5 m) is much smaller than the full aperture (10 m), resulting in more tip-tilt signal, which for frozen Kolmogorov turbulence scales as $D^{-1/6}$, and decorrelates as D^{-1}. Second, there is a delay in measuring and correcting the turbulence, since the correction is made before the light propagates.

A second, slow steering mirror (M3) is used to address all remaining LGS pointing model functions. These include functions for off-axis projection to the sodium layer (as a function of distance and elevation angle), laser system flexure, UTT offloading, Field Steering Mirror (FSM) slaving offsets, and manual acquisition offsets. All pointing model compensations are managed in image plane coordinate space, then summed and translated to laser steering coordinates. The Keck LGS pointing model, described in Summers et al. (2004),[12] allows on-axis and off-axis LGS placement in the field to address a variety of possible observing conditions and modes. M3 alignment and motions are calibrated at the beginning of every LGS AO night as part of our LGS AO checkout procedure. The pointing model performance is critical to our operations, particularly during LGS AO acquisition: it allows us to acquire the Na spot directly on the WFS for any new science target without any overhead. When the Na spot is not seen on the WFS, an automated routine set the optical path for "manual acquisition", records an image on the acquisition camera, then command M3 to center the spot on the WFS.

2.4 Laser Safety and Traffic Control

Our laser safety system is described in References [7-13] and has been performing very well in the context of the LGS AO operations: laser spotters have shuttered the laser on two instances when aircraft from a nearby airbase flew close to the beam propagation direction.

As we have experienced significant delay in building and integrating the all-sky camera, we are still including the laser safety observers (i.e., laser spotters) as part of our two-tier safety system. The use of spotters has strongly impacted LGS AO operations: recruiting a pool of ~20 spotters through a staffing agency; training them for safety and operations; managing schedules and transportation; and coordinating safety and financial aspects all require constant attention. We are still pursuing the development of a safety system that would minimize the requirements on outside laser safety observers.

The second generation Mauna Kea Laser Traffic Control System has been released and is presented in Summers et al. (2006). [14]

2.5 STRAP: the tip-tilt sensor

The tip-tilt sensor and controller is a STRAP unit manufactured by Microgate. It consists of a quad cell of avalanche photodiodes (APDs). The software and hardware of the system have both proved to be very robust. The only difficulty we have experienced is that some light is lost at the center of the quad cell due to imperfections in the lenslet array that directs the light from the focal plane to the APDs. This affects our ability to calibrate two quantities of the tip-tilt sensor: the interaction matrix between the tip-tilt mirror and the STRAP centroids and the focus of the tip-tilt sensor.

The STRAP controller is a configurable four-tap infinite impulse response filter of the form

$$y[n] = -b_1 y[n-1] - b_2 y[n-2] - b_3 y[n-3] + a_0 u[n] + a_1 u[n-1] + a_2 u[n-2] + a_3 u[n-3]$$

where $u[n]$ and $y[n]$ are the inputs and outputs at time n and a_j and b_j are the filter coefficients. In the z-transform domain, this can be written as

$$H(z) = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}}{1 + b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3}}$$

The tip-tilt controller is programmed to use a standard integral controller or an integrator with a Bessel-Thomson low-pass filter with a configurable frequency cut-off. In either case, the gain is also configurable. We have also investigated the possibility of using minimum variance controllers to optimize the performance. For the case of faint stars, we find that the integral controller is the minimum variance controller, so that no performance benefit is obtained by using a more complex control law.[15]

Details on how to find the optimal loop gain are presented in Ref [8]. In practice, the loop gain optimization runs as follows. At the beginning of the night, we take a long sequence of STRAP diagnostic data with the loop closed to determine the centroid gain [16] and the turbulence power spectrum.

For each subsequent star acquired throughout the night, we set the integration time and initial loop gain using a look up table. Immediately upon closing the loop, we use the measured counts due to the sky background and tip-tilt star to optimize the loop gain using the estimates of the turbulence power spectrum and centroid gain calculated earlier. Subsequently, the gain can be further optimized by remeasuring these three quantities. Figure 3 plots the K-band Strehl ratio and FWHM as a function of R-band magnitude for different nights in June 2005.

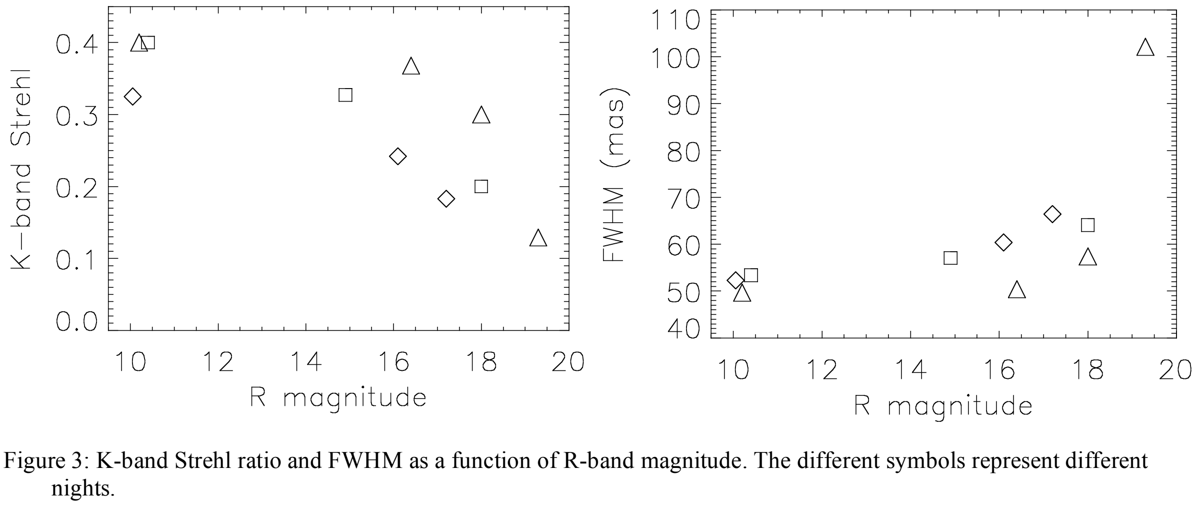


Figure 3: K-band Strehl ratio and FWHM as a function of R-band magnitude. The different symbols represent different nights.

2.6 LBWFS for focus and image sharpening

The low bandwidth wavefront sensor (LBWFS) is a crucial component of the Keck Observatory LGS AO system. The LBWFS takes a fraction (20%) of the light from the tip-tilt guide star and is used as a "truth" sensor. It is used to drive the focus stage of the fast WFS [7,8,12] as well as to correct for quasi-static aberrations induced by the laser guide star.[17] The magnitude of these aberrations, which are pupil angle dependent, can be higher than 1000 nm RMS.

We compensate for these aberrations by changing the centroid references of the fast WFS. We can correct at sufficient bandwidths for tip-tilt guide stars brighter than 16, with the compensation becoming progressively worse for fainter stars. For stars fainter than 18.5, we are unable to measure these aberrations adequately with the LBWFS. As a consequence, we have tried to model these aberrations using 11 Zernike polynomials with pupil-angle dependent coefficients, as can be seen in Figure 4. Unfortunately, the behavior of the aberrations changes from night to night depending on the structure of the sodium layer. Hence, a model of the aberrations constructed on a particular night does not adequately compensate the aberrations on a different night. The strategy we use on faint stars is to only compensate the low order Zernike polynomials rather than on a subaperture by subaperture basis. We are in the process of making the following two upgrades. First, we will obtain a lenslet array with two different sampling modes: 5x5 and 20x20 subapertures. The former will only be used with faint guide stars. Second, we will use a sodium notch filter with a much deeper null (0.01%) than we currently have (0.09%). When the tip-tilt sensor stage is off-axis, we find that the LBWFS and the tip-tilt sensor may become contaminated by the LGS.

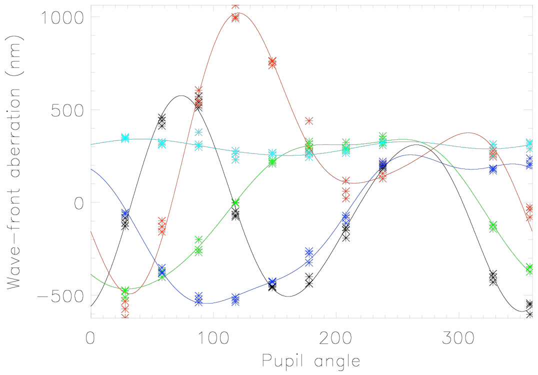


Figure 4: Measurement (stars) and model (solid line) of, from top to bottom at a pupil angle of zero degrees, spherical aberration, y-coma, 0-degree astigmatism, x-coma, 45-degree astigmatism. The laser is located at the top of the WFS when the pupil angle is 116.6 degrees.

2.7 Selecting and tracking the science field

The AO guide star used for TT is the reference for selecting and maintaining the science field of view. STRAP and the LBWFS are both mounted on the x, y, z Tip-tilt Sensor Stage (TSS) which means that the TSS stage motions are critical to AO guide star acquisition, steering, centering on the science array. In addition, the differential atmospheric refraction (DAR) between the AO guide star at the effective wavelength of STRAP and the science target at the effective wavelength of the science instrument must be compensated to center and maintain the science target on the instrument. The software that drives the TSS stage motors includes a module that calculates the DAR compensation depending on elevation, pupil angle, the color of the stars and the guiding and science wavelengths.

Observing programs with NIRC2 spectroscopy or coronagraphy may require a ~ 10 milliarcsec positioning and stability accuracy to maintain the science object centered on the slit or behind the focal mask. The positioning error is composed of the intrinsic mechanical positioning accuracy (~ 5 milliarcsec) and the residual error of the DAR compensation. The main source of error for the DAR compensation comes from the error on the color information (obtained from astronomical catalog such as GSC2.2, USNO 1B, etc) for the AO guide star. The rms positioning error over an hour of observation may vary from 10 milliarsec for well-studied AO guide star to ~60 milliarcsec for the fainter stars.

2.8 Maintaining the LBWFS focus for off-axis observations

As the stage is repositioned in x and y during observing sequences, it is required to keep the LBWFS focused at infinity and correct for field curvature from the telescope and the AO bench. This effect has been investigated by measuring the TSS field curvature using 1) the AO calibration source, and 2) by direct measurement on the Orion and M11 star clusters using a method where off-axis stars are acquired at various TSS x, y positions and centered on the LBWFS, while a bright star is maintained on-axis on the fast WFS. Our two sets of measurements have been compared to the Zemax optical model developed for the telescope and AO bench (see Figure 5). The on-sky data suggest that the focal surface seen by the STRAP and LBWFS is dominated by a slope in the +TSS x direction, probably due to misalignment of the TSS stage. Hence, we implemented in the TSS motion software a module that compensates for the focus for each TSS move; the compensation is derived from the 2nd order polynomial fit to the sky data. Sky tests show that the K-band Strehl ratio improved from 23% to 28% by using TSS focus compensation.[18]

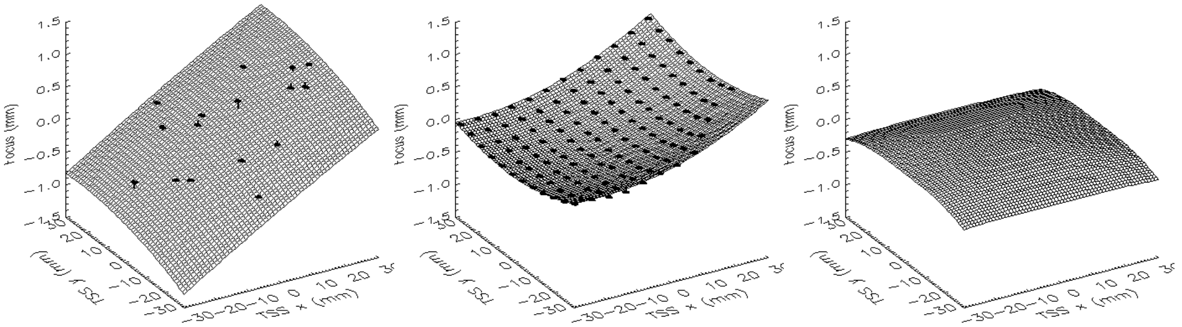


Figure 5: *left:* Second-order model fit to the sky data. Measurements are shown as points, connected to the surface by vectors. *center:* Second-order model fit to the April fiber data. *right:* Field curvature expected from the optical design. All are displayed on the same scale, with light traveling in the +z direction.

2.9 Science Instruments and Telescope

The LGS AO was first integrated with the NIRC2 camera, then with OSIRIS, the new near-IR integral field unit (IFU) spectrograph.[10] The next step will be to integrate it with NIRSPEC, a near-IR spectrograph with high-dispersion echelle, for the December 2006 observing campaign. The changes to the observing software are similar for all science instruments:

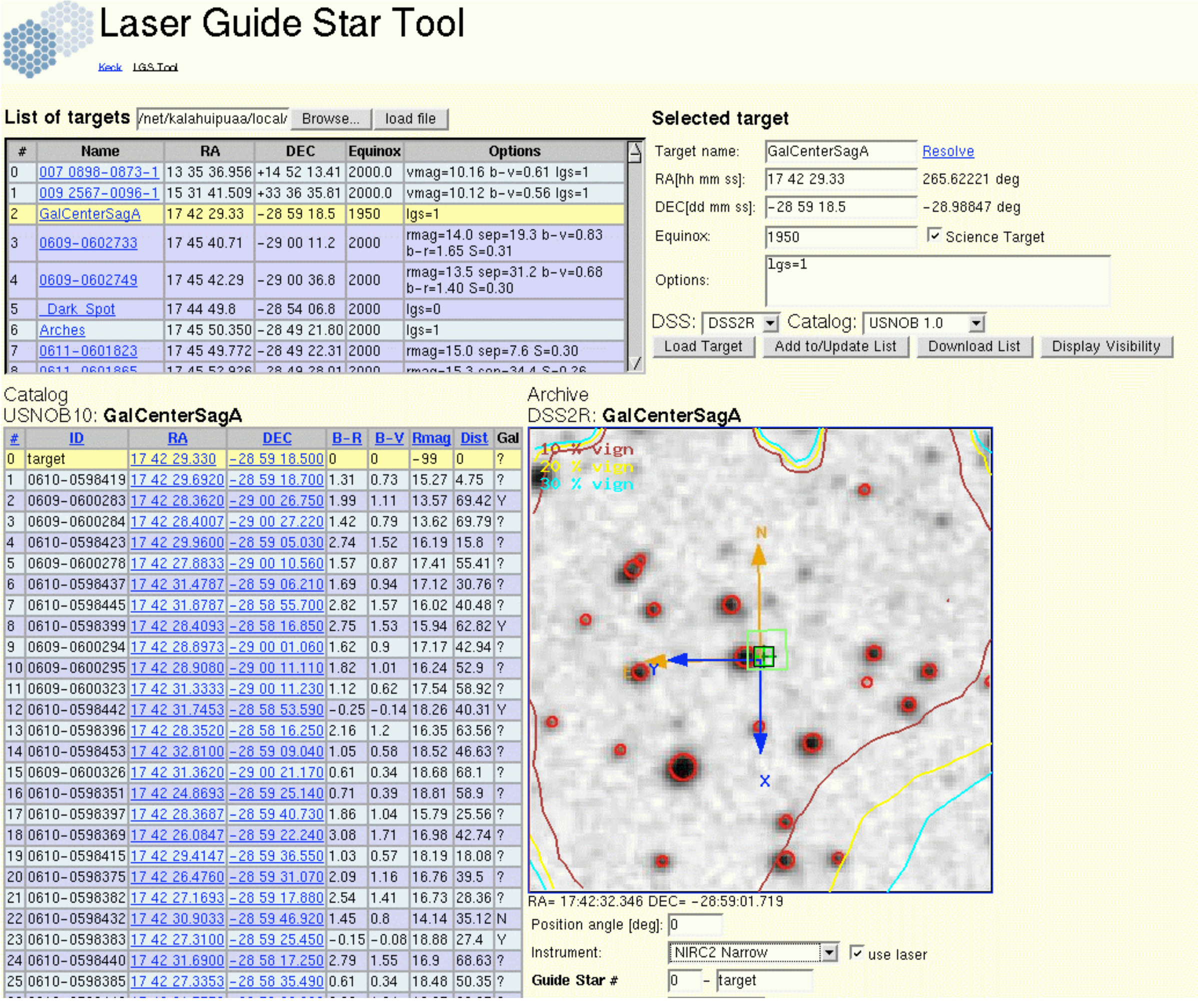
- The command for WFS focus adjustment with filter and camera settings is added to the process that manages the z-position of the Tip-tilt sensor and LBWFS stage.
- All scripts that require offsetting or nodding the telescope need to check that the LBWFS is idle. Optimally we would handle this additional logic by the telescope/AO communications (like normal nodding with AO-instruments). For practical reasons, this has not been done yet.
- At the start of an observing dithering script with less than 5 min on each dither leg, we included an automated sequence to optimize the LBWFS settings. Our intent is to optimize the LBWFS effective bandwidth for focusing and image sharpening while avoiding any overhead during the dithering script.
- During dither sequences, the observer has the option to keep the laser fixed on pixel *x, y* on the science array or move with dither. Observers generally prefer:
    - For narrow field imaging and spectroscopy (field is less than 10'' x 10'' and dither amplitude is less than 5 arcsec), the laser stays centered on the science array at the pixel of choice.
    - For *wide* field imaging (40'' x 40'') with large dither (up to 15 arcsec), the laser stays centered on the center of the science array if the distribution of objects of interest is uniform over the field. In the case of fewer objects, the laser is kept "on top" of the most interesting area.
    - We have not yet investigated the situation where the laser is positioned between the science target and the AO guide star to possibly improve the tip-tilt correction and the PSF quality over the field.

3. LGS AO OBSERVING SUPPORT TOOLS

The detailed time-line sequence for the LGS AO observing is given in Ref [9]. It starts with the 6-month ahead observing proposal process. The LGS AO operations team is responsible for pre-run preparation of the instruments and laser, pre-run preparation meeting with the observers, assignment of the observing support role for each night, coordination for propagation approval, observing support during the night, and follow-up of the run with post-observing comments. The Keck II LGS AO website provides support information for LGS AO observers.[19]

3.1 Pre-run support

The pre-run preparation meeting with observers leads to a detailed observing program. We have developed a set of IDL scripts that help observers to find suitable AO guide stars, and possible PSF stars for the science program (available from the LGS AO web page). An IDL widget called the "TSS widget" is used internally at Keck to review and check the AO guide stars separation and location with respect to the field of regard for STRAP and the LBWFS. Recently, we have added a web-based tool that combines all these IDL tools (see Figure 6) and another web-interface that allows the users to check the format of their target list and submit the file to our support team.



List of targets /net/kalahuipuaa/local/

#	Name	RA	DEC	Equinox	Options
0	007 0898-0873-1	13 35 36.956	+14 52 13.41	2000.0	vmag=10.16 b-v=0.61 lgs=1
1	009 2567-0096-1	15 31 41.509	+33 36 35.81	2000.0	vmag=10.12 b-v=0.56 lgs=1
2	GalCenterSagA	17 42 29.33	-28 59 18.5	1950	lgs=1
3	0609-0602733	17 45 40.71	-29 00 11.2	2000	rmag=14.0 sep=19.3 b-v=0.83 b-r=1.65 S=0.31
4	0609-0602749	17 45 42.29	-29 00 36.8	2000	rmag=13.5 sep=31.2 b-v=0.68 b-r=1.40 S=0.30
5	_Dark_Spot	17 44 49.8	-28 54 06.8	2000	lgs=0
6	Arches	17 45 50.350	-28 49 21.80	2000	lgs=1
7	0611-0601823	17 45 49.772	-28 49 22.31	2000	rmag=15.0 sep=7.6 S=0.30

Selected target

Target name: GalCenterSagA
RA[hh mm ss]: 17 42 29.33 265.62221 deg
DEC[dd mm ss]: -28 59 18.5 -28.98847 deg
Equinox: 1950 ☑ Science Target
Options: lgs=1
DSS: DSS2R Catalog: USNOB 1.0

Catalog
USNOB10: **GalCenterSagA**

#	ID	RA	DEC	B-R	B-V	Rmag	Dist	Gal
0	target	17 42 29.330	-28 59 18.500	0	0	-99	0	?
1	0610-0598419	17 42 29.6920	-28 59 18.700	1.31	0.73	15.27	4.75	?
2	0609-0600283	17 42 28.3620	-29 00 26.750	1.99	1.11	13.57	69.42	Y
3	0609-0600284	17 42 28.4007	-29 00 27.220	1.42	0.79	13.62	69.79	?
4	0610-0598423	17 42 29.9600	-28 59 05.030	2.74	1.52	16.19	15.8	?
5	0609-0600278	17 42 27.8833	-29 00 10.560	1.57	0.87	17.41	55.41	?
6	0610-0598437	17 42 31.4787	-28 59 06.210	1.69	0.94	17.12	30.76	?
7	0610-0598445	17 42 31.8787	-28 58 55.700	2.82	1.57	16.02	40.48	?
8	0610-0598399	17 42 28.4093	-28 58 16.850	2.75	1.53	15.94	62.82	Y
9	0609-0600294	17 42 28.8973	-29 00 01.060	1.62	0.9	17.17	42.94	?
10	0609-0600295	17 42 28.9080	-29 00 11.110	1.82	1.01	16.24	52.9	?
11	0609-0600323	17 42 31.3333	-29 00 11.230	1.12	0.62	17.54	58.92	?
12	0610-0598442	17 42 31.7453	-28 58 53.590	-0.25	-0.14	18.26	40.31	Y
13	0610-0598396	17 42 28.3520	-28 58 16.250	2.16	1.2	16.35	63.56	?
14	0610-0598453	17 42 32.8100	-28 59 09.040	1.05	0.58	18.52	46.63	?
15	0609-0600326	17 42 31.3620	-29 00 21.170	0.61	0.34	18.68	68.1	?
16	0610-0598351	17 42 24.8693	-28 59 25.140	0.71	0.39	18.81	58.9	?
17	0610-0598397	17 42 28.3687	-28 59 40.730	1.86	1.04	15.79	25.56	?
18	0610-0598369	17 42 26.0847	-28 59 22.240	3.08	1.71	16.98	42.74	?
19	0610-0598415	17 42 29.4147	-28 59 36.550	1.03	0.57	18.19	18.08	?
20	0610-0598375	17 42 26.4760	-28 59 31.070	2.09	1.16	16.76	39.5	?
21	0610-0598382	17 42 27.1693	-28 59 17.880	2.54	1.41	16.73	28.36	?
22	0610-0598432	17 42 30.9033	-28 59 46.920	1.45	0.8	14.14	35.12	N
23	0610-0598383	17 42 27.3100	-28 59 25.450	-0.15	-0.08	18.88	27.4	Y
24	0610-0598440	17 42 31.6900	-28 58 17.250	2.79	1.55	16.9	68.63	?
25	0610-0598385	17 42 27.3353	-28 58 35.490	0.61	0.34	18.48	50.35	?

Archive
DSS2R: **GalCenterSagA**

RA= 17:42:32.346 DEC= -28:59:01.719
Position angle [deg]: 0
Instrument: NIRC2 Narrow ☑ use laser
Guide Star # 0 - target

Figure 6: The AO guide star tool is a new web-based interface to select AO guide stars and sky images from a variety of catalogs, given a science target that can be loaded from a file or resolved by Simbad and NED. The tool allows the observer to build a target list including science target and AO guide stars in the Keck LGS AO format. To the right, the tool also overlays the field of regard depending on the science instrument (NIRC2 and OSIRIS) and the observing mode (NGS or LGS).

3.2 Run support

The AO system is calibrated for both the NGS and the LGS modes, for OSIRIS and NIRC2 prior to the run. Most IDL routines for calibrating the WFS, the LBWFS and other sub-systems have been automated. Yet these steps are still performed by operators with very good understanding of the AO system. It takes up to 3 hours to fully calibrate and check the system from a cold start.

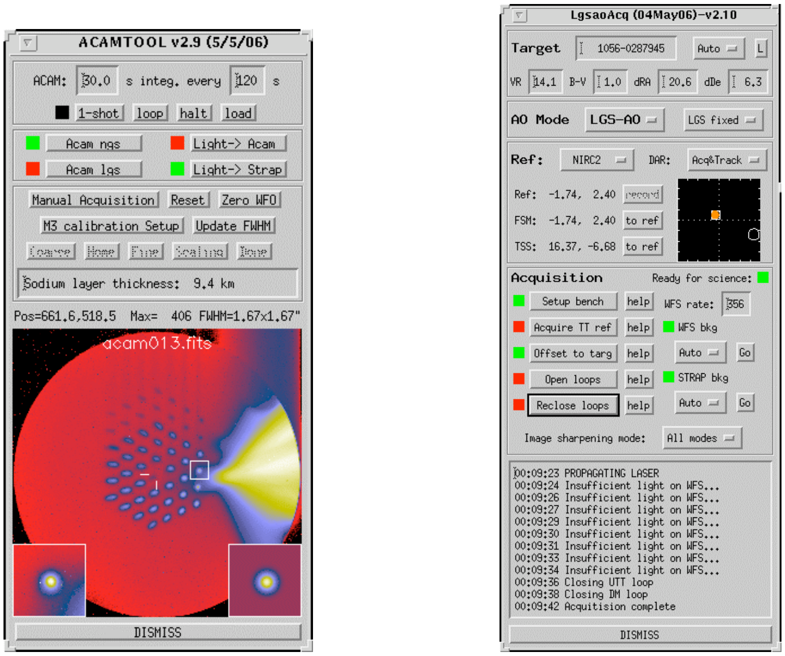
The requirement on human resources for LGS AO run support is documented in Ref. [9]. The direct support for any given LGS AO night includes:

- Two laser technicians to start up the laser in the early afternoon, then monitor the laser and LTCS through the night till dawn. A laser engineer when fine-tuning is required and for troubleshooting (all at the summit).
- A lead spotter and four spotters from later afternoon to dawn (all at the summit).
- A LGS AO operator from late afternoon till dawn (at HQ Waimea).
- A support astronomer from early afternoon till midnight and another from later afternoon till dawn.
- An observing assistant from late afternoon till sunrise.

Starting in August 2006, we will transition to a mode where the LGS AO operator tasks will be performed by the telescope operator from the summit, with the support from our staff astronomer. We anticipate the full implementation of the all-sky camera and integrated aircraft safety system for the beginning of 2008.

3.3 Observing sequence

At the start of the night, we perform a full checkout for the AO system in NGS and LGS mode that includes the laser alignment and Na return characterization. The tool that we use for the laser alignment setup, calibrations and characterization is presented in Figure 7. It allows us to report for each night the values for V-band seeing, laser power, photometry for the Na return at zenith, spot elongation, as well as Na altitude and thickness.



ACAM: 30.0 s integ. every 120 s

Sodium layer thickness: 9.4 km

Pos=661.6,518.5 Max= 406 FWHM=1.67x1.67"

Target 1056-0287945

VR 14.1 B-V 1.0 dRA 20.6 dDe 6.3

Ref: NIRC2 DAR: Acq&Track

Ref: -1.74, 2.40

FSM: -1.74, 2.40

TSS: 16.37, -6.68

Ready for science: 🟩

WFS rate: 356

Image sharpening mode: All modes

```
00:09:23 PROPAGATING LASER
00:09:24 Insufficient light on WFS...
00:09:26 Insufficient light on WFS...
00:09:27 Insufficient light on WFS...
00:09:29 Insufficient light on WFS...
00:09:30 Insufficient light on WFS...
00:09:31 Insufficient light on WFS...
00:09:33 Insufficient light on WFS...
00:09:34 Insufficient light on WFS...
00:09:36 Closing UTT loop
00:09:38 Closing DM loop
00:09:42 Acquitision complete
```

Figure 7: Left: The AO acquisition camera tool allows us to acquire and align the laser, perform the characterization (seeing, return, layer thickness).

The typical observing sequence for each science target includes setting up the bench for the observing mode of choice (NGS or LGS), acquiring the target and the laser, optimizing STRAP and LBWFS, and offset to science field if necessary. These tasks are commanded through the graphical interface shown in Figure 7. Each major step (setup, overall acquisition, offset to target, opening loops) triggers an IDL routine that sequentially sends numerous commands to the various laser and AO sub-systems. The operator may abort these routines at any time. Other specific LGS AO automation routines include opening some of the AO loops, saving the sub-systems parameters and keeping the AO guide star on STRAP when the laser is suddenly shuttered (e.g. telescope collisions); adjusting the LBWFS focus gain, the image sharpening loop gain and the DM offloading parameters during the image sharpening process; checking the sub-systems parameters, checking the WFS background, opening the laser shutters, re-acquiring the laser, performing the LBWFS image sharpening once the laser propagation is permitted, following a closed-shutter event.

Once the AO loops are closed and the science target centered on the science array, the observers have the full control of the observing sequence. They run the observing script as they would in NGS AO mode. Yet, some options are available to dither the laser and keep it fixed on target.

4. LGS AO OBSERVING EFFICIENCY

4.1 LGS AO Image Quality Performance

The main information for the LGS AO performance has been provided above in Section 2 as well as in References [8-19] A new study for the angular anisoplanatism in LGS AO mode is presented in van Dam et al. (2006).[20]

Liu et al. (2006) [1] also summarized the image quality from ~70 long exposure images of brown dwarfs taken during a survey performed at different time of the year with varying observing conditions (seeing, Na return, elevation, AO guide star brightness and distance to the science target). The median Strehl ratio is 0.2 for a median FWHM of 70 milliarcsec.

4.2 Open Shutter Efficiency

The overall efficiency for the 71 nights of LGS AO science operations is given in Ref. [9]. Below, we describe in detail two average nights where we did not experienced any major fault.

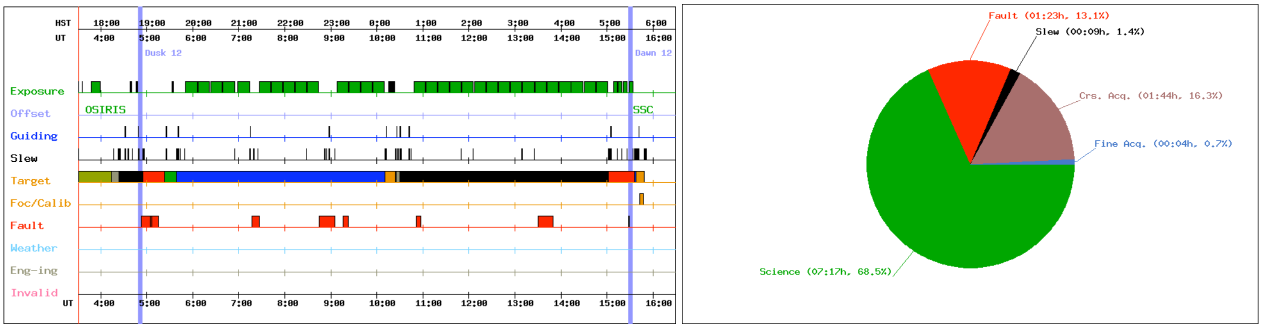


Figure 9: To the left is a summary of activities versus nighttime. The two vertical lines represent the 12° twilight limits. To the right, the pie chart represents the time statistics for the night. See text for more information.

First, we report in Figure 9 on an OSIRIS LGS AO science night where the observing program included only two targets. Though we lost some time at the start of the night due to LGS AO checkout and a laser fault, we spent 68.5% of the night integrating on the science detector. The various faults along the course of the night were attributed respectively to telescope faults, laser faults (power adjustments) and other telescope beam crossing. The main overheads were the LGS AO checkout, the LGS AO acquisition for each target (respectively, 5 and 8 min), and additional dedicated optimization time for each target and AO/DCS handshake while dithering during consecutive exposures.

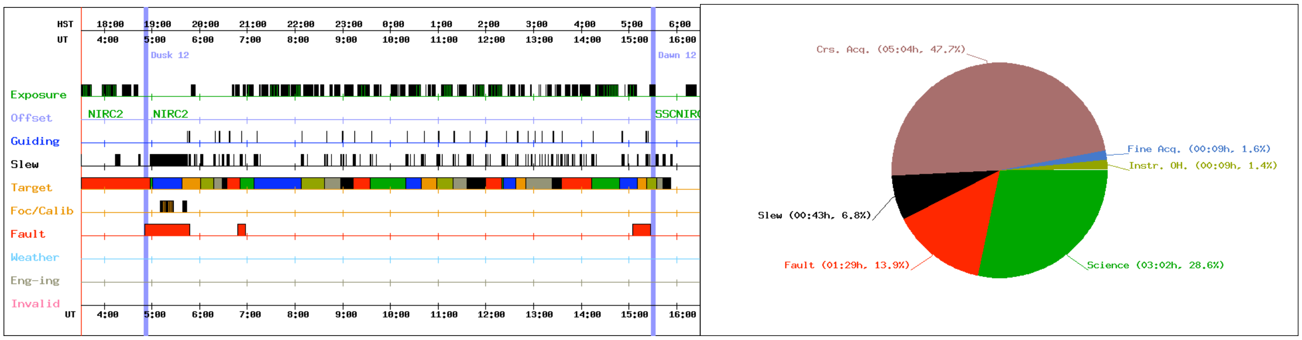


Figure 10: To the left is a summary of activities versus nighttime. The two vertical lines represent the 12° twilight limits. To the right, the pie chart represents the time statistics for the night. See text for more information.

In Figure 10, we present a very different case of observing program: a brown dwarf survey with off-axis faint AO guide star and bright near-IR science targets. During this very successful night, we acquired and observed more than 20 science targets. We experienced a telescope fault at the start of the night, and required some time for tweaking the laser at low elevation. The time fraction for open shutter represents 28.6% of the night, while the time fraction for various overheads is 47.7%. Though the night was scientifically very successful, this illustrates the potential for operation improvements. The science target acquisition including telescope slew, AO guide star identification, LGS AO acquisition, image sharpening, and offset to science target required 7 min on average, [1] which still represents a significant fraction of the time for a survey-mode observing program. The other main overheads are the AO/DCS handshake while dithering during observing scripts and the NIRC2 readout and FITS file write. In addition, a smaller fraction of the overheads was spent on setting up and adjusting the observing parameters for each target and each observing wavelength.

These two examples are to be compared as well with NGS AO operations: the open shutter time fraction for extragalactic programs ranges between 45% and 75%; and the programs that include survey-mode or thermal IR observations have an open shutter efficiency ranging from 30% to 50%.

5. LESSONS LEARNED AND FUTURE PLANS

In parallel to upgrading major components for the wavefront controller in 2007, we have started the design for implementing an LGS AO system for Keck I. This is an opportunity for us to make some changes compared to Keck II. Keck I laser will be a solid state 20 W laser that will make use of a fiber for beam transport. This should solve our problem with reliable laser operations; and the new laser will produce at least a factor two increase in Na return.

The laser launch telescope will be placed behind the Keck I secondary mirror and would result in a factor two reduction of the spot elongation in the WFS subapertures compared to Keck II laser. Because of the new CCD format (CCID56) included in the WFC upgrade to be undertaken in 2007, each subaperture will have 8x8 pixels and the aberrations produced by the combination of spot elongation and quad-cell should be mitigated. As the aberrations will become less of a concern, it would be important to consider a different lenslet geometry for the LBWFS, as mentioned earlier. Optimally, we would like to be able to use the LBWFS and STRAP for stars as faint as R = 20 - 21mag., corresponding to a factor 3 increase with respect to the current system. It would be also particularly important to improve the focus bandwidth on the AO guide star, which is now limited by the LBWFS performance. For easier operations, the LBWFS camera and loop control should be managed differently than the current sub-system and included as well in the AO/DCS handshake during telescope dither.

A critical aspect of LGS AO operations at Keck is the ability to control the laser and all AO sub-systems remotely for the purpose of operations, calibrations, alignment, troubleshooting, and staff technical and operations training (using VNC and other industry-based technology rather than duplicating remote tools).

In parallel, there are current operational issues for any LGS AO system from the summit of Mauna Kea that need to become more efficient, more reliable and less costly: the wide field camera for aircraft detection should be implemented, fully tested and approved by the FAA, and would relieve the laser safety spotters from working at the harsh Mauna Kea summit conditions; we would like to work with the US space command and re-evaluate the agreement to submit the entire target list and any other possible propagation directions 72 hours in advance for approval. We have sent more than 100 requests since 2001 for target lists of ~100 each, corresponding to a total of ~10,000 directions of propagation and we have only experienced closures for one night. It could well be that the laser power does not represent a danger for satellite when propagated in the fixed direction of stars with the current beam divergence. We could envision a scenario where we would notify the US space command of each laser night and accept to shutter when notified of specific space events; the present Mauna Kea laser traffic control operations are going very well, yet we would need to fully understand the possible impact of multiple scattering of laser light for other telescopes with respect to atmospheric conditions; and it may be particularly important to better understand the constraints for LGS AO science operations for ELTs by monitoring the Na layer characteristics and the atmospheric transparency.

As marginal observing conditions may affect considerably the laser and AO performance, it is important to have the ability to switch to other observing programs. At Keck II, the observers that were allocated the LGS AO night may switch to NGS AO or NIRSPEC, depending on their science program. Yet the observatory has not fully considered a flexible allocation of telescope time depending on weather conditions and instrument readiness.

Our community has been very excited by the LGS AO science operations results as it enables science in a new parameter space, and they are asking fore more observing nights. While we hope to address some of the issues mentioned above, the emphasis at Keck remains on supporting the 70 nights of LGS AO operations per semester in 2006 and 2007.

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REFERENCES

1. M. C. Liu, "Astronomical Science with Laser Guide Star Adaptive Optics: A Brief Historical Review, a Snapshot of Current Performance, and a Bright Outlook for the Future", *SPIE Proc.*, 6272-16, (2006).
2. C. Max et al., "Image improvement from a sodium-layer laser guide star adaptive optics system", Science, 277, 1649, (1997).
3. D. Gavel et al., "Recent science and engineering results with the laser guide star adaptive optic system at Lick Observatory", *SPIE Proc*, 4839-354, (2003).
4. P. L. Wizinowich et al., "First Light Adaptive Optics Images from the Keck II Telescope: A New Era of High Angular Resolution Imagery", PASP 112, 315 (2000).
5. M. A. van Dam, D. Le Mignant and B. A. Macintosh, "Performance of the Keck Observatory adaptive-optics system", Applied Optics 43, 29, (2004).
6. Friedman, H. W., et al. "Design and performance of a laser guide star system for the Keck II telescope, *SPIE Proc.*, 3353-260, (1998).
7. P.L. Wizinowich et al., "The W.M. Keck Laser Guide Star Adaptive Optics System: Overview", PASP 118, 297-309 (2006).
8. M.A. van Dam et al., "The W.M. Keck Laser Guide Star Adaptive Optics System: Performance Characterization", PASP 118, 310-318 (2006).
9. D. Le Mignant et al., "LGS AO operations at Keck Observatory:", *SPIE Proc.*, 6270-12, (2006).
10. Keck Observatory Instrument Webpage, http://www2.keck.hawaii.edu/inst/ (2006).
11. Keck Observatory AO bibliography Webpage: http//www2.keck.hawaii.edu/library/biblios/aokeck.php (2006).
12. D. Summers, et. al, "Focus and Pointing Adjustments necessary for laser guide star adaptive optics at the W. M. Keck Observatory", *SPIE Proc.* 5490-121, (2004).
13. D. Le Mignant et al., "FAA Notification of Our Proposal to Conduct Outdoor Laser Operations", Keck AO note #363, (2005).
14. D. Summers, et. al., "Second Generation Laser Traffic Control; Algorithm Changes Supporting Mauna Kea, La Palma, and Future Multi-Telescope / Laser sites", *SPIE Proc.* 6272-143, (2006).
15. D.P. Looze, M.A. van Dam and E.M. Johansson, "Comparison of tip-tilt controllers for laser guide star adaptive optics," *SPIE Proc.* 6272-159 (2006).
16. J.P. Véran G. Herriot, "Centroid gain compensation in Shack Hartmann adaptive optics systems with natural or laser guide star," J. Opt. Soc. Am. A 17, 1430-1429 (2000).
17. M. A. van Dam, A. H. Bouchez, D. Le Mignant and P. L. Wizinowich, "Quasi-static aberrations induced by laser guide stars in adaptive optics," *to appear in* Optics Express (2006).
18. A. H. Bouchez, D. Le Mignant, M. A. van Dam and P. J. Stomski, "Measured field curvature at the tip-tilt sensor stage focal plane," KAON #314 (2005)
19. Keck Observatory LGS AO webpage, http://www2.keck.hawaii.edu/optics/lgsao/, (2006).
20. M.A. van Dam et al, "Angular anisoplanatism in laser guide star adaptive optics," *SPIE Proc*, 6272-106, (2006)