LGS AO operations at the W. M. Keck Observatory

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ABSTRACT

Laser Guide Star Adaptive Optics (LGS AO) has been offered to Keck II visiting astronomers since November 2004. From the few nights of shared-risk science offered at that time, the LGS AO operation effort has grown to supporting over fifty nights of LGS AO per semester. In this paper we describe the new technology required to support LGS AO, give an overview of the operational model, report observing efficiency and discuss the support load required to operate LGS AO. We conclude the paper by sharing lessons learned and the challenges yet to be faced.

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

1. INTRODUCTION

Adaptive Optics (AO) equipped instruments have been used for routine science operations at different observatories around the world since the 1990s. A wealth of science papers (see e.g. Close (2003) [1] and elsewhere) has been produced. Yet, the use of AO instruments has been mostly restricted to planetary and Galactic observations due to the requirement for a bright natural guide star nearby ($R < 14$-mag at a distance of less than 30" in most cases, equivalent to less than one percent of sky coverage) to correct the optical distortions introduced by atmospheric turbulence. The use of a Laser Guide Star (LGS) as a reference target for the AO correction dramatically increases the percentage of observable objects at the diffraction limit of the telescope (more than 50% of sky coverage). While this technique is still in its infancy, it presages a bright era for LGS AO science (e.g. see Liu (2006) [2] for a review of LGS AO papers since 1995).

The W. M. Keck Telescopes have been operating two AO systems in NGS mode for routine science operations with near infrared (NIR) imaging, spectroscopy and interferometry since 2001. LGS AO instruments were offered to our 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 parallel, we began transitioning the LGS AO operations to the observing support group. This group is now supporting 50 nights for 2006A, ramping up to 70 nights in 2007A. 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) [3]. The performance characterization is described in van Dam et al. (2006) [4]. The Keck II LGS AO has produced 13 refereed science papers as of May 2006 in a wide variety of subject areas.

In Section 1, we give some background information on the Keck Observatory operations with particular attention to the NGS AO operations. The different sub-systems required for the Keck LGS AO operations are introduced in Section 2. Section 3 provides a typical time-line for the operations and support activities for an LGS AO observing night, as well as more detailed information on the acquisition and observing sequence. Of particular importance for LGS AO operations is the human element, described in Section 4. The performance and efficiency of the systems is presented in Section 5. We conclude the paper by discussing current limitations and revealing our future operations plans.

1.1 Keck Observatory Operation Support Paradigm

Science operations at Keck Observatory are performed in "classic" mode: astronomers fly 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. Observing from the mainland has also been demonstrated and continues to increase in popularity. This can take the form of full control from the mainland site, or simply eavesdropping via video and computer links while a colleague in Waimea controls the instrument.

Observers are supported by a Support Astronomer (SA) who provides information and guidance on using the instrument and on observing techniques; an Observing Assistant (OA) who operates the telescope and provides observing advice; and a number of LGS AO support personnel. The latter include a second Observing Assistant operating the LGS AO optimizing software, a laser operations technician, and a laser traffic control monitor. Currently all of these support functions are staffed the entire night, unlike non-LGS AO observing, which is supported by an SA for the first 2–4 hours of the night and an OA the entire night.

There are a number of Time Allocation Committees (TACs) that assign time on the telescopes: Caltech, Univ. of California, Univ. of Hawaii, NASA, NOAO (on behalf of the TSIP program) and Gemini. They have requested more than 50 nights per semester, the maximum that Keck Observatory personnel can currently support.

1.2 The Adaptive Optics Systems and their NGS AO Operations

The Natural Guide Star AO systems that are installed on each of the left Nasmyth platforms of the Keck telescopes are nearly identical in their hardware and software configurations [5]. The two systems underwent a period of characterization and improvements after their integration [6]. The list of instruments fed by the Keck II AO system includes KCAM (decommissioned in 2001), NIRSPEC-AO, NIRC2 and the newly integrated OSIRIS [7]. Both Keck I & II AO feed the interferometer dual star module [7] and the fiber-based Ohana interferometer [8]. In addition, Keck I has been very recently equipped with an engineering NIR camera, SHARC.

Most real-time software has been developed in EPICS. The user-level operations software was built in IDL, while some GUI tools were developed in Java. We have also developed a number of automated sequences for

- Calibrations performed either for preventive maintenance on the system or for observing
- Night time setup and end-of-night scripts
- Acquisition and optimization sequence on a target, based on a well-calibrated look-up table for the AO parameters
- System health monitoring, fault detection and recovery

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 Observing Assistants who operate the telescope from the summit for any science night are the designated AO operator. The automated setup takes less than 2 min once the telescope is pointed at the target with the target centered on the WFS.

The Keck AO systems performance has been described in [6]. 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.

As of May 2006, 85 astronomy papers based on Keck NGS AO instruments have been published in refereed astronomical journals [9]: 76 with 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 uneven distribution.

2. SUB-SYSTEMS FOR LGS AO OBSERVING

In the Keck II LGS AO design, the 589.2 nm photons emitted by the 15W dye laser excite sodium atoms located in the upper layer of the mesosphere at ~90 km above sea-level. The Na D2 light emitted from the atoms in this thin layer and within a cylinder of ~50 cm base and 5 - 15km length will appear as a V~9.5-mag spot for the AO system. Yet LGS AO systems still require an AO guide star: as the light from the laser creates a spot at a finite yet varying altitude, the tip-tilt and focus information cannot be retrieved from the Na spot. In addition to observing the Na spot in the direction of the science target, LGS AO requires observing a natural AO guide star that can be as faint as R=19^{-}mag and separated by ~ 70” or less. Furthermore, the location of the laser launch telescope on one side of the telescope results in an elongated Na spot that produces semi-static aberrations on the WFS. These need to be dynamically calibrated by simultaneously observing the faint AO guide star.

In this section, we briefly review the various sub-systems required for LGS AO observing from the laser itself to the policies and tools that regulate the photon traffic in the Mauna Kea skies.

2.1 The Keck Laser Guide Star

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 [3-10]. 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 an equivalent V=9-10-mag star (or ~175 to 70 photons s^{-1} cm^{-2}), at zenith, depending on sodium density.

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. The UTT software has a built in capability to overlay a high frequency dither pattern on UTT during operations, allowing for power spectrum analysis and calibration functions when desired. UTT offloading for maintenance of fast steering mirror dynamic range is accomplished as one of several slow pointing mirror functions.

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 allows on-axis and off-axis LGS placement in the field to address a variety of possible observing conditions and modes. Summers et al. (2004) [11] provides further information on the Keck LGS pointing model.

2.2 The AO system in LGS AO mode

The design and implementation for AO system changes between NGS AO and LGS AO are detailed elsewhere [3],[4]. Figure 1 below shows a schematic representation of the AO systems for NGS AO (left) and LGS AO (right).

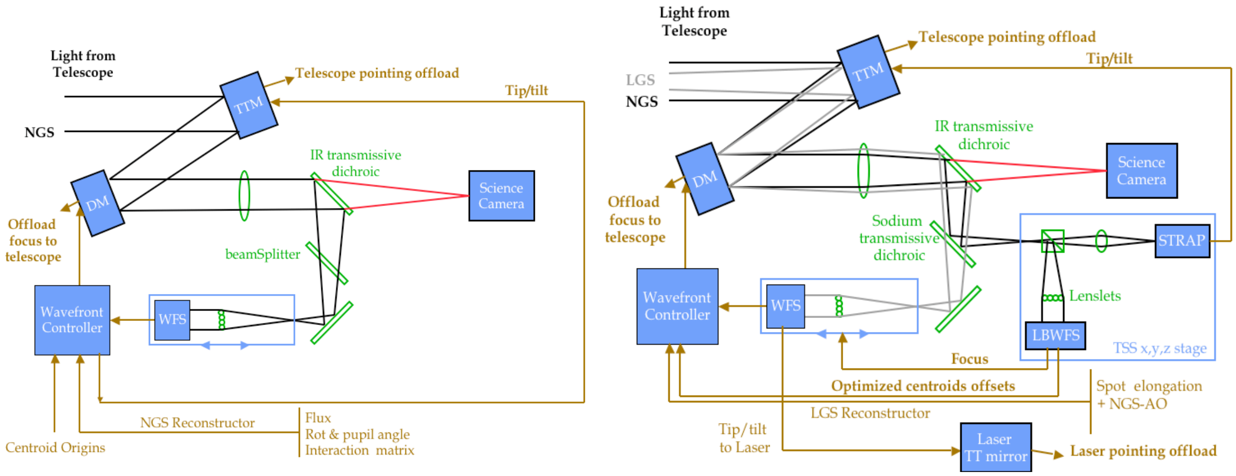

Figure 1: Schematics of the AO systems in NGS AO and LGS AO configuration. The LGS AO main additions are the LBWFS, STRAP, TSS and UTT (see text)

Here we briefly list the main additions to the NGS AO system:

- A dedicated tip-tilt sensor (a STRAP unit), for the AO guide star, suitable for targets as faint as R=19mag.
- A low bandwidth wavefront sensor (LBWFS), used on the AO guide star provides the critical measurement for the focus correction. It also provides an independent way to assess image quality and correct for the semi-static LGS-induced aberrations.
- STRAP and the LBWFS are mounted on an x, y, z Tip-tilt Sensor stage. This stage has to reposition itself dynamically in z as a function of off-axis distance to correct for field curvature. It also needs the ability to track in x, y in the image plane with 4 milliarcsec accuracy to compensate for differential atmospheric refraction.
- The real-time control for the wavefront controller (WFC) includes the Laser tip-tilt correction (or Uplink TT). The correction to be applied is derived from the average centroids of the fast WFS. The negative averaged UTT mirror position is then offloaded to the M3 laser pointing mirror. The real time WFC also includes the ability to switch from NGS AO (fast WFS only) mode to LGS AO (STRAP for TT, fast WFS for DM and UTT)
- The Supervisory Control system was modified to include a focus manager [11] and the interface to the LBWFS.
- The AO reconstructor includes a model for laser spot elongation versus elevation, altitude and pupil parallactic angle that allow us to estimate the x and y gain for each subaperture.

The IDL high-level operation software includes new modules: the *LGS AO acquisition* module that handles NGS AO/LGS AO system setup, AO guide star acquisition on STRAP, propagation and acquisition of the laser. Another tool is used to align the laser with the optical axis of the telescope, calibrate the pointing M3 mirror motions and perform routine characterization (spot size and elongation, Na light return, Na layer thickness).

2.3 Science Instruments

The instruments that can be used for LGS AO are the same as those for NGS AO [7]. NIRC2 is a near-IR imager with three camera plate scales, coronagraphic spots, and a long-slit grism mode for spectroscopy. OSIRIS is a new near-IR integral field unit (IFU) spectrograph. The NIRSPEC near-IR spectrograph, with high-dispersion echelle and low-dispersion modes, is normally used without AO, but can be moved behind the AO bench and fed with scale-changing optics to provide AO-corrected images. NIRSPEC is generally used behind AO in echelle mode, since the low-dispersion capabilities are mostly duplicated by the other two instruments.

LGS AO observing requires the following changes for the instrument operation scripts:

- 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.

2.4 Laser Safety for Propagation

The Keck II Laser System is a Class IV laser which requires an array of safety features to ensure safe operations. These safety features include both engineering and procedural components to protect personnel, equipment and the general public as a result of sky propagation. Per ANSI standard Z136.1 (Safe Use of Lasers) and Z136.6 (Safe Use of Laser Outdoors), a Laser Safety Officer is charged with overseeing the safety aspects of the laser system.

The Keck II Laser is controlled by a Modicon Programmable Logic Controller (PLC) with extensive logic, interlocking the subsystems within the laser. These interlocks assure proper control of the laser, allowing only certain functions depending on the current status and health of the laser. The PLC constantly monitors the system status and health and will automatically put the laser into a safe state if necessary. The user is alerted to a change of status or problem through an alarm handling GUI.

2.5 Aircraft safety, satellite avoidance & clearance procedure

In addition to providing safety at the laser and facility level, there are external regulations that must be met in order to propagate a laser onto the sky. Keck interfaces with both the Federal Aviation Administration (FAA) and the Laser Clearinghouse of the US Space Command at Cheyenne Mountain for nighttime propagation. For annual approval from the FAA, personnel must closely monitor the nighttime sky to prevent accidental propagation in the direction of aircraft [12]. Keck procedures provide a two-tier system. The first tier is the use of 2 spotters on opposite sides of the observatory to monitor the nighttime sky during propagation; this tier is required by the FAA. Due to its isolated location and Mauna Kea's elevation, the laser has only been shuttered twice due to aircraft. The FAA issues a standing NOTAM (notice to airmen) for every night of laser propagation. The second tier is an infrared camera boresighted to the laser for detection of aircraft. This camera is tied into the PLC system and will automatically shutter the laser if an aircraft is detected. Our longer-term goals are to implement a wide field (all-sky) camera for aircraft detection, and possibly the use of a Hawaii-wide radar feed to alleviate the need for spotters.

For each observing night, the LGS AO operation team provides the list of targets to the US Space Control Center for approval. The Keck laser dither radius is 3 arcmin. The list includes all pointing coordinates including science targets, the Keck zenith coordinates, and a subset of V~10mag. star positions (for possible troubleshooting through the night). This ensures that laser illumination does not damage any satellites. The list is sent 72 hours before the observing program starts and the clearinghouse will fax back and email on the afternoon of the observing a list of blackout periods when the laser needs to be shuttered.

These blackout periods are rare at Keck but there have been occasions where the clearinghouse has called requesting an end to propagation immediately due to a "space event."

We also have a procedure in place with the Laser Clearinghouse for targets of opportunity that we use on very rare occasions, to request approval with very short notice (~12 - 24 hours).

2.6 Laser Traffic Control

A Laser Traffic Control System (LTCS) has been developed for use as a laser beam avoidance safety system for LGS operations. The LTCS calculates all beam crossing geometries between laser-equipped telescopes, and participating non-laser equipped telescopes. The current system models a configurable cylindrical Rayleigh laser column, the LGS, and the fields of view of non-laser equipped telescopes. Using static configuration data (position, aperture sizes, etc.), along with dynamic telescope state and pointing data reported via URL software at each participating observatory, the software models the geometric conditions of a site's lasers and telescopes. The Mauna Kea LTCS maintains a three-hour sidereal motion model used for prediction of beam collisions. The system allows simulated previews and operator queries to assist operators plan observations. GUIs are provided to monitor URL input data, system states, output data, and system health. Additional information regarding LTCS core system software is provided elsewhere [13].

In addition to LTCS core system software, observatory specific ancillary software is required for effective operations. Foremost among this software is the reporting of telescope state and pointing position URL data. Keck's implementation of URL reporting software is handled by a single program with access to both Keck I and II Telescope Control Systems (TCS). A variety of automation tools has been implemented to relieve operators from having to set system parameters manually. Laser emission sensitivity has been automated via monitoring of telescope and guider tracking state. Laser state reporting has been automated via monitoring of laser permissive states, laser operational state, and a shutter indicator. Field of view reporting has been automated via monitoring of the selected instrument and a FOV lookup table.

Pointing positions are reported from each TCS, with translations from Az/El frame to FK5 apparent RA/Dec when required to meet the URL specification.

The remaining ancillary software performs automation of minor functions such as startup and shutdown of different software needed for LGS and/or non-LGS nights based upon required email notifications from lasing facilities, and integration of LTCS system URL and health indicators into the laser operator alarming system. This allows the laser operator to receive an audible warning and latched indicator if the reporting status of a participating observatory or the system health requires attention.

2.7 Policies and Procedures

The restrictions on laser propagation and procedures for LGS AO operations are driven by three factors: safety of personnel and aircraft, preventing light contamination at other observatories and optimizing efficiency and coordination among the observatories or within the operation team. Here are some key-examples:

- Laser safety observers (also called laser spotters): requirements & guidelines on recruitment, training, high altitude and harsh work conditions, and data reporting.
- Weather cancellation policy: tools and guidelines for laser Rayleigh scatter monitoring; guidelines from briefly canceling the propagation to canceling LGS observing for the entire night; guidelines for backup programs and instruments.
- Operations: procedures for laser and AO preparations, setup and calibrations; procedures for laser alignment and LGS AO system characterization; procedures for target acquisition and guidelines for the observers.
- The Mauna Kea Laser Guide Star Technical Working Group (MKLGSTWG), composed of members of observatories, recommends policies and guidance for laser operations on Mauna Kea [14]. Our LGS AO operations team supports MKLGSTWG meetings and activities. Included are coordination of LTCS development improvements, supporting observatory tests and studies, participating in policy discussions and issues resolutions, and planning for future LGS operations enhancements (such as for all-sky camera, mosaic radar, etc.).

Most if not all of these procedures are available from our LGS AO public web pages [15]. They are regularly updated as our operations mature.

3. TIME-LINE SEQUENCE FOR AN LGS AO OBSERVING PROGRAM

The time-line sequence starts with observers writing and submitting proposal for LGS AO science. A non-LGS back-up program needs to be included in each proposal. The LGS AO operations team is responsible for pre-run preparation of the instruments and laser, 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. A pre-run preparation meeting with observers leads to a detailed observing program. Finally, some specific issues (science calibrations, observing scripts or operation tools) may require more investigation and further actions. The Keck II LGS AO website provides support information for LGS AO observers [15].

3.1 Pre-run preparation

Preparation for a Keck laser run begins with a teleconference held approximately one week prior to the run. During this teleconference, organized by the support astronomer, and attended by the observers and appropriate Keck staff, we review the science program, provide an update of the laser and instrument status, and work through the early object list requirement imposed by the Laser Clearinghouse. We also use this meeting to familiarize the observers with the planning procedure and tools, and to be sure that the observer will arrive prepared with a backup program should high cirrus or technical problems prevent use of the laser. We require that the target list be submitted three days prior to their first night, so that we can submit a target request to US Space Command. A format conversion is required which, at this writing, is only semi-automated. A web page is available for submitting the list. Also available, to assist the observing team with their target list preparation are several stand alone IDL routines. A web page is used for the final check and submission once the complete list has been compiled. Finally, a web-based acquisition-planning tool allows the observers to plan their observing sequences, including offsetting, and the shape and size of their dither patterns. An effort is underway to integrate all of the above functionality into a single, web-based, tool (see the LGS AO web page for the latest release).

In parallel, the laser is prepared for the run and operated prior to the run (without propagation to sky) for general checkup. We also coordinate with the FAA for issuing the NOTAM. On the first day of the run, the AO system is calibrated for NGS and LGS and for each instrument to be used during the run.

3.2 An LGS AO observing day and night

- At 2:00 p.m. on an LGS AO observing night, the visiting observers meet with an SA to review the observing program, instrument readiness, observing scripts and commands, etc.
- At 4:00 p.m., the SA for the night (usually different than the afternoon SA) runs a short meeting involving the visiting observers, laser engineer and technicians, LGS AO operator, and other support staff. The visiting astronomers briefly describe their science program. The laser engineer or technician reports on the laser status, and the SA describes the timeline for the night's operation.
- At sunset, the OA opens the dome and slews the telescope to the first target for system checkout. The LGS AO operator and SA test the system performance on a bright (V=10-mag) star in full NGS AO mode and in NGS-STRAP mode. The staff optimizes STRAP parameters on the bright star, then later use these parameters as an optimization starting point for science targets.
- Once finished, the OA slews the telescope to the zenith to begin the laser checkout. Keck is only allowed to propagate the laser between 12° twilight, so the laser checkout takes some part of what is traditionally regarded as "dark time". Once propagating at zenith, the support staff calibrate the optics that steer the return from the laser guide star onto the wavefront sensor and determine the laser guide star spot size and sodium layer altitude and thickness. The telescope is finally slewed to the bright star used for the NGS AO checkout to acquire the star and the laser and to perform full image sharpening and characterize the image quality in LGS AO mode for a bright AO guide star. Full checkout of the LGS AO system requires about 25 minutes after 12° twilight.
- The science program begins and continues until 12° dawn twilight. The LGS AO acquisition overhead is summarized in the next section. The observing program may not require the laser; it is possible to switch between NGS AO and LGS AO at the observer's convenience.
- In case of marginal observing conditions or technical difficulties, the observers have the choice to switch to their backup observing programs.

3.3 LGS AO observing sequence for a target

The LGS AO observing sequence is described in detail in [15]. We give here a summary of the main steps:

- To identify the next object to acquire, the observer provides the summit OA and the LGS AO operator both the target science name and the NGS TT reference to be used. While the observer prepares the finding chart for the next target and checks basic observing parameters (e.g. rotator mode and angle), the telescope slews to the science field and the LGS acquisition tool loads the target information (AO guide star: RA, Dec, epoch, R mag. and B - R color. Science target: RA, Dec, epoch). The LGS AO acquisition tool configures the AO system for target acquisition; it also uses the AO guide star brightness and a lookup table to setup the individual sub-systems (STRAP, LBWFS, WFC) with appropriate parameters (integration time, gains, etc).
- Once the telescope is tracking the field, the summit OA requests AO guide star identification from the observer and moves the telescope to the requested pointing reference (e.g. science instrument). The OA immediately requests permission to propagate from the laser spotters. Once the summit OA has granted permission to propagate, a two-minute window to propagate the laser begins. If the laser is not propagated within this two-minute window, the OA must set permission back to deny.
- Meanwhile, the LGS AO operator triggers the LGS AO acquisition script that acquires the guide star on the tip-tilt sensor, checks measured flux vs. that expected and adjusts STRAP and LBWFS parameters if necessary. Once laser propagation permission is granted, the LGS AO acquisition tool closes DM and UTT loops if there is sufficient Na light on the WFS; performs a quick check on the altitude of the Na layer; triggers the image sharpening on the LBWFS; and performs an optimization of STRAP.
- As soon as the LGS AO acquisition is complete, the LGS AO operator updates the observer on the progress on

image sharpening and lets him/her know whether test exposures can be recorded on-axis and/or whether the offset to science target has been performed and/or "the target is ready for observation." The typical overhead associated with the acquisition sequence is 5 min or less for stars brighter than R=16-mag, ~5 - 10 min for star brighter than R=17.5-mag and up to 10 - 12 min for stars as faint as R=19-mag. [2-15]

- The observer may request a switch to NGS AO mode and observe a photometric or astrometric standard at any time during the night. Switching between NGS AO and LGS AO takes about one minute and does not add any overhead to the acquisition sequence, as this is done during telescope slew.

4. LGS AO OPERATIONS: THE HUMAN ELEMENT

The Keck Observatory management has opted to dedicate more resources in 2005-2006 (mostly FY2006) to transition LGS AO operations from the LGS AO engineering group to the observing support group. As of May 2006, LGS AO operations require a significant fraction of time from the following resources: one AO scientist (AOS), two support astronomers (SA$_{1, 2}$), one laser optics engineer (OE), two laser optics technicians (OT), one laser assistant, (LA) one software engineer (SE), and one LGS AO operator (LO). In addition, the observatory is supporting other tasks related to LGS AO such as LGS AO operations training for SAs and observing assistants, laser and AO maintenance including preventive maintenance, LTCS upgrades, new pre-observing tools, increased support for telescope operation tools, etc. The four laser spotters and the lead spotters are hired through a temporary staffing agency.

Table 1 presents an estimate of the major HR allocations for direct support of LGS AO operations. The resources for the telescope operations are not included in the table. We assume an observing run is 5 nights on average and our accounting is *in hours and per unit of LGS AO observing night.*

Effort description	Total hours per staff per unit of observing night
Coordination and supervision	2.0 AOS
Pre-run preps for laser / AO	
Laser readiness	3.0 OE + 3.0 OT
Spotters and laser scheduling & logistics	2.5 LA
AO readiness and calibrations	0.5 AOS
Pre-run preps with observers	
Pre-observing meetings	1.0 SA$_1$ + 0.5 SA$_2$ + 0.5 LA
Target list support and processing & FAA NOTAM	1.0 SA$_2$ + 0.5 LA
Pre-observing night preps	
Laser startup and tune-up	6.0 OE + 6.0 OT + 0.5 SE
Introducing the observer to the instrument	4.0 SA$_2$
Observing night support	
Laser and LTCS operator	6.0 OT + 11.0 LA
LGS AO operator	12.0 LO
Science support	12.0 SA$_1$ + 5.0 SA$_2$
Laser lead spotter (and driver)	12.0 LdS
Laser spotters (x4)	48.0 LS
On-call support	1.0 SE + 2.0 AOS + 2 .0 OE
Post-observing support	
Laser safety reports and spotters follow-up	0.5 LA
Metrics	0.5 SA$_2$
Science data follow-up	0.5 SA$_1$
Totals:	9.0 OE + 15.0 OT + 15.0 LA + 48.0 LS + 12.0 LdS 14.0 SA$_1$ + 11.0 SA$_2$ + 4.5 AOS + 1.5 SE

Table 1: Resource budget for one night of LGS AO observing. Note included: AO, Laser and instrument maintenance, telescope operations, visiting observers & occasional breakdown support.

As we are in our first year of operations and also operating a new and complex science instrument (OSIRIS), there are a lot of LGS AO training, coordination and peripheral activities happening. In parallel, we are working on reducing the resources needed for LGS AO operations by integrating more automated sub-systems such as an all-sky camera and optimizing LGS AO operator tools to merge this role with the OA roles.

5. LGS AO PERFORMANCE METRICS

5.1 Overall LGS AO Efficiency

Figure 2 is a pie chart of LGS AO time accounting for all available dark time of science nights starting from 1 Nov 2004.

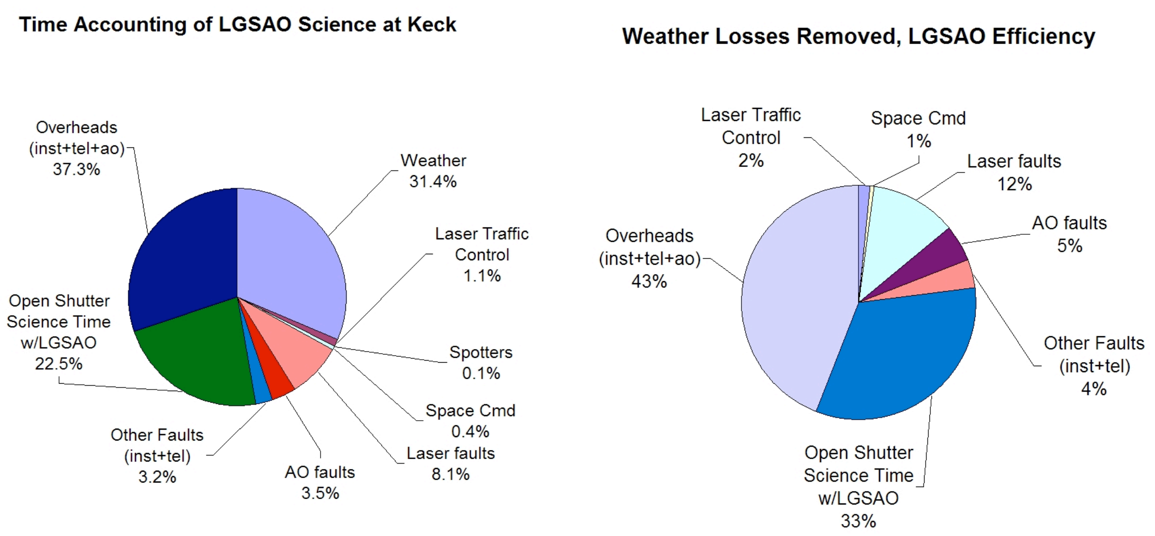

Figure 2: Time accounting of LGS AO operations. The chart shows the amount of time spent for science integrations with the loops closed on the laser. Note that some of the time accounted for laser faults and weather may have been spent doing non-LGS AO science.

Open shutter science time:

The time spent integrating on source with the loops closed on the laser, full up LGS AO mode, is shown in green and accounts for 22.5% of the total. Note that weather loss and laser fault categories, totaling 40%, include any time the laser was prevented from propagating which may include science time with NGS AO backup programs. Thus, Figure 2 is specific to LGS AO science efficiency. For comparison, we typically experience from 70% to 30% open shutter efficiency during NGS AO observing, depending on the type of observing.

Weather:

Bad weather (any type that would prevent propagating the laser) accounts for about a third of direct lost time. In the last six months, which included some bad winter storms, the time lost to weather accounts for 50% of the total observing time. A change in our operations from classic mode to a more flexible mode such as queue scheduling is yet to be considered in details.

Science Instruments / AO and Telescope Overheads:

These are the major contributors to AO inefficiency: up to 43% of the total time, once the weather losses are removed. The NGS AO overhead continues to exist with LGS AO operations and other overheads are added, which may be unavoidable in such a complicated system.

The different types of overheads that we can identify are the following:

- LGS AO checkout: setup, alignment and performance monitoring takes 30 min at the start of each night.

- Telescope slew and coarse acquisition to center the AO guide star on STRAP: this step takes 5 to 10min on average depending on the slew, the brightness of the AO guide star, the response of the observer to identify the AO guide star and the possible requirement on correcting the telescope coordinates.
- Setup & acquisition time: the typical setup and acquisition time for LGS AO on a science target has been reduced to 5 to 10 minutes on most objects, compared to 15 to 20 minutes early in 2005A. Note that our LGS AO acquisition efficiency has allowed us to acquire and observe more than 20 targets per night during brown dwarf survey-type observing campaign. [2-16]
- LGS AO optimization: laser return and observing conditions may vary, requiring an adjustment of the WFS speed, fine-tuning of STRAP or the LBWFS. This may account for ~ 2 min for every hour spent on an object.
- Dithering/offsetting the telescope: one of the largest observing inefficiencies is associated with the technique for removing systematics in the data that involves moving the telescope periodically to allow the science object and sky to register in different parts of the detector, referred to as dithering. Dithering forces the telescope, instrument, AO loops control, natural guide star pointing, and laser guide star pointing to all be synchronized through system handshaking. Most of the handshakes occur serially leading to a period of up to 30 sec overhead per dither. In NGS AO mode, this overhead has been reduced to ~ 10 sec. We get additional overhead with the tip-tilt sensor in tracking mode and we hope to mitigate this problem.
- Instrument inefficiency: Infrared imaging, especially at longer wavelengths, requires many dithers and short integrations, which induces system inefficiencies (NIRC2 total overhead time is typically 10 sec per science frame). Spectroscopic observations typically use much longer integrations and far fewer dithers. Thus the observing program is the primary driver in the current differences between low and high efficiency nights. For example, the LGS AO nights which use the newly commissioned integral field spectrograph OSIRIS are often as high as 70% science but L band imaging with NIRC2 can be as low as 20%. See Le Mignant et al. (2006) [16] for more information on observing efficiency as a function of the observing program.
- Setup and observing strategy overhead: the observing often requires checking image quality and adjusting setup (integration time, coadds and readout mode, location on the array, etc), which leads to some additional overhead. Note that the classical observing mode in place at Keck may lead to a situation where the observer strategy is to focus on getting the best possible data for a high priority target, which could require waiting for better observing conditions, increasing the numbers of dithers or reads per frame; all these possibly resulting in lower open shutter time.

LTCS, space events and aircrafts:
An inspection of the graph highlights that the relative time lost to aircraft safety, laser traffic, and space events are ~ 3 % of the weather removed, which is very negligible. The new LTCS includes a preview mode that allows us to check for possible collision with other telescopes before slewing to a target.

System faults:
We have been experiencing various types of system faults:

- Laser: the laser reliability is a major weakness in our operations: it requires a lot of maintenance and constant monitoring and tuning during operations. Some of these laser adjustments require to halt propagation. The laser faults account for 12% of the weather removed time. Included in these laser faults are a few nights we lost in 2005A and B due to dye contamination and manpower shortage.
- Opto-mechanical stages for AO and laser: we lost some time (5%) due to faults that we experienced during LGS AO, and not during NGS AO: TSS and M3 faults as well as general failure of the optics bench crate. We have started to change some of our pre-run procedures to mitigate the crate faults. We are restraining the stage motions to prevent the faults and added scripts in the operation software for prevention of faults as well as automated detection and recovery of faults.
- Telescope and other faults account for 4% of weather removed time and are no different that any observing night at Keck Observatory.

5.2 LGS AO Image Quality

It is important to measure and optimize the image quality both from the images and from AO telemetry data. There is a Strehl meter that calculates the Strehl ratio of NIRC2 images in real time. This is used extensively during engineering nights and at the beginning of each science night to quantify the image quality and resolve any performance issues. Typical K-band Strehl ratios near zenith in good seeing range from 30-40% for bright tip-tilt stars to 10% for 19-mag tip-tilt stars, as plotted in Figure 3, along with the corresponding FWHM. For a measurement sample of Keck LGS AO off-axis PSF from science observations, see Liu (2006) [2].

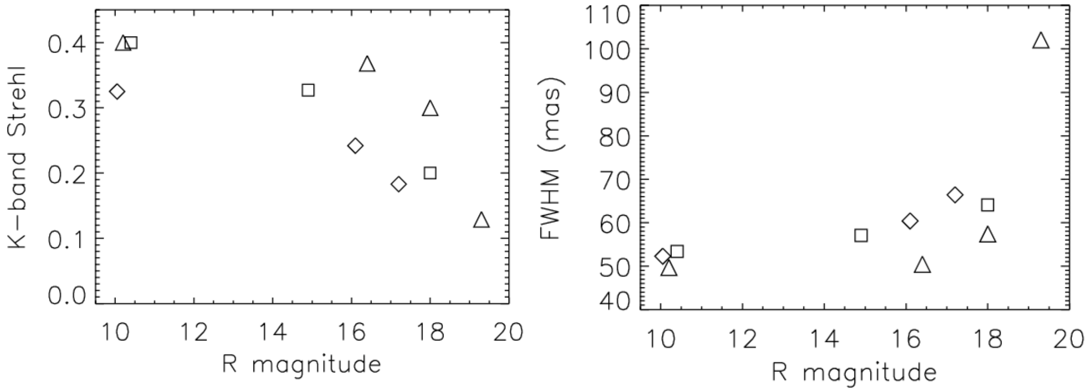

Figure 3: K-band Strehl ratio and FWHM as a function of tip-tilt guide star magnitude

Diagnostic tools measure and optimize the error terms of each of the control loops [4]. An IDL user interface is used to take short bursts of full frame telemetry data. This data is analyzed to compute the bandwidth and measurement noise errors [6]. From this data, the turbulence power spectrum and noise floor are estimated and used to calculate the optimal frame rate and loop gains for the tip-tilt sensor and higher-order wavefront sensor loops. Similarly, the wavefront error measured by the LBWFS is reported and this estimate is used to change the integration time of the LBWFS or alter the number of wavefront modes that are corrected. These settings are generally optimized at the beginning of an observation and used throughout the observation, unless there is an obvious change in the observing conditions or image quality. More information on the performance of the LGS AO system can be found in References [2-4-6]. We are in the process of better understanding the effects of isoplanatism on the image quality, both from a theoretical and experimental point of view [17]. From our preliminary measurements, we plot the sky coverage in Figure 4 [4].

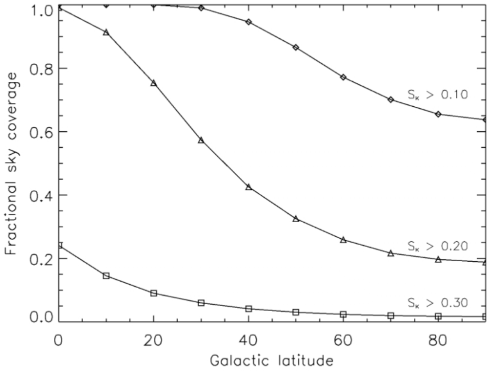

Figure 4: Sky coverage as a function of galactic latitude

5.3 Publications, subscription rate

The AAS 207th meeting hosted a special session for LGS AO science that included numerous Keck and Lick LGS AO results. As of May 2006, thirteen refereed papers based on Keck LGS AO data have been accepted for publication [2-9-15]. The proportion between planetary, galactic and extragalactic is respectively 3, 6 and 4, which could be seen as an indication for a better sky coverage with LGS AO. Our user community is very interested by the potential of LGS AO and LGS AO observing requests have over-subscribed by a factor 2 the number of offered nights. More than 70% of the proposals are for extragalactic science and we have noted a clear decline of NGS AO proposals, particularly for NIRC2.

6. DISCUSSION AND FUTURE PLANS

It is a great achievement to offer 50 to 70 nights of LGS AO science per semester to our astronomers' community and see exciting science results from the LGS AO data. Yet, there is a price to pay for the LGS AO design and integration strategy we have developed at W. M. Keck Observatory, and the lessons learned on this first LGS AO integration for a large telescope have been dramatic:

- The combination of quad-cell for the WFS and laser projection geometry (projection from the side of the telescope) results in semi-static aberrations as the hexagonal pupil tracks the sky. We had not expected that the operations and performance of the LBWFS, that plays a key-role for compensating for these aberrations, would be so critical to our operations. Today, the LBWFS design is limiting our performance (only one lenslet array geometry, simplistic camera software, rudimentary and little integration of the control software).
- One of the main reasons for the current reliance on human resource can be attributed to the relatively low priority in the LGS AO project on designing and building tools for efficient LGS AO operations. This is particularly true for the AO/telescope/instrument handshakes and for the LGS AO operator tools, which are a composition of Java, IDL and Tcl/Tk GUIs. We also note that the delay in building the wide field camera (which is yet to be built and delivered by Gemini per an inter-observatory agreement) induces much higher operations and logistic costs.
- The dye lasers are a major point of weakness in our operations and requires constant attention and tweaking from our laser team. We are considering a possible upgrade path to replace the two dye lasers for the seed light which are the most difficult to adjust. As the laser performance is difficult to maintain and predict, and due to limited access time during runs and limited manpower, we have been forced to delay the design and implementation of automated operations for laser startup. As a result, many steps in laser operations are manual and most laser operations tools are engineering-grade operation tools.

While our focus is to support more LGS AO science nights, we are still planning for a major upgrade in 2007 to replace the wavefront controller and the CCD. We also hope to replace our LBWFS sensor at the same time. Once the all sky camera is in place and the proper procedures reviewed and agreed on by the FAA, we hope to reduce our current staffing for laser safety observers. In addition, we plan to combine the LGS AO operator and the observing assistant role. In parallel, we have changed some of our setup procedures to mitigate the number of faults from the AO systems, based on results from the time lost analysis.

One of the major advantages to classic observing mode is the interaction between the visiting scientist and the technical staff. The science program can often benefit from a more specific understanding of the technical capabilities when ascertained by direct experience. Graduate students' involvement in observing, LGS AO, and instrument usage is also considered important. Also, many of the support staff are astronomers or are interested in astronomy and are very keen to understand the science. A better understanding of the science goals can lead to better performance and better priority allocation of limited resources. The parent intuitions and the observatory are strongly coupled in many respects and observing runs are an example of this. The observatory has been resistant to implement service or queue observing similar to other major observatories, although the advantages of queue observing are recognized. The issue is often discussed, especially in the context of LGS AO. However, classical observing remains the observing mode of choice for Keck Observatory.

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