

Focus and pointing adjustments necessary for laser guide star adaptive optics at the W. M. Keck Observatory

Douglas Summers^{*a}, Antonin Bouchez^a, Jason Chin^a, Adam Contos^b, Scott Hartman^a, Erik. Johansson^a, Robert Lafon^a, David Le Mignant^a, Paul Stomski^a, Marcos van Dam^c, Peter Wizinowich^a

^a W. M. Keck Observatory, 65-1120 Mamalahoa Hwy., Kamuela, HI 96743

^b Ball Aerospace & Technologies Corp, P.O. Box 1062, Boulder, CO 80306

^c Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550

ABSTRACT

The W. M. Keck Observatory Adaptive Optics (AO) team recently celebrated a milestone first AO-corrected image with the new Laser Guide Star (LGS) system. This paper details focus and pointing changes implemented for the LGS AO system. The combination of variable sodium altitude, elevation-dependent distance to the LGS, off-axis projection, and equipment flexure require both focus and pointing adjustments to keep the laser spot located and its size minimized on the wavefront sensor. We will describe the current approach to LGS focus and pointing-compensation adjustments, and provide some insight into issues seen thus far during engineering activities at the W. M. Keck Observatory.

Keywords: laser guide star, adaptive optics, laser control software

1. INTRODUCTION

Adaptive Optics at the W. M. Keck Observatory has entered a new age with the addition of a 589-nm sodium LGS AO capability. This much-anticipated expansion in sky coverage for near diffraction-limited observations enables the observatory to extend its current AO capabilities into the realm of extra-galactic science. The improvements come, however, at a cost in AO system complexity.¹ To achieve an LGS AO capability, several changes were made to the existing Natural Guide Star (NGS) AO system and new components were added. These include addition of the laser, a higher sensitivity Avalanche Photo Diode (APD) based down tip-tilt control system, a Low-Bandwidth Wavefront Sensor (LBWFS), new optics (beam splitter and sodium dichroic), laser Uplink Tip/Tilt (UTT) control, and new software infrastructure for automated laser pointing and focus control. LGS AO system components can be seen in Fig. 1. There are significant differences in the operational concepts for NGS AO and LGS AO. Focus and pointing differences are briefly described below.

In the Keck NGS AO system, the Wavefront Sensor (WFS) is mounted upon a single-axis positioning device named the Focus Control Stage (FCS). Focus is established by a combination of daytime calibrations and nighttime adjustments. Daytime calibrations are performed using a fiber light source located conjugate to the science camera focus position. The FCS is moved until the fiber source focus (as read by the WFS) results in a flat DM. Final nighttime focus adjustment is made using a star. The WFS control and offloading loops are enabled and focus is adjusted via DM shaping commands and secondary piston commands (as a result of offloading). The telescope is considered in focus when the DM is centered within its dynamic range. Subsequent focus changes are caused by either atmospheric turbulence, and/or by temperature and elevation changes affecting the telescope truss structure. Assuming temperature and elevation compensation controls are enabled within the Telescope Control System (TCS), the remaining wavefront errors can be assumed to be atmospheric, and the AO system is used to correct these errors. Periodic secondary piston is used to offload focus from the DM, maintaining DM actuator dynamic range.

*dsummers@keck.hawaii.edu; phone 808.885.7887; fax 808.885.4464; <http://www.keckobservatory.org/>; W. M. Keck Observatory, 65-1120 Mamalahoa Hwy., Kamuela, HI 96743

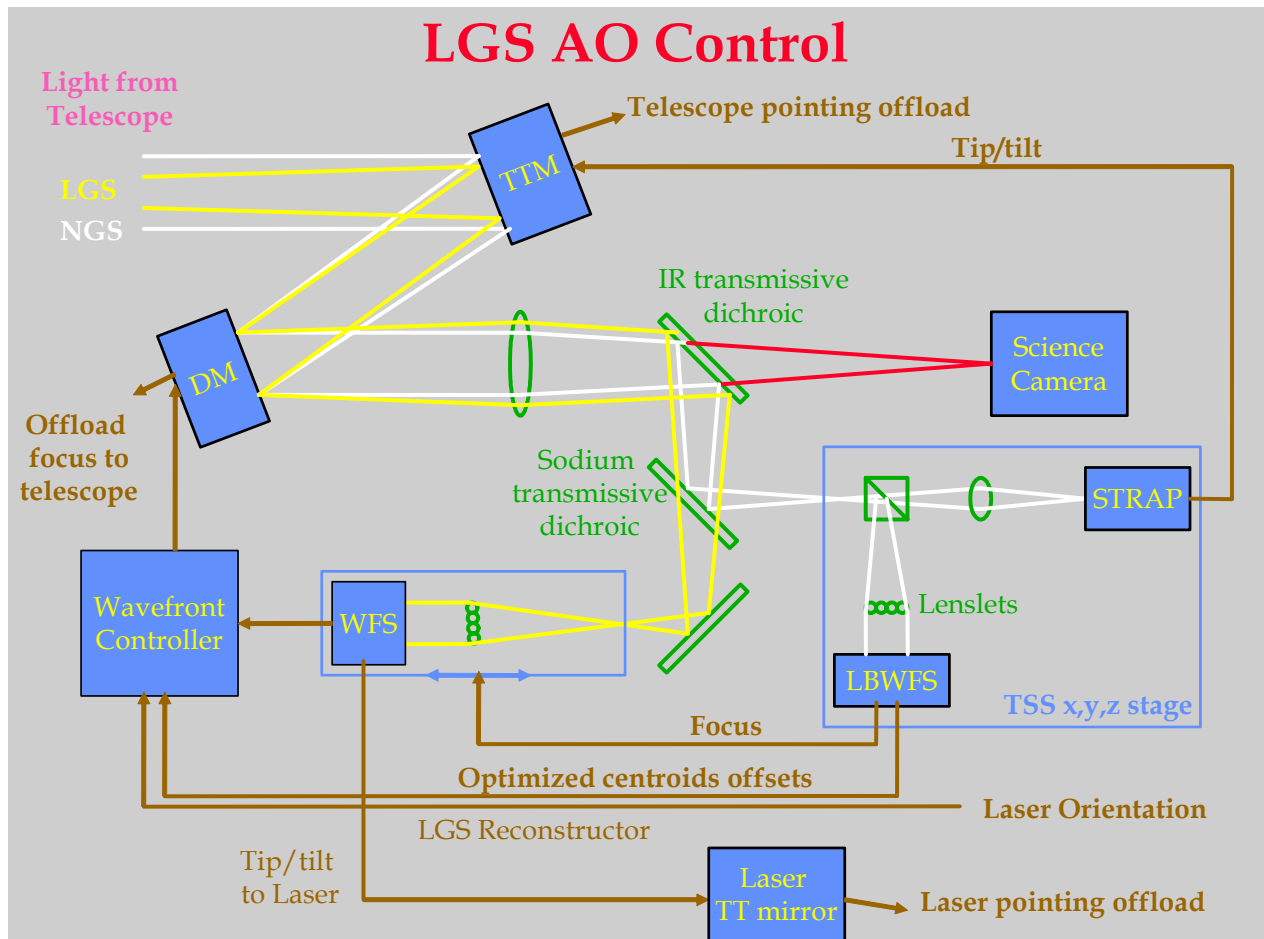


Fig. 1. LGS AO system components.

In the Keck LGS AO system, a 589-nm sodium laser is pointed at the mesospheric sodium layer and the fluorescent return signal wavefront is monitored by the WFS for atmospheric turbulence. Consistent with NGS AO, shaping commands are sent to the DM to correct sensed wavefront errors. However, several characteristics of the LGS differ from the NGS, and not all wavefront errors visible in an NGS are visible in an LGS. At Keck, the use of off-axis laser projection complicates the laser pointing model. Focus complications are generic however, and apply to any LGS AO system. Atmospheric tip/tilt must be handled separately from LGS wavefront processing. Two significant complications for LGS AO discussed in this paper relate to establishing and maintaining proper focus, and maintaining correct laser pointing. Both of these functions are impacted primarily as a result of variable sodium distance away from the telescope.

Sodium distance variations are a function of sodium layer height, telescope elevation angle, and to a lesser extent, structural features of the sodium column density and random layer altitude drifts. These variables require changes to be made to the focus stage in the AO system. Instead of the focus stage being set once during calibration/acquisition, the focus stage must be used as a continuously updating tracking device. Variable sodium distance affects laser pointing in an off-axis system in that accurate measurement of the layer height is required to correctly position the LGS on the WFS. Finally, the fact that the laser is being propagated from the ground upward, through the same atmospheric turbulence being measured, implies tip/tilt corrections must be done via wavefront monitoring using a separate NGS. However, tip/tilt corrections applied on the NGS signal affect the common light path of the laser return signal to the WFS. This requires a UTT control system to maintain accurate centering of the LGS on the WFS. The following paragraphs explain these issues in more detail, and discuss the implementation of focus and pointing compensation control software at the Keck Observatory.

2. FOCUS CONTROL

To accurately set the focus in LGS AO mode, the FCS position must be driven to a location conjugate to the sodium layer. Given a sodium height range between 80 km and 100 km, Keck's FCS must be positioned between 230-280 mm away from the NGS focus position (at the zenith). Figure 2 shows the Keck FCS position sensitivity for a range of sodium layer height and elevation angles. To understand how critical the position setting of the FCS is to focus, an understanding of the focus requirement is needed.

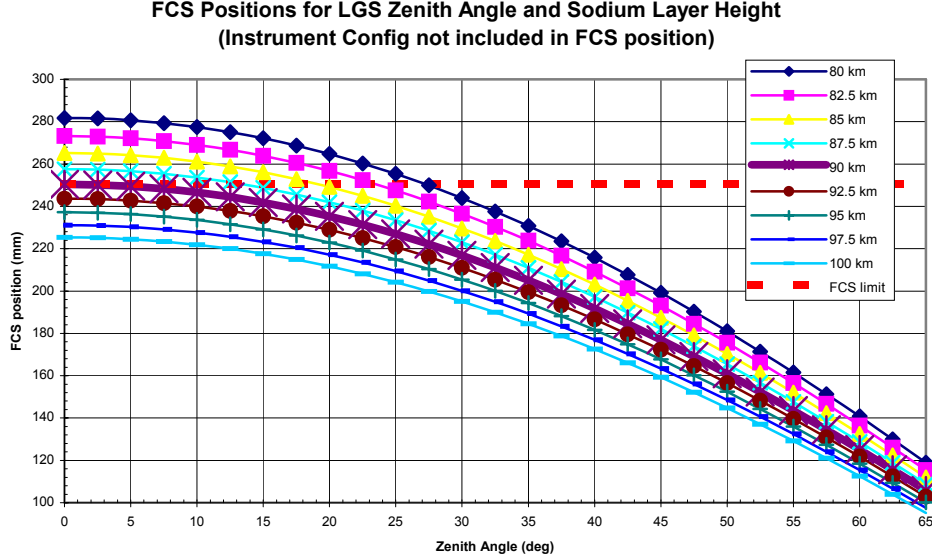


Fig. 2. FCS positions versus zenith angle and sodium layer height

The focus control requirement for the LGS AO system has been set to maintain diffraction-limited image quality on the science object.² At H-band the diffraction limit of the Keck telescope is 0.034 arcsec. The degradation due to all focus sources is not allowed to exceed 10 percent of the diffraction limit. This implies an allowable focus error of:

$$\text{Allowable focus error (arcsecs)} = [(1.1 \cdot 0.034)^2 - (0.034)^2]^{1/2} = 0.0156 \text{ arcsec} \quad (1)$$

The plate scale of the telescope is 0.727 mm/arcsec, which implies an allowable focus shift of 0.0156 arcsecs * 0.727 mm/arcsec = 0.0113 mm. This is converted to an allowable *focal plane* shift by multiplying by the telescope focal ratio (15), so $\Delta Z = 0.17$ mm. This is the requirement at zenith. The defocus contribution is allowed to grow as a function of zenith angle to match the diffraction-limited image size for a given zenith angle. For example, at a zenith angle of 60°, $\Delta Z = 0.034 \text{ arcsec} * 0.727 \text{ mm/arcsec} * 15 = 0.37$ mm. Clearly, the focus requirement is much more stringent than can be maintained without correction for variations in sodium distance. For LGS AO, a change of the FCS from a statically positioned device to a dynamic tracking device was required. Additionally, appropriate sodium distance compensation modeling and tracking device control software had to be developed to manage focus. To correctly set the position of the FCS stage, the following equation is used:

$$Z_{\text{FCS}}(h, \xi) = f^2 \cos \xi / (h - f \cos \xi), \quad (2)$$

where: h is the height of the sodium layer above the telescope at zenith,
 f is the focal length of the telescope (150 m), and
 ξ is the zenith angle.

The zenith angle and focal length of the telescope are well known. However, the sodium height value used in the calculation can seriously impact the quality of the resulting focus tracking curve used to position the FCS. An error in calculated sodium height will cause the FCS to be out of position during closed-loop operations. This will be viewed by the WFS as a defocus term, resulting in both DM shape commands, and secondary piston (as a function of offloading). To correct for the possibility of a flawed sodium altitude setting causing an induced focus error through FCS tracking, a true source of infinite focus must be monitored. This is done via a faint NGS using an LBWFS running at a slower frame rate than the fast WFS. High-frequency focus terms captured in the LGS are corrected, and any low-frequency errors in setting a correct sodium altitude (and or sodium height variations) are discovered via the NGS source and corrected by summing a (negative) term into the total focus position of the WFS.

A critical requirement of the LGS AO system is to correctly determine and maintain knowledge of the sodium layer height. Knowing the height reduces focus and pointing errors (discussed elsewhere in this paper). The LBWFS focus residual can be used with the FCS position to reverse engineer the actual sodium altitude. This might seem strange at first, given that the FCS focus position is determined using a given sodium height, but a software feedback loop can calculate and converge on the value of the sodium altitude given an initial guess at the sodium layer height and sufficient iterations of the LBWFS image processing loop for NGS focus. Given the focal properties of the telescope, the position of the FCS, and the NGS focus residual zernike from the LBWFS, the formula of the sodium altitude is:

$$sodium_alt = (f^2 \cos(\xi) / (Foc_{LGS} + Foc_{LBWFS})) + f \cos(\xi) \quad (3)$$

The software implemented at Keck performs two redundant calculations of sodium altitude using the LBWFS focus zernike and also DM focus offloading data from the WFS. The AO operator can view both calculated results, and set a sodium height from either calculation (or a manually entered setting). This drives the calculation of both FCS stage tracking, and the sodium height calculation used for pointing. AO focus control has been centralized into a GUI-based focus manager where control of all variables affecting FCS position is managed.

3. POINTING CONTROL

Laser pointing control at Keck is accomplished via a variety of hardware and software. Figure 3 shows the relative positions of the telescope, laser table, and projection system (note, however, that the image shows the laser table located above right Nasmyth, when in fact the actual position is on below right Nasmyth). The projection system is off-axis. The pointing optics are housed on the dye laser table. The table contains, among other optical components, all the mirrors used for pointing control.

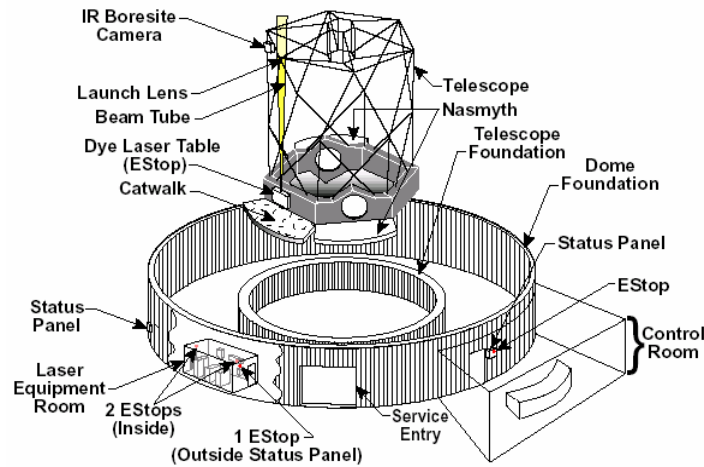


Fig. 3. Laser configuration.

The laser table also houses optics for monitoring and controlling table flexure and for analyzing beam quality. Multiple software algorithms are used in conjunction to determine the correct pointing angles for laser subsystem mirrors. Figure 4 shows a side view of the laser table and the mirrors influencing pointing.³ Of primary interest are the mirrors labeled uplink tip/tilt, and trombone M3.

3.1 Pointing alignment

At the beginning of each observing night, an alignment of the laser to the optical axis is required. This is performed while the telescope is at the zenith, minimizing pointing errors associated with flexure in the projection tube assembly. This position serves as the zero point for sodium distance pointing compensation (discussed in Sec. 3.4). The telescope acquisition camera on the AO bench is used to support laser alignment. The laser operator sets the FCS focus position for the LGS and drives the laser M3 trombone pointing mirror with motor commands to position the LGS onto the acquisition camera. This accomplishes *coarse* alignment. Once laser light is visible on the acquisition camera (LGS or Rayleigh), the AO operator uses a software acquisition tool to achieve *fine alignment* of the LGS onto the WFS. When the LGS is centered on the WFS, the pointing mirror encoders are nulled to mark the optical axis position. A mode state change occurs in the laser pointing software, allowing encoder feedback to be used for positional reference to the optical axis. The laser-pointing model makes use of positional offset references (from the optical axis) in calculating pointing position commands.

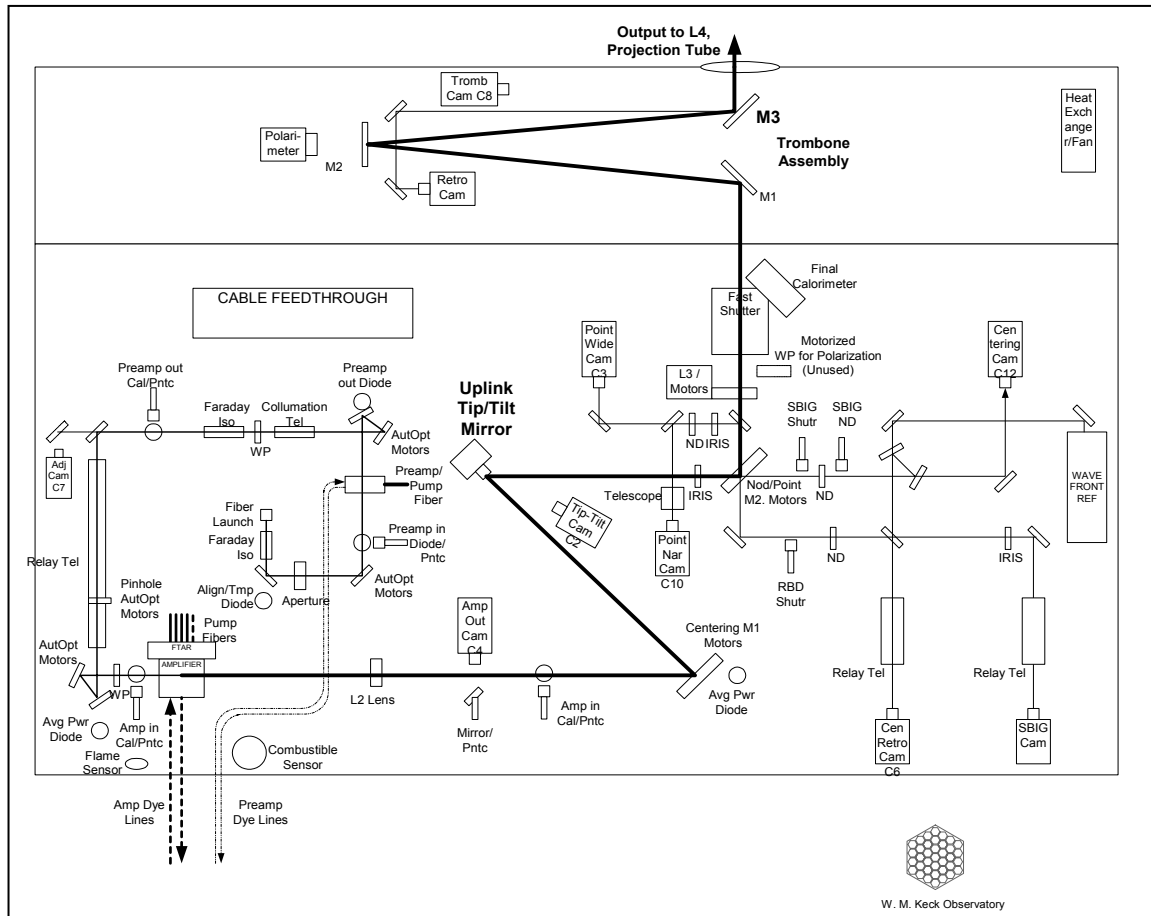


Fig. 4. Laser table.

Operator commands during the fine alignment sequence are processed in acquisition camera pixel coordinates (or alternatively, a direct image plane coordinate destination command). The software performs a coordinate conversion from camera pixel coordinates into image plane coordinates. Following this, a motion command is generated in the image plane and sent to the laser-pointing function. The laser-pointing function performs a second coordinate

transformation from the image plane into laser mirror coordinates. This is required because the Keck image plane is behind the image de-rotator on the AO bench, but the laser pointing mirror is mounted on the side of the telescope. Thus, image plane coordinates are rotated by the pupil angle in the mirror coordinate system (and visa versa). All laser-pointing and compensation commands are output in image plane coordinates consistent with all AO devices. This allows the AO supervisory control software to have a consistent device control interface for offsetting, nodding, and slaved pointing motions.

3.2 Pointing compensation functions

The off-axis projection system used at Keck necessitates a more sophisticated laser pointing model than would be required in an on-axis projection system. In fact, the laser pointing model of any large-aperture telescope employing off-axis projection will be found to be very sensitive to the issues associated with varying distance to the sodium layer. In smaller aperture telescopes (such as with the off-axis LGS AO system at Lick Observatory), the off-axis projection distance may not sufficiently degrade the pointing accuracy to warrant building a corrective model. However, at Keck, without the additional modeling and correction, the LGS would not remain on the WFS during tracking. The Keck laser-pointing model supports calculations of offsets for nighttime LGS AO operations including laser optical axis alignment, sodium distance, tube flexure, uplink tip/tilt control offloading, Field Steering Mirror (FSM) slaving, and acquisition/manual positioning.

The operations sequence is as follows: following an initial laser-pointing alignment operation performed by the AO operator, the laser-pointing software is put into a compensation control mode. In this mode, the pointing software uses encoder count positions relative to the optical axis for current pointing position. Modeled calculations of required offsets in the image plane are used for the desired destination pointing position. All compensation functions are summed, and a final destination offset is calculated from the difference between the desired destination and current position. Commands are then sent to the M3 pointing mirror to achieve the desired destination. Each of the compensation functions and their associated issues are described in the subparagraphs below.

3.2.1 Sodium distance offsets

The sodium layer distance varies as a function of the telescope elevation angle and the height of the sodium layer. In an off-axis projection scheme, the laser projector must be aimed to intersect the center of the sodium layer on the optical axis of the telescope. Figure 5 is a plot of the required projection angle (toward the telescope optical axis) as a function of zenith angle for multiple sodium layer altitudes between 84 km and 100 km. The projection angle follows the cosine of the zenith angle. Without compensation, the LGS image, aligned at the zenith, would shift continuously on the WFS and acquisition camera as the telescope tracked to different elevations. The equation for the error is:

$$error = \arctan \{ [(H_{sod} - H_{tel}) / (X_p^2 + Y_p^2)^{1/2}] / \cos(zen) - 90^\circ \} \quad (4)$$

where H_{sod} = height of sodium layer above sea level
 H_{Keck} = height of Keck telescope above sea level
 (X_p, Y_p) = projector position in telescope coordinates

The geometry of the Keck laser projector is 6.1m radially off-axis at an angle of 26.8 degrees (clockwise relative to the gravity vector as viewed facing the primary mirror when the telescope is pointed toward the horizon).

The sodium distance calculation provides the magnitude of the offset as measured in a direction toward the optical axis. The offset vectors in the Az/El coordinate system are calculated, and then rotated into image plane coordinates using the pupil angle. However, because the telescope is aligned to the optical axis at the zenith (where the pointing mirror encoder zero points are), the pointing correction is actually pre-loaded into the initial alignment procedure. The calculated sodium distance offset must actually be backed out of the pointing as the telescope moves to higher zenith angles. Finally, because the sodium altitude changes as a function of elevation angle (among other variables), the calculation must be repeated at least as often as the elevation angle changes. Paired calculations of the current sodium height must be performed; one for the magnitude of the error at zenith, and another for the magnitude of the error at the current elevation angle. The difference between these calculations is the offset term to be applied in the compensation function for the current elevation.

Determining the distance to the sodium layer is critical to pointing accuracy in this function. The distance to the sodium layer is calculated as a result of focus calculations in the focus manager (discussed in Sec. 2). The sensitivity can easily be seen in Fig. 5, given that the linear range of the Keck WFS is roughly 1.277 arcseconds. Pointing errors equal to twice this magnitude are possible with an incorrect sodium layer height setting. The UTT function has sufficient dynamic range to overcome this problem (assuming light is on the wavefront sensor at all), but modeling and correction are preferred methods of handling this effect.

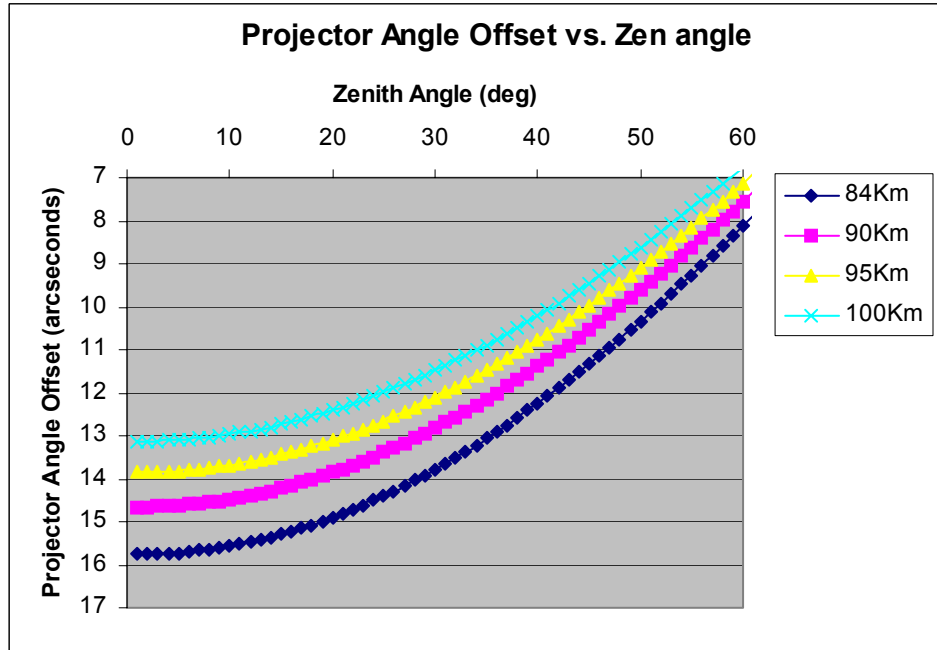


Fig. 5. Sodium distance error as a function of zenith angle and sodium height.

3.2.2 Flexure offsets

The Keck laser projection subsystem contains flexure that is independent from the rest of the telescope structure. While the projector tube is mounted to the side of the trusses, and thus somewhat subject to flexure consistent with the telescope truss structure, there are additional projection components that add and subtract from the telescope flexure vector. These cause laser pointing errors that must be modeled and compensated for in the laser software. Multiple laser subsystem flexure measurements have been taken in the past to characterize the effects⁴, and each of these has been helpful in understanding portions of the system. However, the authors believe that the most appropriate way to address LGS AO flexure is in a systematic procedural measurement. The measurements at Keck used the following procedure:

- Align laser at zenith, and zero the pointing control encoders
- Perform a fine alignment to center the LGS on the WFS
- Disable the UTT system
- Enable sodium distance compensation
- Drive telescope to a new elevation angle
- Use manual offsets and/or image plane commands to re-center the LGS on the WFS
- Document the offset needed in the image plane to accomplish re-centering on the WFS
- Repeat at multiple elevation angles spanning a range of acceptable elevations.
- Curve fit the flexure data to an equation and insert into the compensation model.

The flexure of the Keck 2 laser projection assembly has been measured and modeled to provide corrective offsets in the image plane. The magnitudes of the offsets in X and Y can be seen in Fig. 6. Note that the Keck laser is limited to the elevation range 20 deg <= elevation <= 90 degrees. The data sets captured so far are in agreement, but continued tuning is expected over time.

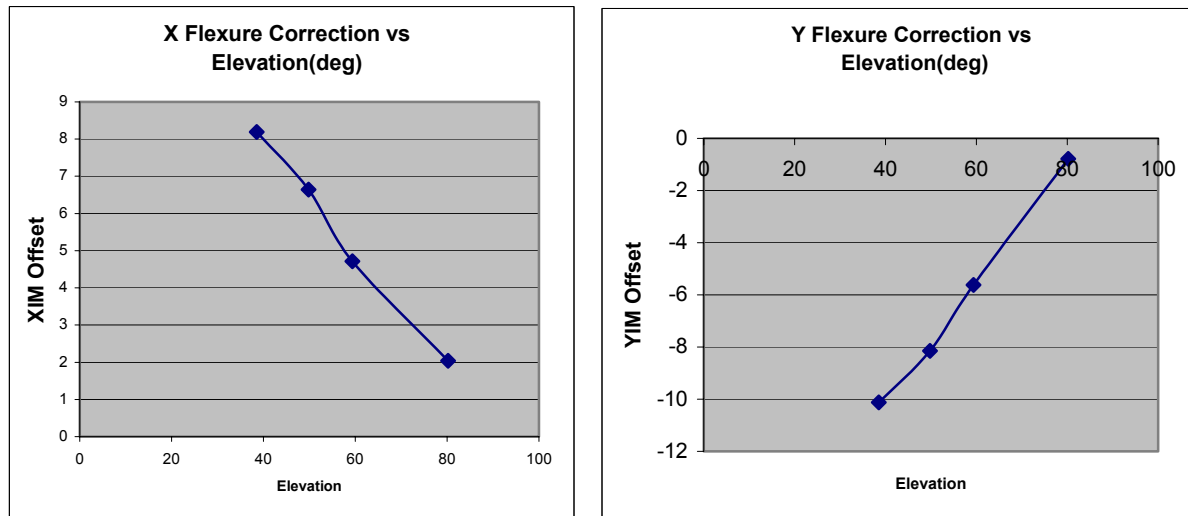


Fig. 6. Corrective laser projection flexure offsets as a function of elevation angle.

3.2.3 Tip/tilt residual offsets

Residual offsets are useful for multiple purposes during acquisition and closed-loop operations. During acquisition, residuals compensation serves as the offsetting mechanism to center the LGS onto the WFS. Following acquisition (i.e., during tracking operations on a science target), residual offsets are used to offload boxcar-averaged UTT residuals to keep the UTT mirror well centered in its dynamic range. Uplink Tip/Tilt is discussed further in Sec. 4.0.

3.2.4 Acquisition

After initial alignment of the laser at the zenith, any move away from the zenith to a new object position (prior to enabling pointing compensation) will result in positioning errors on the WFS. These errors as discussed above are a result of flexure and sodium layer distance changes. In this circumstance, it is possible that the object will (at best) not be centered on the WFS, or (worse), not be located on the WFS at all. Acquisition controls for LGS AO have been added to the compensation toolset to allow the operator general flexibility in entering offset positions for the LGS. Although useful for acquisition, the tool can serve as a general purpose offsetting and nodding tool. The operator may enter a destination offset in either image plane coordinates, or by entering the current pixel location from the acquisition camera display. When used in this particular mode, destination information is obtained from either a reference named pointing origin, or a specific destination in the image plane.

3.2.5 Field steering position slaving

It is not always the case that the optical axis is coincident with the desired LGS pointing position. For these cases, it is typical that the AO operator will use the Field Steering Mirrors (FSMs) to position the field to an offset position. Rather than have the operator enter this position as an acquisition offset, automation has been provided to allow the LGS to slave its pointing to the FSM field position in the image plane. Because there is a simple coordinate conversion between the FSMs and the image plane, this function is a simple enable switch that either slaves or does not slave the control of the laser offset to the FSM position. Control of this function provides multiple mode options for offsetting and nodding operations.

4. UPLINK TIP/TILT (UTT)

As background for understanding the UTT function, it should be noted that the WFS is incapable of processing and canceling atmospheric tip/tilt from the LGS. This is a limitation imposed by ground-based laser projection. The fact that the laser signal propagates up and back through the same atmospheric turbulence, and that the turbulence changes much more slowly than the signal propagates, implies that the atmospheric tip/tilt errors are complementary during propagation. The propagated laser light deflects upward to a position in the sodium column that is different from the intended pointing position (due to atmospheric turbulence). The return signal from the sodium fluorescence deflects downward to the telescope and sensing optics through the same tilt angle. From the perspective of the sensing optics,

the laser pointing was exactly as intended. To address this limitation, the tip/tilt signal from an NGS is required. The NGS can be faint because the measurement of tip/tilt only requires centroid data as opposed to higher order wavefront information requiring the wavefront photons to be divided among many lenslets. The NGS tip/tilt signal at Keck is monitored via an APD-based system named System for Tip/Tilt Removal using Avalanche Photodiodes (STRAP).⁵

The UTT function is used to keep the LGS centered on the WFS during closed-loop operations of Downlink Tip/Tilt (DTT) control using STRAP. Although the WFS monitors and corrects the errors seen in the LGS wavefront, it is also subjected to the common light path of the NGS being monitored and controlled by the DTT function. The result of atmospheric tip/tilt sensing for the NGS is correction terms being applied to the DTT mirror. This in turn inserts atmospheric tip/tilt into the LGS as viewed on the WFS (this is undesired). The UTT function removes this byproduct of DTT, and stabilizes the WFS centroids. The frame rates of the DTT and UTT loops are matched to the frame rate of the WFS. Having the UTT operating when the DTT loops are closed ensures that quality image sharpening can be done on the science object. The UTT function employs a proportional integral controller of the form:

$$x[n] = x[n-1] - k1 * u[n] - k2 * u[n-1] \quad (5)$$

where: $x[n]$ is the control output,
 $x[n-1]$ is the previous iteration's control output,
 $k1$ is a gain term,
 $u[n]$ is the WFS centroid error, and
 $u[n-1]$ is the previous iteration's WFS centroid error.

The software runs on a VME-based dedicated Motorola processor board. Operator commands allow for changing the frame rate and scaling parameters for the WFS spot size. Commands for control messaging and diagnostics are included.

The boxcar-averaged tip/tilt bias from the UTT mirror must occasionally be offloaded to the laser-pointing system. This is analogous to the down tip/tilt component offload to telescope pointing. This keeps the UTT mirror centered within its dynamic control range. At Keck, the linear range of the WFS is approximately 1.277 arcseconds (assuming an LGS spot size of approximately 2.4 arcseconds). The dynamic range of the UTT mirror is over 7 arcseconds, so the need to offload the UTT mirror is minimal. This has been verified by exercise during nighttime engineering tests.

5. SOFTWARE IMPLEMENTATION

Laser-pointing control software is composed of a layer of EPICS database logic (implemented in CAPFAST), and three operator GUIs. These GUIs are used for initial alignment, object acquisition, and real-time compensation functions. Keck utilizes a keyword layer above the EPICS database level. As such, all laser-pointing control functions are accessible to IDL and other scripting tools. Currently, the developed GUIs are at an engineering level. However, it is expected that IDL GUIs and/or other user interfaces will replace the current set of GUIs as the system matures with usage. The engineering control screens for these functions are shown in Figs. 7, 8, and 9.

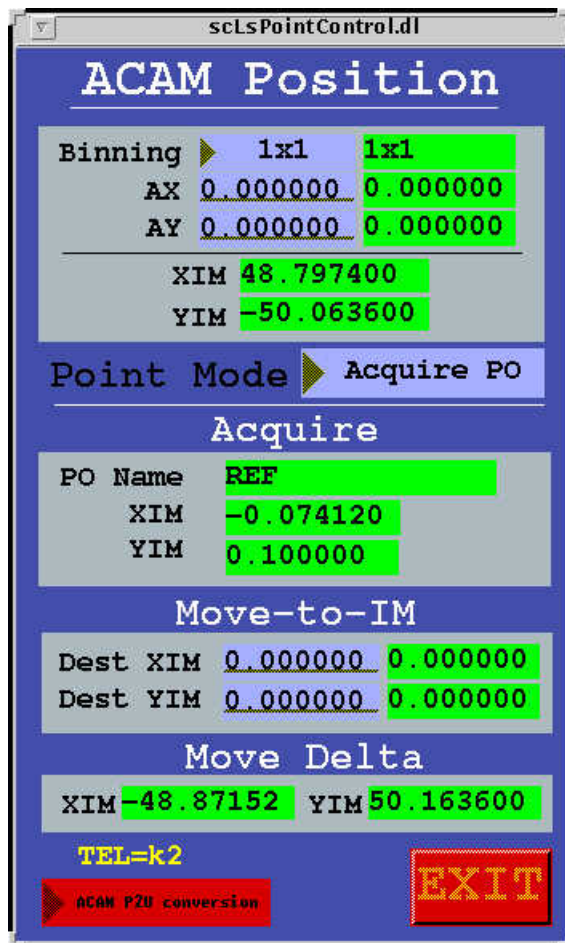
5.1 ACAM Position

This GUI is primarily used for initial alignment of the LGS to the optical axis of the telescope. It can also be used as a general purpose LGS offsetting tool. Following periodic maintenance of the laser hardware to include laser table alignments, the first propagation to the sky following the maintenance requires finding and resetting the location of the LGS. The laser is propagated to the sky at the zenith, and this screen is used to enter the LGS coordinates in acquisition camera pixel space. Typically, the LGS is found within a radius of one arc-minute of the optical axis. The operator enters the coordinates for the LGS, and enables a one-shot alignment to re-point the laser. In the future, it is envisioned that the process of on-sky alignments at zenith will be automated. A conversion is made between pixel coordinates and image plane coordinates for use in preparing internal commands to the laser steering mirror.

5.2 M3 Pointing Control

The M3 Pointing Control GUI is used to control LGS pointing modes and command streams to laser pointing. Moves must be explicitly enabled. Function controls exist for both initial alignment (one shot moves), and for automatic,

periodic pointing updates supporting tracking compensation functions. Moves are performed from a source position to a destination position. Sources can be either operator inputs (as in the case of initial alignments using ACAM), or driven from laser steering encoder knowledge (for compensation functions). Destinations follow similar logic as for source positions. Other functions for homing the encoders, updating calibration information for the coordinate system, and for seeing intermediate calculations are provided on the GUI as well.



The screenshot shows the 'ACAM Position' window with the following data:

Binning	
1x1	1x1
AX	0.000000 0.000000
AY	0.000000 0.000000
XIM	48.797400
YIM	-50.063600

Point Mode: Acquire PO

Acquire

PO Name	REF
XIM	-0.074120
YIM	0.100000

Move-to-IM

Dest	XIM	YIM
Dest XIM	0.000000	0.000000
Dest YIM	0.000000	0.000000

Move Delta

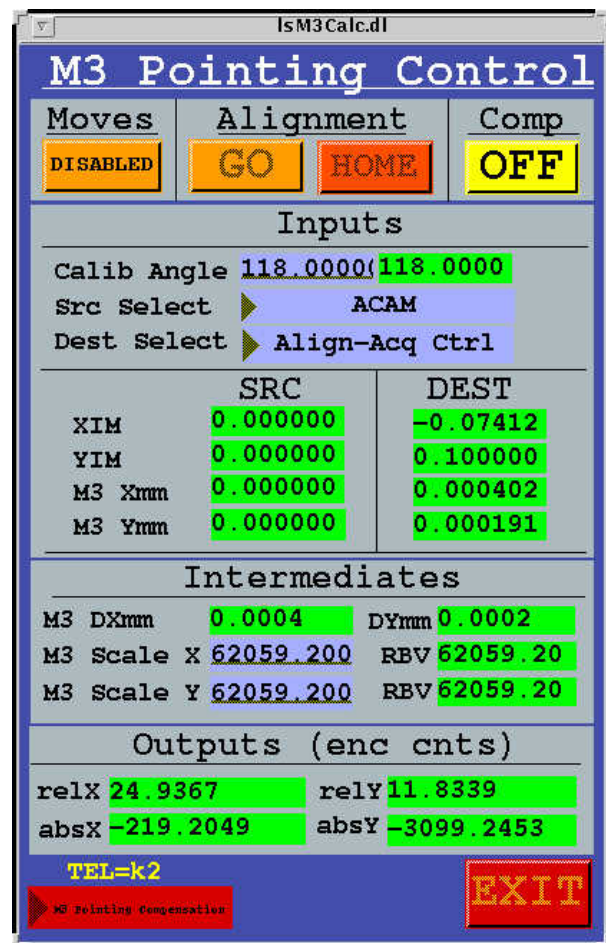
XIM	YIM
-48.87152	50.163600

TEL=k2

ACAM P2U conversion

EXIT

Fig. 7. Acquisition screen.



The screenshot shows the 'M3 Pointing Control' window with the following data:

Moves	Alignment	Comp
DISABLED	GO	HOME
		OFF

Inputs

Calib Angle 118.0000 118.0000

Src Select ACAM

Dest Select Align-Acq Ctrl

	SRC	DEST
XIM	0.000000	-0.07412
YIM	0.000000	0.100000
M3 Xmm	0.000000	0.000402
M3 Ymm	0.000000	0.000191

Intermediates

M3 DXmm	DYmm
0.0004	0.0002
M3 Scale X 62059.200	RBV 62059.20
M3 Scale Y 62059.200	RBV 62059.20

Outputs (enc cnts)

relX	relY
24.9367	11.8339
absX -219.2049	absY -3099.2453

TEL=k2

M3 Pointing Compensation

EXIT

Fig. 8. M3 pointing control.

5.3 M3 Pointing Compensation

This operator GUI provides the main control for enabling and disabling compensation functions. All enabled compensation functions are calculated such that their values are summed into a total offset in image plane coordinates relative to the optical axis. Compensation functions may be enabled or disabled, and controls for gains and axis flips are provided. Intermediate outputs are shown in both image plane coordinates (mm), and in arc seconds. In the case of acquisition offsets, source information is selectable between direct image plane offsets (useful for nodding), or from acquisition camera offsets entered on the ACAM acquisition control screen and enabled via the 'entry type' control. Elevation angle and sodium altitude settings are shown for convenience. Because sodium distance and flexure compensation functions are dependent on elevation, simulation for elevation angle is provided. This allows testing without control of the telescope.

IsPntComp.dl

M3 Pointing Compensation

Sod Alt 90000.000 (M) **Total X** 0.0000 (IM)
EL 89.999997 (Deg) **Total Y** 0.0000 (IM)

Controls						Outputs (IM)	
	Enab	Gain	RBV	FlpX	FlpY	X	Y
Acquire	OFF	1.0000	1.000	OFF	OFF	0.00000	0.00000
FSM Slave	OFF	1.0000	1.000	OFF	OFF	0.00000	0.00000
Sod Dist	OFF	1.0000	1.000	OFF	OFF	0.00000	0.00000
Flexure	OFF	1.0000	1.000	OFF	OFF	0.00000	0.00000
Residuals	OFF	1.0000	1.000	OFF	OFF	0.00000	0.00000

Acquisition Offset Entry Type **ACAM**
 XIM (mm) 0.000000 0.000000 X Y
 YIM (mm) 0.000000 0.000000 ArcSecs -0.1019 0.13757

FSM Slaved Offset
 XIM (mm) 0.100000 X Y
 YIM (mm) 0.000000 ArcSecs 0.13757 0.00000

Sod Distance Offset
 Zenith Offset -7.106319
 El Offset -7.106319
 R Distance 0.000000 X Y
 ArcSecs 0.00000 0.00000

Flexure Offset X Y
 ArcSecs 0.00000 0.00000

Residuals Offset
 XIM (mm) 0.000000 0.000000 X Y
 YIM (mm) 0.000000 0.000000 ArcSecs 0.00000 0.00000

Simulation TEL=k2!
 LGS El (deg) **ON** State SimVal RBV
 90.0000 90.00000

EXIT

Fig. 9. Compensation control screen.

6. CONCLUSIONS/LESSONS LEARNED

Management of focus in an LGS AO environment is non-trivial. The Keck AO team has expended a considerable amount of time to gain understanding of system variables influencing focus, and to gain confidence in the software used to manage the dynamic focus tracking process. The team continues to learn subtleties associated with measuring and setting sodium layer height, and expects to continue gathering data related to seasonal and nightly variations in the sodium layer over Mauna Kea.

Investigation into control loop optimizations between LBWFS processing and DM offloading is expected. There is a subtle interplay between the linear sensitivity of the WFS, maintenance of the DM dynamic range, LBWFS integration times, and secondary piston commands (a result of DM offloading). Our goal is to find the optimal settings for LBWFS integrations and DM offloading such that secondary piston commands are minimized while keeping the DM well centered in its dynamic range and WFS centroids in the linear region of the sensor.

The pointing errors associated with off-axis LGS projection in large-aperture telescopes are non-negligible. The performance of acquisition, tracking, and offloading will be affected if modeling and compensation are not employed to remove these error terms from the LGS pointing system. The authors were surprised to learn that a similar laser system at Lick did not model off-axis pointing compensation and yet was not impacted. After calculating the parameters of the

Lick system, the calculation confirmed that the error is small due to the small distance of the off-axis projector. For large apertures in the 8- to 10-m class, on-axis projection or modeling/compensation is required.

In an environment where off-axis projection is used to implement LGS AO, corrections for sodium pointing must be made prior to measurement and correction actions for flexure. A failure to do this will cause the measurements of flexure to be offset by the magnitude of the pointing errors. While this can easily be done, usually it's easier to factor this in and produce the equation of motion for flexure after the pointing error associated with sodium distance has already been factored out.

Some complicating factors associated with image de-rotation warrant mention. In the Keck system, compensation terms are applied as corrective offsets from the optical axis. The pointing encoders are set relative to the optical axis. The combined offsets for sodium pointing and flexure result in positions for the laser that would nutate if rotated, even though the light is optically centered. The ability to offset about a position that is not on the optical axis is not currently handled by the pointing model. This will need to be investigated and addressed (if needed) as a future upgrade.

Several laser table diagnostics were severely impacted with the introduction of the UTT function. It was falsely assumed that high-frequency motion introduced by DTT in the WFS light path (and corrected by UTT), would be invisible to the much slower diagnostics controls running on the laser table at 1 Hz. However, during engineering test of the UTT loops, the slower diagnostics easily captured the offsets. This invalidates the original design concept for the table stability loops, and affects the real-time diagnostic camera output for Power-In-The-Bucket (PIB) measurements. A redesign of the fold mirrors used for diagnostics on the table is under way to restore these capabilities. It is believed that the flexure of the table is minimal, so redesign of the optics associated with the PIB camera diagnostic may be sufficient to address the limitations imposed by the UTT function.

ACKNOWLEDGEMENTS

The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

REFERENCES

1. A. Gleckler, "Focus errors, and their correction, in an adaptive optics system utilizing a laser guide star," Keck Adaptive Optics Note 034, June 1995.
2. A. Contos, P. Wizinowich, D. Le Mignant, "Low Bandwidth Wavefront Sensor (LBWFS) Technical Description & Requirements," Keck Adaptive Optics Note 245, March 2002.
3. Lawrence Livermore National Laboratory, "Keck Laser System: General Description document," February 2001.
4. D. S. Acton, "L3-L4 Flexure Measurements for the AO Laser Guide Star Subsystem," Keck Adaptive Optics Note 210, May 2001.
5. Microgate Company, "STRAP Electronics Hardware Manual," June 2000.