

Keck Adaptive Optics Note #_____

Low Bandwidth Wavefront Sensor (LBWFS)
Technical Description & Requirements
*** D R A F T ***

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Preface

This document provides the technical overview for the Low Bandwidth Wavefront Sensor, or LBWFS, to aid in its implementation. Refer to other documents (listed at the end) for further information; in particular, see “Low Bandwidth Wavefront Sensor Software Design” for LBWFS software description, and “Keck II Adaptive Optics Subsystem Action Plan” for scheduling and responsibilities.

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1 INTRODUCTION

1.1 Purpose

When observing with the Keck II telescope in laser guide star (LGS) mode, the Low Bandwidth Wavefront Sensor (LBWFS) is used to provide a “focus truth sensor” to the LGS measurements. Monitoring a natural guide star (NGS), the LBWFS used to determine corrections for the high bandwidth Wavefront Sensor (WFS), which is monitoring the LGS. When the laser is used, the laser will generally be pointed at the science target, and the NGS must be within 60 arcsec. Although the WFS operates up to 672 Hz, the LBWFS will integrate for as long as a few minutes, allowing for the use of dimmer stars. The LBWFS is co-mounted with the Tip/Tilt Sensor (TTS) on the 3-axis Tilt Sensor Stage (TSS). The TTS is a quad-lens detector incorporating four avalanche photodiodes (APD).

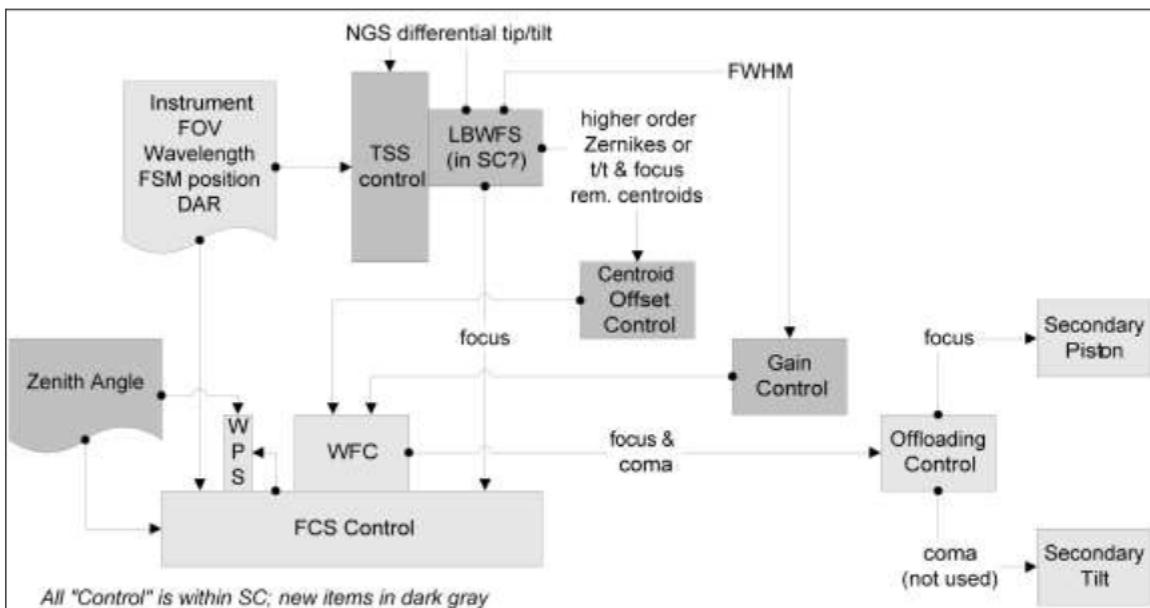


Figure 1: Schematic view of the LBWFS operation. Question: does the LBWFS control occur in the SC or WFC?

1.2 Overview of LBWFS Operation

Refer to above figure; details to come.

1.3 Difference in Measurements Between WFS and LBWFS

- The LBWFS samples the cylinder of light from a NGS, whereas the WFS samples a cone of light from the LGS, as shown in Figure 2.
- Atmospheric turbulence above the sodium layer is negligible since the layer is at ~90km, and most of the turbulence is below ~10-15km.
- The WFS measures—or doesn’t distinguish—changes in the height of the sodium layer.
- The WFS has no tilt information for the science object. The LBWFS has time averaged tilt info (the TTS has the high bandwidth tilt info).
- All of the LBWFS info is time averaged, whereas the WFS has high bandwidth info.
- The LBWFS source looks the same in all of its subapertures, but the WFS source (the LGS) looks different in each subaperture, depending on the subaperture’s position with respect to the laser projector.

- The LBWFS has science object time-averaged focus information, which the WFS only has indirectly. We indirectly make use of this information by correcting the FCS position, which drives the DM focus, which ultimately offloads to the secondary piston.

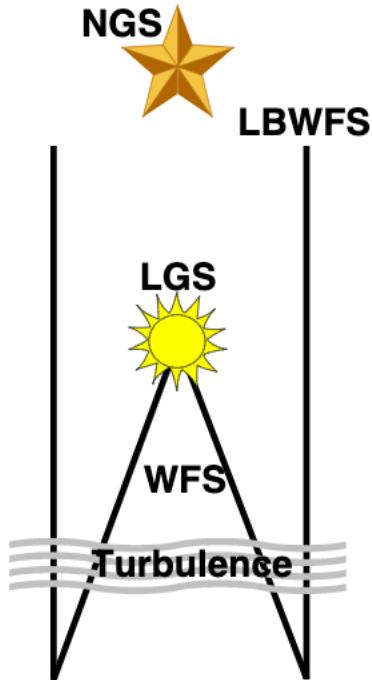


Figure 2: The LBWFS samples the cylinder of light from a NGS, whereas the WFS samples a cone of light from the LGS.

2 Overall requirements and constraints

Need to work how these requirements flow into the other categories.

2.1 Opto-mechanical

- One-to-one mapping with the high bandwidth WFS subapertures. This implies that the corners of the LBWFS lenslets must register to an accuracy of <1% of the 7mm actuator spacing with the DM actuators over the entire TSS field.

2.2 Performance

- Capable of computing and handing off focus, subaperture centroid offset and FWHM (for all 304 subaperture), on stars < 16th Vmag, in a < 30 sec cycle time including detector integration time.
- Capable of computing and handing off focus, subaperture centroid offset and FWHM (for all 304 subaperture), on stars < 18th Vmag, in a < 2 min cycle time including detector integration time.
- Capable of computing and handing off focus on a 20th Vmag star in a < 5 min cycle time, including detector integration time.
- Cycle time of exposing and processing one image < 5 sec.
- Measure focus to < 0.1 (?) mm
- Measure centroid to 0.1 (?) arcsec (2/3 pixel)
- Measure FWHM to < 0.05 (?) arcsec (1/3 pixel)
- Maintain focus on science instrument so that it does not significantly degrade the diffraction-limited image quality. When degradation from all sources is limited to 10%, the allowable shift of the FCS is 0.17mm.

- The average focus term on the DM during a LBWFS integration must be measured by the SC as it is needed to determine the focus term measured on the LBWFS.

2.3 Output and Diagnostic tools

- Average intensity for each subaperture
- Ellipticity for each subaperture (the magnitude of the ellipticity and angle wrt x-y subaperture grid)
- First ~10 Zernikes for overall wavefront across pupil (the same as used by the WFS: 1st order x-tilt, 1st order y-tilt, 1st order focus, 3rd order astigmatism (45 deg), 3rd order astigmatism (0 degrees), 3rd order x-coma, 3rd order y-coma, 3rd order spherical (AO CDR 1996, sec. 9.2.1.6.7), plus trefold
- RMS wavefront and peak-to-valley wavefront measurement
- Raw image output in fits format (not background or flat corrected, but this could be a GUI option)
- All diagnostic tools available at all cycle times
- Selectable software binning choice of 2x2 pixels (dim stars), or no binning (bright stars) of image.

2.4 Design Constraints

- Must use existing Photometrics CH350L camera.
- Share the NGS used for the tip/tilt sensor.
- Co-mounted with the tip/tilt sensor on the TSS.
- Must communicate with the EPICS-based AO system.
- Must communicate to the outside world (GUIs, FITS headers, etc.) through keywords.
- Capable of operating in NGS mode as well as LGS mode. In NGS mode, it will not control the FCS, but can measure the FWHM of the spot in each subaperture. In LGS diagnosis mode it will measure the FWHM in two directions.

2.5 Questions

- Can we meet the requirements on the time/magnitude for NGS? What SNR?
- Somehow we need to turn FWHM measurements into gains; how do this? Where algorithm resides (WFC, SC, PRC, etc)? ANSWER: SC.
- To what accuracy measure P-V wavefront? <50 nm RMS?
- Is 1 arcsec FWHM on the spot size enough for image motion?
- Need requirements on fov for subaperture; is 1 arcsec spot size enough for image motion?
- With a few pix across centroid, what is the accuracy in pix size with respect to image motion due to seeing?
- What is the sky coverage available for a given limiting LBWFS star magnitude (how many stars of magnitude M per arcmin is there?)?
- Where is the RMS wavefront and P-V measurement calculated?

3 Optics

3.1 Optical Path

As shown in Figure 3, the LBWFS is mounted on the tip/tilt sensor stage (18). For light to reach the LBWFS, it first enters from the telescope, passing through the image rotator (1), tip/tilt mirror (2), off-axis parabolic mirror #1 (3), deformable mirror (4), off-axis parabolic mirror #2 (5), then the visible light reflects off of the IR transmissive dichroic (6). The visible light reflects off the sodium dichroic (12), while the sodium light passes through. After (12), the visible light reflects off the intermediate fold mirror (16), then 90% passes through the 90/10 beamsplitter of the acquisition fold stage (17) to the TSS stage where the TTS and LBWFS are located.

With the use of a 90/10 beamsplitter cube on the TSS stage plate, 90% of the incident light is transmitted to the TTS and 10% is directed to the LBWFS. An assembly drawing of the two subassemblies is shown in Figure 4. Mounted on the side of the beamsplitter cube and common to both light paths is a 0.5" diameter sodium rejection filter. After the light passes through the filter and is reflected in the beamsplitter, it passes

through the lens and field stop mounted in a tube, as shown in Figure 5. The light is collimated and then passes through the lenslet array, mounted on an x-y motorized stage with manual rotation adjustment. The lenslets are imaged on a Photometrics 512x512 CCD detector. A photograph of the assembly is shown in Figure 6.

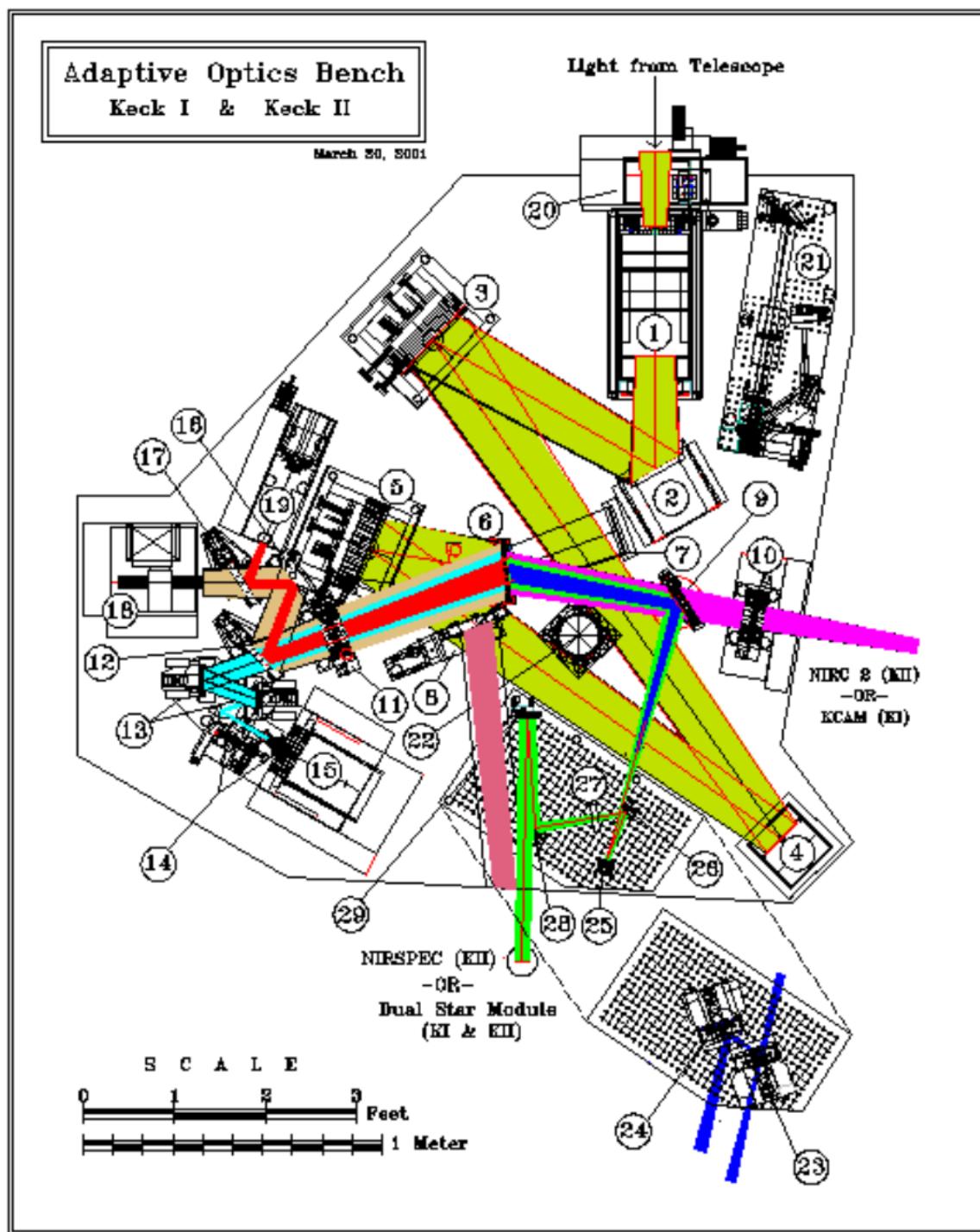


Figure 3: Adaptive Optics bench layout (placeholder for higher resolution version): 1-ROT, 2-TTM, 3-OAP1, 4-DM, 5-OAP2, 6-IR Dichroic, 8-DFB, 9-IFM, 12-SOD, 13-FSM, 14-FCS, FSS, SFS, WLS, WND, 15-WCS, 16-Intermediate Fold Mirror, 18-TSS, TTS, LBWFS, 19-AFS, ACAM, 20-SFP, 22-WYKO Fold Mirror, 25-29-NIRSPEC OPTICS.

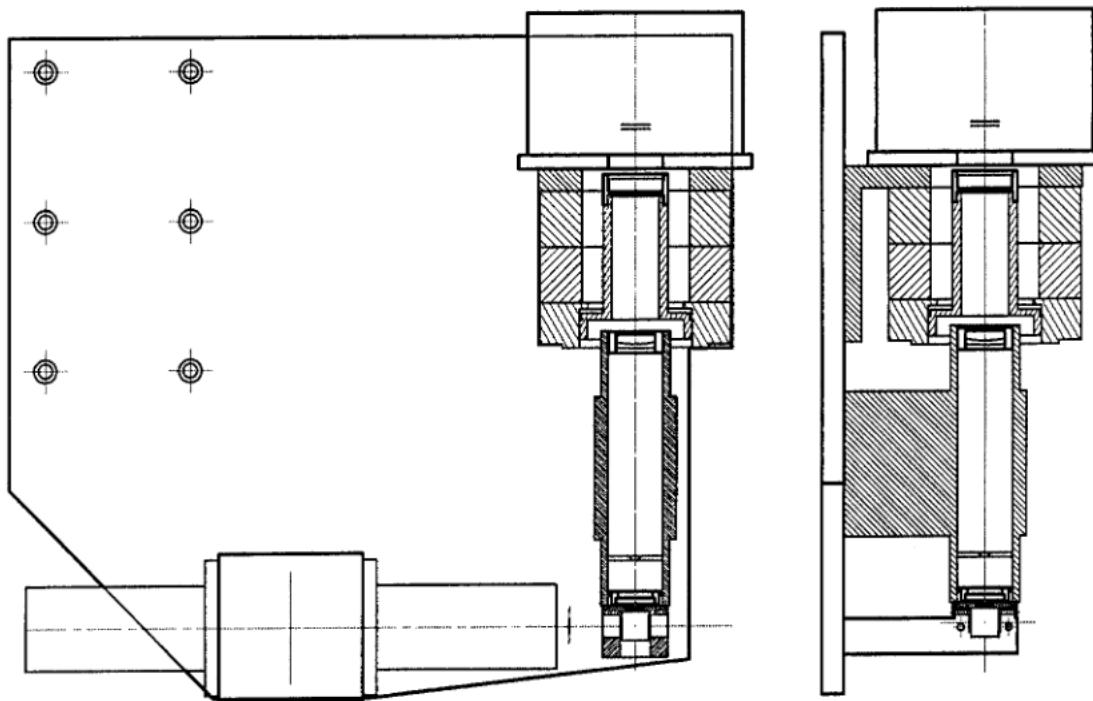


Figure 4: TTS/LBWFS assembly drawing (left: front view; right: side view). The TTS is located on the bottom of the TSS mounting plate, and the LBWFS is on the right. The 90/10 beamsplitter cube is in the lower right of the front view.

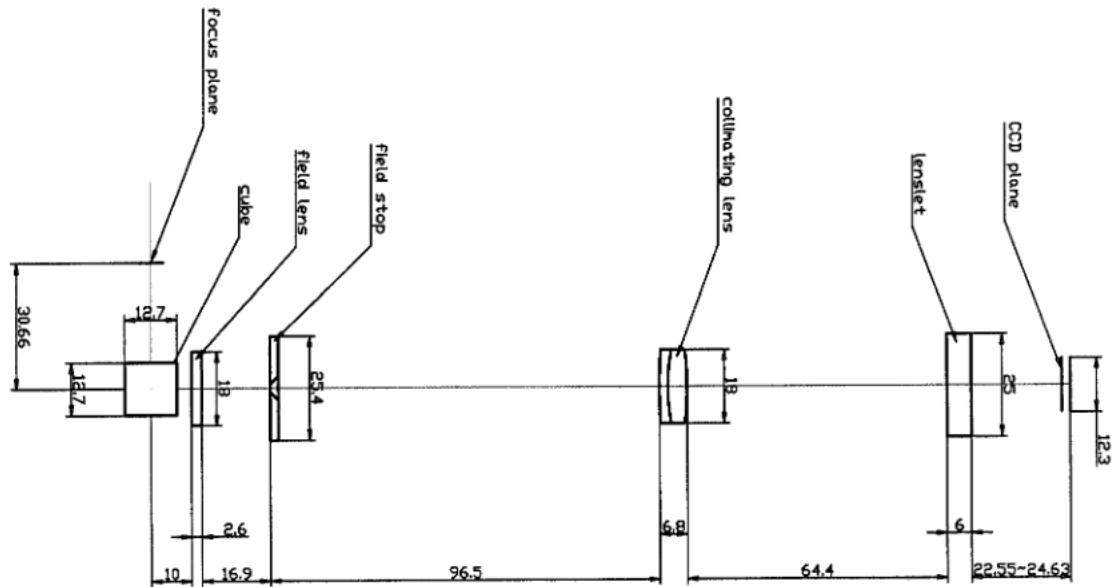


Figure 5: LBWFS subassembly optics. Light enters from the bottom (at left) and passes through a sodium rejection filter (not shown but located in the beamsplitter cube mount). Light is then reflected to the right at the beamsplitter cube, enters the optics tube and passes through the field lens and field stop, collimated by the collimating lens, and then through the lenslets to the CCD detector.

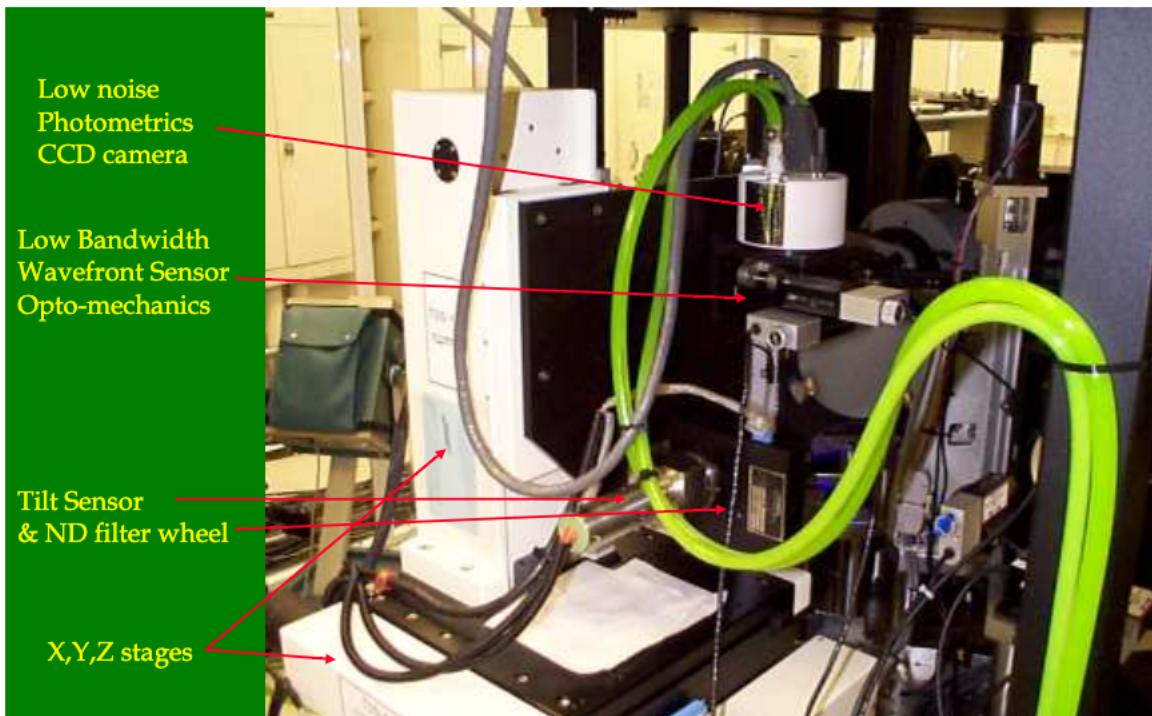


Figure 6: Photo of the assembled TSS with the TTS and LBWFS attached.

3.2 Optics

Table 1: DM spacings

Exit pupil – field stop distance	19948 mm
Actuator spacing on DM	7 mm
Actuator spacing on lenslet array	400 μm = 0.4 mm
Actuator spacing on exit pupil	74.8 mm
Actuator spacing on primary	562.5 mm

Table 2: Optical components of LBWFS assembly.

90/10 beamsplitter	Newport 05BC** (custom); 500-900 nm; Rs, Rp +/- 2%; Ts, Tp +/- 2%; absorption 4 +/- 2%
Singlet (field lens)	Melles Griot 01LQB249
Field Stop	National Aperture, 2.44 arcsec diameter field of view
Doublet (collimating lens)	Melles Griot 01LAO123

3.3 Lenslet Array

The lenslet optics are a Shack-Hartmann style lenslet array, with the specifics given in Table 3.

Table 3: Lenslet array specifications.

Manufacturer	AOA
Part number	0400-24-S
Substrate	25.4 x 6 mm round, BK7 glass
Lenslet diameter	400 μm
Lenslet focal length	24 mm

3.4 CCD Camera

Table 4: CCD specifications

Manufacturer	Photometrics CH350L
Chip	SITE 502 grade 1 512x512 pixel thinned CCD with VIS-AR coating
Shutter	Mechanical, 25 mm diameter.
Cooling	Thermoelectrically cooled with glycol
Image depth	16-bit (saturate at 65535)

Table 5: Noise contributors

Read noise	~3 e/pix
Dark noise	0.017 e/pix/sec
Dark current	1 e/min
Sky background noise (depends on Moon)	1.67 e/sec/arcsec (KAON113, but check w/ CFHT for better)

3.5 Subapertures

In terms of the number of pixels per subaperture, the LBWFS is larger than the WFS and therefore has better resolution. The subaperture to subaperture mapping is identical to that on the WFS.

Table 6: Lenslet Subaperture Information (most from KAON 113)

Hartmann spot FWHM	~ 0.5 arcsec
Subaperture FOV	2.44 arcsec, as defined by field stop
Incident flux for mag. M star at a subaperture	1.1 * 10^(8-M/2.5) photons/sec/subaperture at the lenslets (empirical). Implies ~3 photons/sec/subaperture for M=19. (Check with Allen or KAON 51)
Plate scale	~0.2 arcsec/pixel (per KAON 113; wrong?)
Pixel size	24 μm (or 48 μm if 2x2 binning)
Pixels across subap	400 μm / 24 μm = 16.7 pixels (or 8.3 if 2x2 binning)
Centroid disk	~ 1 arcsec diameter

Binning choice of 2x2 pixel binning (dim stars) or no binning (bright stars), selectable in software. To get the highest accuracy possible in the centroid calculations, binning is not used on brighter stars. Since there is effectively no dark current, the binning should be a noiseless process.

3.6 Questions

- Poorly illuminated pixels can be ignored (or do they give the best info) ?

4 Opto-mechanical

4.1 Tilt-Sensor Stage

The focus for the LBWFS is controlled by the Tilt Sensor Stage (TSS) Z-axis, and the position of the camera for off-axis acquisition is controlled by TSS-X and TSS-Y. The LBWFS will be moved to various parts of the 60-arcsec (43.5 mm at image plane) radius field of view in order to acquire the NGS. TSS motion control is accessed via the “TSS” button in Figure 7.

4.2 X-Y Lenslet Motion Control

An X-Y translation stage on the LBWFS allows the lenslet array to be moved to compensate for the shift of the pupil image that occurs when the sensor is moved in the field. Since the actuator spacing in the DM as seen at the exit pupil is 75 mm, when moving from the center to the extreme edge of the field, according to KAON 113, the pupil image will shift by 0.58 subapertures. To account for any randomness to the WFS centroid errors in moving between subapertures, the lenslet is shifted to counter the pupil shift, maintaining

alignment between the lenslets and the DM actuators. As noted in KAON 113, the dynamic range needs to be 0.58 subapertures ($0.58 \times 400 \mu\text{m} = 232 \mu\text{m}$), and a precision/repeatability of 0.1 subaperture diameter (or needs to be 0.01 instead) (or 40 μm).

Lick has done testing and found that the Newport 850G encoders are not able to reliably find home using their internal encoders; unreliable enough that they use external encoders for any application. As we will be using 850G encoders, it is expected that we will use external Renishaw encoders for the X and Y stages. LBWFS motion control is accessed via the “LBS” button in Figure 7.

4.3 Questions

- How to control TSS X, Y, Z? Need documentation to describe.

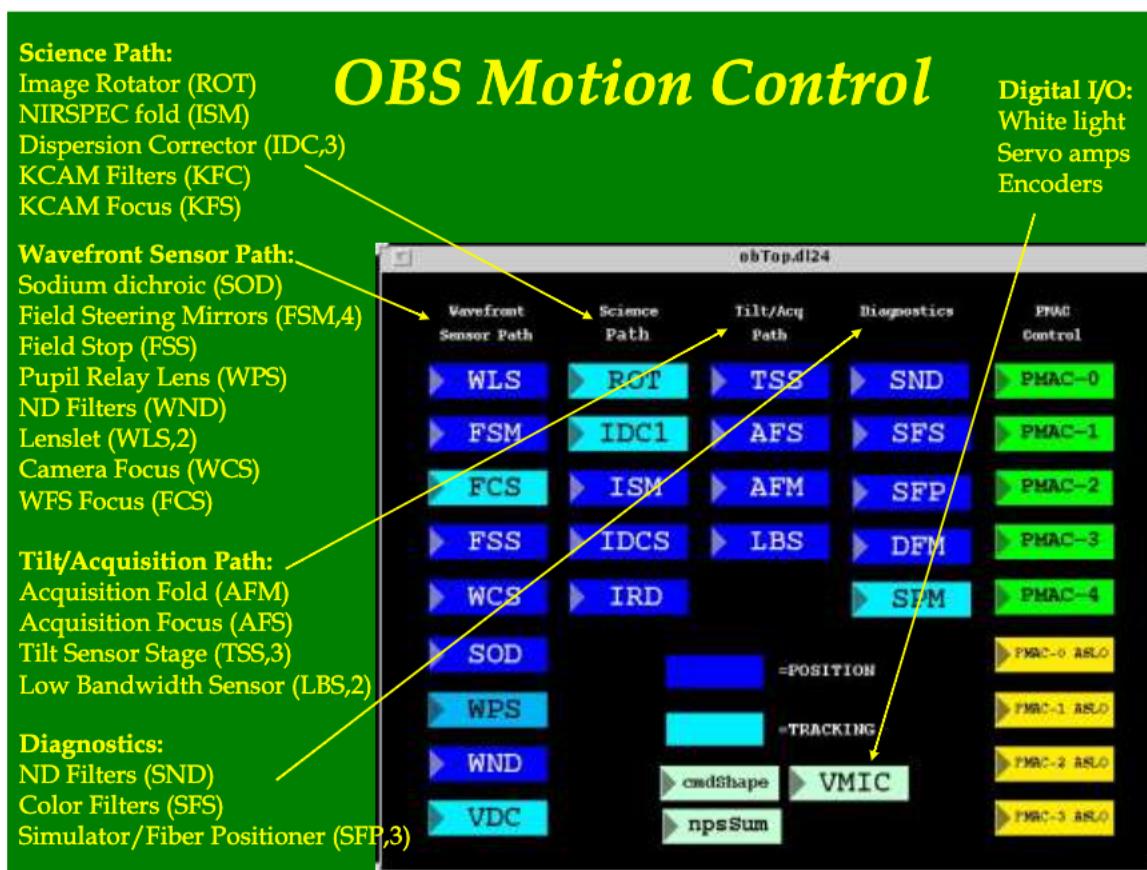


Figure 7: OBS motion control, with location of the “LBS” control indicated as a “Tilt/Acq Path” item. This is the X-Y translation stage referred to in this section. Also note the “TSS” control choice which can move the TSS in X, Y, and Z.

5 LBWFS Operation

5.1 Acquisition Mode of CCD

Need to describe how these requirements are derived from the overall requirements, and make sure they link together.

5.1.1 General Operation Requirements

- We need to have integration times between 1 sec and 300 sec.
- Need notification when integration complete

- Take single image as well as continuous cycle (i.e. closed loop)
- We need to be able to reset integration time as well as abort the current integration (abort needed as some exposures may be long)
- Need choice of 2x2 or no binning.

5.1.2 Commands

- Start acquisition
- Reset integration time
- Abort current integration
- Binning
- Exposure time

5.1.3 Status Output

- Exposure in process
- Exposure complete
- Reading ccd
- Writing to disk

5.1.4 Display Mode

- Raw image
- Subtracted image
- Zoom on image subarray

5.2 Image Reduction Algorithm

Insert appropriate documents from Hartman/Stomski documents (what other figures/info to include?).

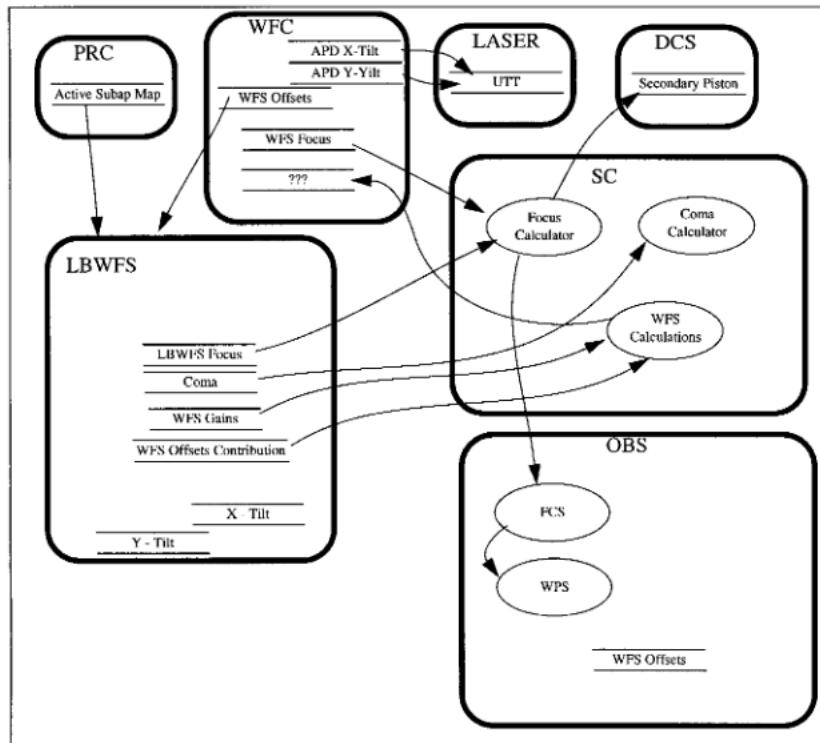


Figure 8: Laser Adaptive Optics Context Diagram (from Figure 3.2 of /home/shartman/ao/lbwfs_sd_dsgn.fm). Modifications: in “LBWFS”, remove “Coma”, replace “WFS Gains” with “FWHM”, “WFS Offset Contribution” to “Centroids”; in “SC” remove “Coma Calculator”; need to add outputs from Section 6.1.

5.3 User Interface and Display

The LBWFS aids in calibration of the DC offsets associated with the WFS when in LGS mode, by measuring the static centroid offsets which are then nulled by applying a correction to the fast WFS offsets. The LBWFS unloads the pointing corrections for each subaperture to the WFC. It also provides the gain to the WFC. The focus it senses is offloaded to the Focus Camera Stage (FCS).

5.3.1 General Requirements

- Operate ccd (see ‘acquisition mode of ccd’)
- Display images
- Display outputs
- Scriptable with needed information residing in keywords, as is done in the WFS

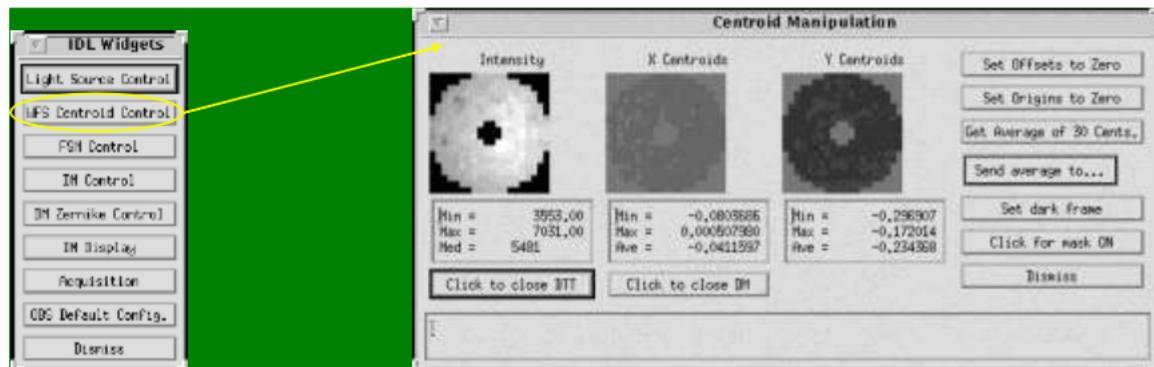


Figure 9: This is the WFS centroid manipulation. A similar display to provide information about the LBWFS centroids is anticipated (eg with intensities, FWHM, etc).

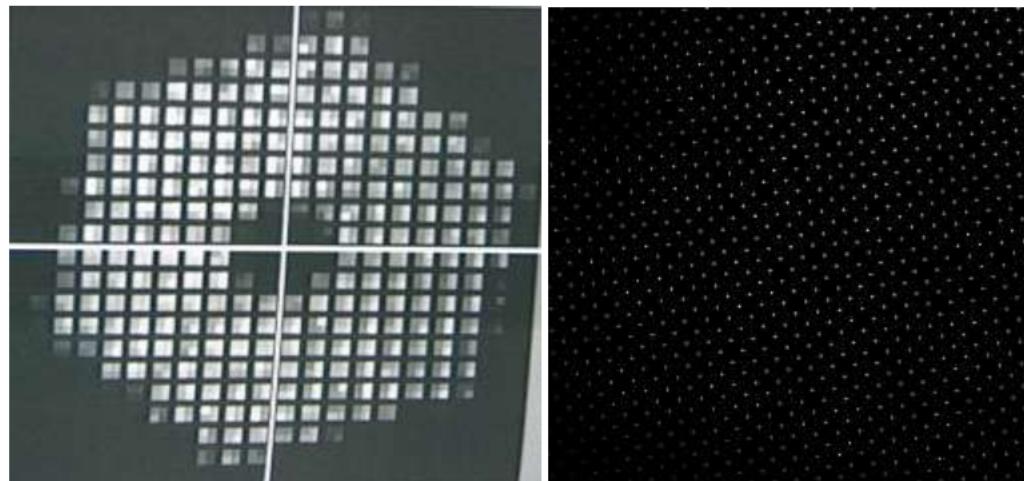


Figure 10: Left: This is the AOA (Adaptive Optics Associates) video camera display of the telescope pupil in the WFS camera. AOA was the manufacturer of our WFS camera. A similar display is anticipated for the LBWFS. Right: A test image from the lab using the LBWFS camera (replace with one with proper vertical orientation and even illumination).

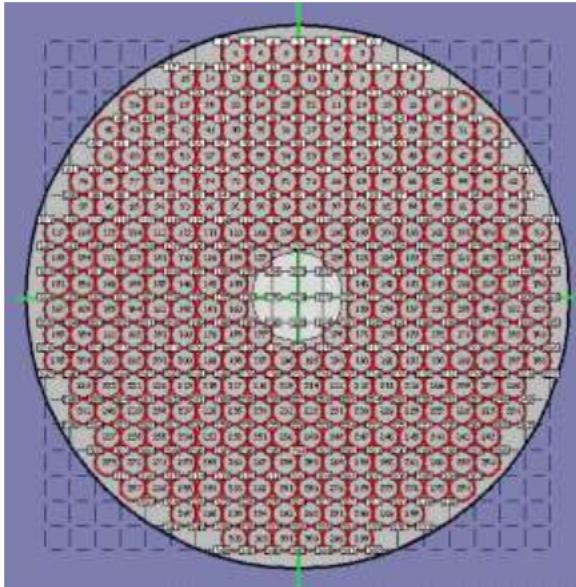


Figure 11: DM pupil with actuators (squares) and subapertures (circles). (placeholder: some numbering errors). Since both the LBWFS and WFS map to the DM (and hence each other), the actuator control relationship should be the same.

5.4 Questions

- What do we want to include in a display (similar to Figure 9 and Figure 10-left) for LBWFS output?
- What dead band to use?

6 LGS-Mode Information Outputs

6.1 Output Overview

6.1.1 Primary Outputs

- Raw fits image with header
- Array of x, y centroids
- Array of x, y, FWHM
- Array of integrated intensities within the subaperture (pixel sum)

6.1.2 Optional Outputs for Diagnosis

- Array of ellipticities and angles
- Array of maximum intensities
- Array of integrated intensities within the FWHM

6.2 Focus

The Strehl ratio and measured FWHM on the science instrument are a function of the focus of everything in the optical path to the science instrument. The dynamic focus contributors include the atmosphere, telescope and deformable mirror (DM). There are also some fixed focus terms due to the AO and science instrument optics. There are also some fixed, but changing focus terms such as when science instrument filters or plate scale are changed or an atmospheric dispersion corrector is installed. Here we will only deal with the dynamic focus contributors.

6.2.1 Definitions

The following quantities are focus shifts, along the optical axis, with respect to the science instrument's focal plane. The effect on F_{SCI} is positive when the individual focus terms are positive (positive is away from the telescope = into the science instrument):

- Z_{SCI} = focus shift on science instrument away from optimal position.
- Z_{ATM} = focus shift due to ATMospheric & dome seeing.
- Z_{TEL} = focus shift due to the TELEscope.
- Z_{SOD} = focus shift due to the SODium layer being at a different distance from the telescope than the distance we assumed for positioning the FCS.
- Z_{FCS} = position along the optical axis of the Focus Camera Stage (FCS) that supports the WFS. $Z_{FCS} = 0$ when the DM is flat and the FCS is conjugate to the science instrument focal plane.
- Z_{TSS} = position along the optical axis of the Tilt Sensor Stage (TSS) that supports the LBWFS. $Z_{TSS} = 0$ when the DM is flat and the TSS is conjugate to the science instrument focal plane.

The following quantities are focus terms. There is a one-to-one relationship assumed in these equations between focus terms and focus shifts:

- F_{DM} = focus term on Deformable Mirror (DM).
- F_{WFS} = focus term measured on high bandwidth WaveFront Sensor (WFS).
- F_{LBWFS} = focus term measured on Low Bandwidth WaveFront Sensor (LBWFS).

6.2.2 Requirement

We want to maintain the focus on the science instrument so that it does not significantly degrade the diffraction-limited image quality. At H-band the diffraction-limit is 0.034 arcsec. If we say that defocus, due to all contributing sources, cannot degrade the image by more than 10% then the allowable contribution is $[(1.1 * 0.034)^2 - (0.034)^2]^{1/2} = 0.016 \text{ arcsec} * 0.727 \text{ mm/arcsec} = 0.0113 \text{ mm}$. This is converted to an allowable shift in the focal plane by multiplying by the telescope $f/\# = 15$, so $\Delta Z = 0.17 \text{ mm}$. This should be the requirement at zenith.

It would be acceptable to allow the defocus contribution to grow as a function of zenith angle. If we allowed the defocus to match the diffraction-limited image size at a zenith angle of 60° , then $\Delta Z = 0.034 \text{ arcsec} * 0.727 \text{ mm/arcsec} * 15 = 0.37 \text{ mm}$.

6.2.3 Equations

With the AO DM loop off: $Z_{SCI} = Z_{ATM} + Z_{TEL} + F_{DM}$.

With the AO DM loop off and the DM flattened: $Z_{SCI} = Z_{ATM} + Z_{TEL}$.

6.2.3.1 NGS Mode

With the AO DM loop on: $Z_{SCI} = Z_{ATM} + Z_{TEL} + F_{DM}$.

Ideally the time averaged $\langle Z_{SCI} \rangle = 0$, because the control system tries to drive the wavefront sensor measured focus $F_{WFS} = Z_{ATM} + Z_{TEL} + F_{DM} - Z_{FCS}$ to zero by driving $F_{DM} = -(Z_{ATM} + Z_{TEL}) + Z_{FCS}$. Since the AO system was calibrated at the ideal FCS position, $Z_{FCS} = 0$; this position should not have changed, except to correct for a change requested to compensate for a science instrument change. If the FCS position has changed since calibration, then $\langle Z_{SCI} \rangle = Z_{FCS}$.

6.2.3.2 LGS Mode

With the AO DM loop on and in the absence of any LBWFS information:

$Z_{SCI} = Z_{ATM} + Z_{TEL} + F_{DM}$.

The control system drives the wavefront sensor measured focus $F_{WFS} = Z_{ATM} + Z_{TEL} + Z_{SOD} + F_{DM} - Z_{FCS}$ to zero by driving $F_{DM} = -(Z_{ATM} + Z_{TEL} + Z_{SOD}) + Z_{FCS}$.

Since the distance to the sodium layer varies as a function of the zenith angle, ξ , the FCS stage should be driven as a function of zenith angle:

$Z_{FCS}(h, \xi) = f h / (h - f \cos \xi) - f = f^2 \cos \xi / (h - f \cos \xi)$, where h is the height of the sodium layer above the telescope at zenith and f is the focal length of the telescope (150 m).

Table 7 provides some examples, and gives a feel for the magnitude and sensitivity of the FCS positioning.

Table 7: FCS positions for various LGS altitudes and zenith angles.

H (km)	ξ ($^{\circ}$)	Z_{FCS} (mm)
Infinity (NGS)	0	0
85	0	265.17
89.95	0	250.56
90	0	250.42
90	1	250.38
90	59	128.87
90	59.95	125.29
90	60	125.10

To determine the FCS position based upon distance to the LGS, the above equation of $Z_{FCS}(h, \xi)$ for 90 km sodium layer height yields $(112.58 - 250.42) / (200 - 90) = -1.2531$ mm/km and results in the following equation to determine Z_{FCS} based upon distance to the LGS:

$$Z_{FCS}(d) = -1.2531 * d_{LGS} + 363.2 + Co$$

where

- $Z_{FCS}(d)$ = position of the FCS (in mm)
- d_{LGS} = the distance to the LGS (measured in km)
- $Co = Z_{FCS}$ initial position for a given instrument (*is this in disagreement with above statement of $Z_{FCS} = 0$ at Co ?*)

The LBWFS measures $F_{LBWFS} = \langle Z_{ATM} \rangle + \langle Z_{TEL} \rangle + \langle F_{DM} \rangle - Z_{TSS}$. Here, “ $\langle \rangle$ ” indicates the time-average over the LBWFS integration.

If we set the TSS position with the DM flat, so that the LBWFS measured focus is zero when the fiber image is at best focus on the science instrument, then $Z_{TSS} = 0$ (this will be assumed from now on). Inserting the WFS driven $\langle F_{DM} \rangle$ equation from above, then we get $F_{LBWFS} = -\langle Z_{SOD} \rangle + \langle Z_{FCS} \rangle$. This is just the error in how accurately we have managed to drive the FCS to match the distance to the sodium layer. Note that this requires time-averaging the F_{DM} term during the LBWFS integration.

6.2.4 LGS Focus Conclusions

- FCS tracking as a function of zenith angle needs to be done to a fairly high accuracy.
- The LBWFS measured focus should be directly offloaded to the FCS position.
- The LBWFS measures the error in conjugation between the FCS position and the sodium layer.

6.3 Centroid Offset and Gain

The offsets as measured on the LBWFS will be applied to the WFS, subaperture by subaperture, with opposite sign.

Olivier Lai had a tool to do zonal and modal gain adjustment (part of the PRC tool—see KAON __ (?)). The gain is applied through the reconstructor. Since the spot is elliptical, we need to set the gain differently for x and y directions (the gain is set higher for the longer dimension because it is less sensitive). More difficult if spot is at an angle. Not sure how to implement, maybe a geometrical model.

The gains are an issue for the WFC or PRC. Since the spots are elongated on the WFC and get longer as you move away from the laser projection telescope, each subaperture must have an X and Y gain term. The FWHM measured by the LBWFS will then just be an additional factor effecting these gains:

$$\begin{aligned} \text{Gain (in the direction of elongation)} &= \text{factor } x [(\text{LGS length})^2 + (\text{seeing})^2 + (\text{optics})^2] \\ \text{Gain (perpendicular to elongation)} &= \text{factor } x [(\text{LGS width})^2 + (\text{seeing})^2 + (\text{optics})^2] \end{aligned}$$

6.4 Higher-Order Zernike Terms

- The choice is available to apply either the centroid (individual subaperture offsets) or a subset of Zernike terms (computed from the entire pupil). The Zernikes gains can be applied through the PRC. Note that the centroids need to have tip-tilt and focus removed before they can be applied since we send the LBWFS focus term by itself to the FCS.
- Once the wavefront is reconstructed from the individual subaperture, we decompose the wavefront into a Zernike base and then apply (with tip/tilt and focus removed) a given Zernike set to the WFS.
- Instead of just subaperture offsets and gains, can compute a Zernike offset and gains. There will probably be the same gain scaling factor for all subapertures.

6.5 Questions

- Need to determine how well we can control the Z_{FCS} for resolution in H, and how frequently we can update based upon zenith angle, ξ .

7 Diagnosis and Other Operating Modes

7.1 NGS Mode Diagnosis

- The LBWFS is not required for NGS observing. However, in the future we would like to incorporate it to act as a diagnostic tool.
- Use the LBWFS to measure the FWHM of the spot in each subaperture. We could use this as the gain corrections to the WFS system.

7.2 LGS Mode Diagnosis

- Look at the LGS with the LBWFS to measure the FWHM in two directions: along the line to the laser projector and orthogonal to this axis. This gives us the two gain terms we need for the WFS system.
- Look at the LGS with the LBWFS to determine the distance to the sodium layer. Just move along the TSS-Z axis until the average spot size is minimized. This corresponding position could be applied to the FCS for best focus on the sodium layer.

7.3 Issues Affecting LGS Mode Diagnosis

- The only opto-mechanical change required is to use the beamsplitter instead of the sodium dichroic (item 12 in Figure 3).
- There is a sodium rejection filter in front of the TTS/LBWFS beamsplitter cube. However, by switching from the sodium dichroic to the beamsplitter we should have around 4x more sodium light getting to the LBWFS, and the LGS is now in focus.
- Although using the beamsplitter instead of the sodium dichroic should provide enough signal, this needs to be verified. Additionally, it has to be determined if the TSS-Z stage has enough range to focus on the LGS. It needs the same range as the FCS.

7.4 Questions

- Is it possible to measure the LGS FWHM on the LBWFS, given the size of the LGS?

8 Other LBWFS Considerations

8.1 LGS Pupil Tracking

The Wavefront sensor Pupil Singlet (WPS) must also track linearly with the FCS in order to maintain pupil to lenslet registration. The position of this singlet is defined in KAON 137. From Appendix B of this KAON the first surface of this singlet should be located 15.04 mm from the back surface of the proceeding doublet, and 34.03 mm from the front of the lenslet array for a NGS. The change in this position for the LGS at 90 km is 3.07 mm, with respect to the NGS position, towards the lenslet. The change in this

position for the LGS at a distance of 200 km is 1.38 mm, with respect to the NGS position, towards the lenslet.

The WPS will track the FCS, and since the FCS position will be based upon focus, so to will the WPS. The WPS positions quoted above for the LGS at 90 and 200 km yield the following relationship, with slope $(32.65 - 30.96) / (200 - 90) = 0.0154 \text{ mm/km}$:

$$\text{WPS to lenslet distance (in mm)} = 0.0154 * \text{LGS distance (in km)} + 29.5773$$

$$d_{\text{WPS to lenslet}} = 0.0154 * d_{\text{LGS}} (\text{in km}) + 29.5773$$

where

- $d_{\text{WPS to lenslet}}$ = distance of the WPS from the lenslets (in mm)
- d_{LGS} = the distance to the LGS (measured in km)
- Co = Z_{FCS} initial position for a given instrument (*is this in disagreement with above statement of $Z_{\text{FCS}} = 0$ at Co?*)

8.2 LGS Calibrations

This section needs to be created, but refer to Appendix 1 for information from the Lick LGS system. It might be good to start observing on bright star to stabilize the system before going to a dim NGS on the LBWFS. One calibration procedure that is required is the same lenslet-to-DM registration procedure for the LBWFS as is used for the WFS.

8.3 Timing for Information Passing

TBD (see questions).

8.4 Questions

- The timing of offsets is not an issue?

9 Release Notes

0.1	2/6/2002	Document creation
0.2	2/11/2002	WFS/LBWFS comparisons and other modes added, initial comments incorporated.
0.3	2/22/2002	Additional figures.
0.4	2/25/2002	Further comments, figure changes, initial internal group release
0.5	3/28/2002	Initial comments from internal group
0.5b	10/1/2002	Added equations on FCS, WPS tracking of LGS

10 References and Further Reading

10.1 Keck Adaptive Optics Notes (KAON)

- 051 **Keck Adaptive Optics Error Budget**, Peter Wizinowich, 15 Sep 95 (*KeckShare – PDF & Word*)
- 098 **Motion and Position Control Specifications**, D. Scott Acton, 11 Apr 96 (rev. 26 Sep 96) (*KeckShare – PDF*)
- 113 **A Low-Bandwidth Wavefront Sensor**, D. Scott Acton, Thomas Gregory, Peter Wizinowich, 09 Aug 96 (*KeckShare – PDF*)
- 114 **The Opto-mechanical Design of the Acquisition Camera**, D. Scott Acton and Thomas Gregory, 15 Aug 96 revised 03 Dec 96 (*KeckShare – PDF*)
- 115 **The Sodium Rejection Filter**, D. Scott Acton, 19 Aug 96

- 120 **Quad-cell Issues**, D. Scott Acton, J. Nelson, J. Brase, 06 Sep 96 (*KeckShare – PDF*)
 143 **Low Bandwidth Wavefront Sensor Optical Design**, Peter Wizinowich, 12 Dec 97
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 Acton, Peter Wizinowich, Paul Stomski, Chris Shelton, Olivier Lai, J. Brase, 20 Mar 98,
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 Kona, Hawaii.
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 182 **Characterization of the lenslet arrays. (DRAFT)**, D. Scott Acton, 13 May 99 (rev. 9/2/99)
 (*KeckShare --PDF*)
 184 **Keck Adaptive Optics Facility Hardware Manual #1, Nasmyth Platform (DRAFT)**, 16 Aug
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 185 **Adaptive Optics Task List**, P. Wizinowich, 26 Aug 99 (*KeckShare – Word*)
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 the first year at the telescope**, P. Wizinowich, D.S. Acton, O.Lai, J. Gathright, W. Lupton, P.
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 Astronomical Telescopes & Instrumentation 2000, 27-31 March 2000, Munich, Germany.
 196 **Initial performance of the Keck AO waveform controller system**, E. Johansson et al., Mar
 2000 (*KeckShare – PDF*), Proceedings of SPIE's International Symposium on Astronomical
 Telescopes & Instrumentation 2000, 27-31 March 2000, Munich, Germany.
 212 **Status of the optics bench on Keck I and II**, D.S. Acton, 12 Jun 2001 (*KeckShare – Word*)

10.2 Other Documents

- *Task Notes and Gantt Chart for Keck II AO Subsystem Action Plan*, Adam Contos, 2/2002
- *LBWFS & TTS Notes from Conversations with S. Acton*, 8/2001, Adam Contos, 8/29/2001
- *Keck Adaptive Optics Software Design Book (v 2.7)*, 7/5/1996.
- *Keck Observatory Report No. 208, Adaptive Optics for Keck Observatory*, 1/1996.
- *Low Bandwidth Wavefront Sensor Software Design*, S. Hartman, 1/21/2001.
- *AO Software Status*, P. Stomski, 1/16/2002.

11 Appendices

11.1 Appendix 1: Lick System Documentation

The following steps are from observation at Lick using their LGS. They were still working on the procedure and will be updated soon. Additionally, it refers to Lick-specific steps and will need to be modified for Keck, but is a baseline. Their slow WFS works by illuminate 4 lenslets (out of 100's), and is used only for focus sensing. If more than four subapertures are illuminated, adjust the large beamsplitting cube in front of TTS. It is not incorporated into a servo loop and offsets are calculated and applied manually.

11.1.1 Lick AO Alignment

- move 2nd dichroic and WFS steering mirror as needed (?)
- turn off fiber source
- take background image
- take image with science camera (IRCAL) to see position
- when pointing done, fix centering
- if display problems, sync camera WFS
- close AO loop
- focus IRCAL so has same focus as AO system (use bracket-gamma filter with white light source)

- plot strehl vs focus position to find optimal
- do image sharpening (work on zernike modes for IRCAL to find zero point shape for DM)
- note: after internal alignment, get internal strehl of .9-.95, .6-.7 on a NGS, .3-.4 with off-axis 12th mag NGS

11.1.2 Lick Slow WFS Calibration Setup

- internal focus WFS and IRCAL
- on sky: focus telescope to minimize open-loop w/ NGS on fast WFS
- close loop
- take slow WFS image, and define this as the 'in focus' baseline
- move fast WFS to nominal LGS focus
- propagate laser
- on LGS: adjust fast WFS to minimize open loop focus

11.1.3 Tracking Sodium Layer Height Variations at Lick

- while closed on LGS, take a slow WFS image, measure focus
- move fast WFS according to chart (move -2mm if +2mm is the measurement)
- if there are large focus changes on fast WFS open/close, offload focus to secondary