Keck Next Generation Adaptive Optics

Keck Adaptive Optics Note 452

Multi-Object Adaptive Optics and Multi-Conjugate Adaptive Optics Architectures

System Design Trade Study

WBS 3.1.2.1.1

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Abstract

This trade study is intended to build our expertise with Multi Object and Multi Conjugate AO. The existing MOAO and MCAO design studies should be reviewed. This report is a summary of the issues related to these two approaches, including an understanding of the potential risks, technical challenges, limitations, advantages and room for improvement with each of these approaches.

1 Introduction

Astronomical adaptive optics systems have been traditionally targeted toward high resolution narrow field imaging and spectroscopy applications. The field of view with effective AO correction is limited by the *isoplanatic* angle, the angle over which a single wavefront phase correction for the atmospheric aberrations is coherent at the science wavelength, and this angle is usually much smaller than the telescope's designed field of view. Telescope time however is expensive, and a means of multiplexing the science of AO observations is of interest. The Keck Telescope, in the Next Generation Adaptive Optics (NGAO) program, is investigating wide-field multiplexing options for AO correction. The system will need multiple guide stars in order to measure wavefront and its variation over the field, making the wavefront measurement system effectively a tomographic probe of the atmospheric turbulence. The architecture of AO wavefront control however has a number of options and variations, which are the subject of this report.

There are two basic approaches: 1) *Multiple Conjugate Adaptive Optics* (MCAO), first proposed by Beckers[1] and pursued for the Gemini Telescope by Ellerbroek and Rigaut.[2] MCAO places multiple deformable mirrors at optical conjugates to specific altitudes in the atmosphere with the objective of minimizing the anisoplanatic effects by placing the correction optically closer to the points at which aberrations are introduced. The MCAO optical relay and deformable mirrors (DMs) are designed to pass the entire science field of view, and, generally, all the "technical" field which includes laser guidestars and tip/tilt stars. 2) *Multiple Object Adaptive Optics* (MOAO), first introduced as the ESO Falcon instrument[3], and later suggested as an instrument option for the Thirty Meter Telescope (TMT), uses separate narrow field wavefront correctors for each of several objects in the field. The MOAO units are deployable over the field and each contains its own AO relay and DM. The technical field must be handled by a separate relay, or possibly, using similar MOAO units for each guide star.

Diagrams of generic MCAO and MOAO architectures are shown in Figure 1. A hybrid MCAO/MOAO architecture is depicted in Figure 2.

-Discussion of the features of each architecture…-

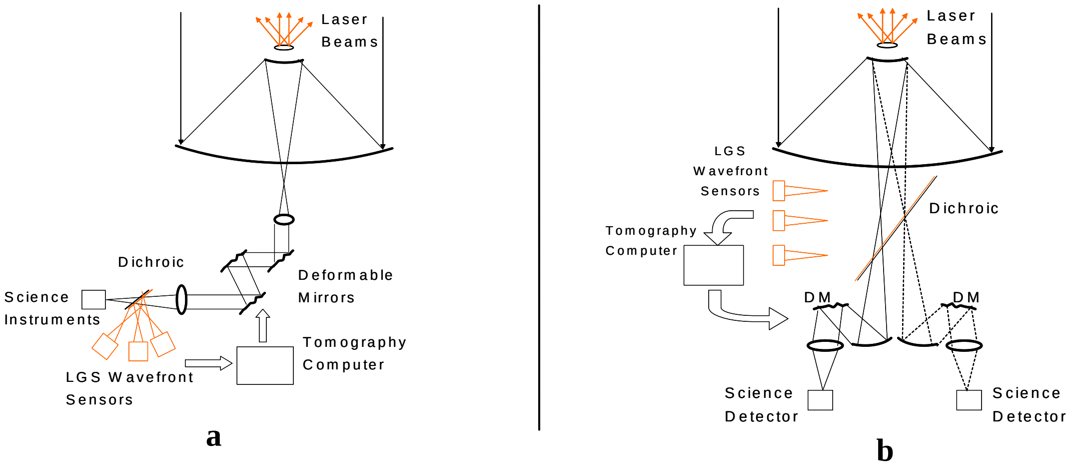


Figure 1 Configurations of astronomical adaptive optics systems: a) multiple conjugate, b) multiple object.

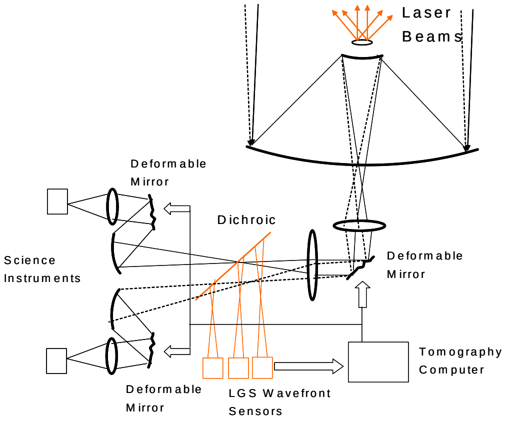


Figure 2 Hybrid MCAO/MOAO configuration.

In MOAO, each science object has its own deformable mirror with a correction determined by a line integral in that direction though the tomographically measured volume of atmosphere.

The wide field tomographic wavefront measurements enable correction of tip/tilt stars on the field. A corrected tip/tilt star is more efficient for tilt measurement per photon than an uncorrected star, therefore if control loops could be “boot-strapped” to close on dimmer tip/tilt stars than could be done in open seeing, this would increase the system’s sky coverage by increasing the on-sky density of useable tip/tilt stars.

2 Summary of Present Systems and Concepts

2.1 Thirty Meter Telescope (TMT)

The Thirty Meter Telescope project has completed a conceptual design for a baseline AO instrument based on the MCAO architecture, the Narrow Field Infrared Adaptive Optics System (NFIRAOS).[4] Although not initially intended for wide field science (its first-light instrument is a 2-arcsec field integral field spectrograph), the MCAO system passes a 2 arcminute technical field and has two deformable mirrors, one conjugate to the ground and one conjugate to 10 km. The wider technical field of the AO relay passes the laser guidestar constellation and tip/tilt stars. The laser guidestar light thus probes the DM figure in a closed loop control architecture. The tip/tilt stars will gain some benefit of AO correction which will enable higher sky coverage through the use of dimmer tip/tilt stars favorably positioned to reduce tilt anisplanatism.[5]

TMT has also done a feasibility study for the Infrared Multiple Object Spectrograph (IRMOS) instrument which will use the MOAO concept to produce high resolution images of up to 20 objects on a 5 arcminute diameter field[6]. Separate integral field units (IFUs) will slice up these fields to produce spectral data cubes of each object. Each subfield being a 40x40 grid of 50 milliarcsecond spatial elements and the spectrograph operating at up to R=4000.

2.2 Gemini South MCAO

Gemini Observatory has built a 5 LGS, 3 DM MCAO system, scheduled to see first light in 2007, which is designed to feed a wide-field diffraction-limited IR imager (GSAOI) and a multi object deployable arm spectrograph (Flamingos-2) on the southern telescope at Cerro Pachon. This system is expected to have a Strehl of 0.5 or better at 2 microns over a 60 arcsecond radius field of view.[7]

2.3 European Southern Observatory MCAO Demonstrator (MAD)

ESO has fielded a demonstration MCAO instrument on one of the 8 meter VLT telescopes. This system uses a constellation of natural guidestars (only) to do MCAO using either the star-oriented (3 stars into Shack-Hartmann wavefront sensors) or layer-oriented (up to 8 stars with pyramid wavefront sensors) approach. The system has two deformable mirrors, one conjugate to the ground and one conjugate to 10 km altitude, and is expected to get approximately 39% Strehl in K-band on a 2 arcminute field of view . This is intended only as a demonstrator for OWL and next generation VLT AO system technology and no serious science use is envisioned.[8] Miska LeLouarn reported at the 2006 SPIE meeting that the system had been successfully tested in the laboratory and it has been recently deployed at VLT where it has achieved reasonable MCAO correction performance on-sky over a 110 arcsecond field with an asterism of 3 natural guide stars.[9]

2.4 European Southern Observatory Falcon Concept

Falcon was proposed for the VLT by researchers at U. Paris-Meudon as a multiple deployable unit wavefront sensing and correction system over a very wide (25 arcminute) field.[3] This is presently at a conceptual design phase.

2.5 Very Large Telescope (European Southern Observatory, Chile) AO upgrades

Opticon is a project funded by the European commission bringing together 47 European research partners. One of the "Joint Research Activities" is concept, technology, and design development of adaptive optics upgrades for the ESO Very Large Telescopes in Chile, lead by Norbert Hubin. Systems under study include Natural Guide Star (NGS) Extreme AO (XAO), Multi-Conjugate Adaptive Optics (MCAO) with multiple Fields of View, and multi Laser Guide Star (LGS) systems[10]. The study includes a serious development of an adaptive secondary mirror for a ground-layer AO system which will feed a bank of multiple visible light spectrometers (MUSE) and a wide field infrared camera/spectrograph (HAWK-I). HAWK-I will place 0.1 arcsec/pixel on a 7.5 arcmin square field.

2.6 European Extremely Large Telescope (E-ELT)

ELT has recently completed studies on instrumentation carried out under the EU Framework 6 Design Study. Instrumentation studies for AO included[11]

- a high resolution infrared spectrograph (HISPEC)
- a multi-object, multi-field spectrometer and imager (MOMSI) for extragalactic stellar populations well beyond the Local Group
- a wide-field spectrograph employing deployable MOAO units
- an exoplanet imaging camera and spectrograph (EPICS)
- a near infrared diffraction-limited imager

3 Candidate Science Merit Functions

The goal of any scientific instrument is to obtain sufficiently accurate data to make scientific conclusions quickly, assuredly, and at reasonable cost. Taking this a step further, one might hypothesize a quantitative merit function that incorporates cost, accuracy, and time to conclusions and then seek an architecture and a design subspace that is near the optimum. Note that engineers would also include a measure of risk to meeting construction cost or schedule but, for the moment, we suspend disbelief and assume the what we envision we can build, and will deal with risk analysis and mitigation later. Since Keck NGAO is more or less a system of instruments rather than one instrument with a specific purpose, it has a number of possibly competing goals and scientific merit functions. Here, we will endeavor to start the process of a few merit functions that might be useful to evaluate for the science cases as an aid in architectural or design parameter downselects.

There are a number of subtle difficulties in setting up the one definitive system merit function. In a world of many users, the key danger is that it is easy for the advocate of any particular merit function to be inadvertently or even explicitly biased toward his own scientific case of interest. What I attempt to do here is present some possible starting points for discussion, certainly subject to revision, adjustment, or throwing out. Also, I am not suggesting that a quantitative merit function necessarily must be the principal decision or downselection tool. It could simply function as an additional input to the process.

The following are a set of possible ideas:

3.1 Merit based on science efficiency

$$m = \text{Strehl x sky\_coverage} \times \text{multiplicity} \times \text{throughput/background\_noise}$$

This is a traditional approach that counts useful photons per hour of exposure time. There would be additional factors that depend on spectral resolution and bandwidth. This merit function would probably favor the galaxy survey science cases since it doesn't directly address crowded contiguous fields.

3.2 Merit based on science accuracy

$$m = \text{resolution} \times \text{psf\_knowledge} \times \text{(field\_of\_view/star\_density)} \times \text{confusion\_limit\_magnitude(Strehl,star\_density)} \times \text{throughput/background\_noise} \times \text{sky\_coverage}$$

This one is more tuned to the crowded field stellar population science cases.

3.3 Merit based on allocation of telescope time

$$m = \Sigma_i \text{ (\%time allocated to science case } i\text{) x (performance merit for science case } i\text{)}$$

This approach attempts to be fair to each science case, but requires judgment of importance (reflected in a prediction of allocated telescope time) of each case.

Factors to consider in formulating the merit functions:

- Instrument "multiplicity" = number of simultaneous independent science channels. Could be MOAO units, or patches of contiguous field, or simultaneous spectral channels.
- Size of science instrument field.
- Spatial resolution
- Spectral resolution
- Photon efficiency as it depends on system architecture

- Sky coverage, e.g. as limited by natural guide star availability, but factoring in tilt accuracy requirements: e.g. diffraction-limit or spectrometer slit size.

4 AO architectural configurations

4.1 Conventional AO architecture

Generic configuration diagrams are illustrated below. The purpose of these diagrams is to enumerate the components and where they would go in the light path. The first diagram (Figure 3) shows a "conventional" architecture, i.e. one that is similar to almost all of the single-conjugate AO systems in use today (with the exception of the MMT, which uses an adaptive secondary), and to the Gemini South MCAO system.

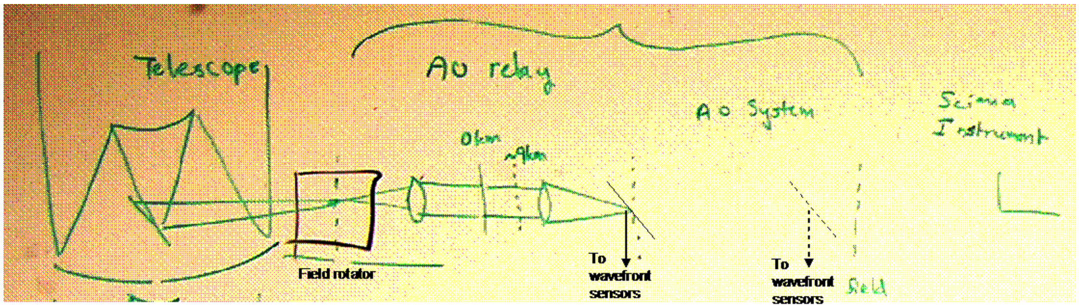


Figure 3 Generic "conventional" architecture. The AO system is on the Nasmyth. Component blocks are the field rotation mechanism (K mirror), large AO relay which handles the largest field of regard for any downstream science instrument and containing one or more conjugate deformable mirrors, followed by the a possible secondary AO system that might be specialized to the science, e.g. MOAO units, then followed by the science instrument. The front-end relay can act as a common "woofer."

4.2 Closed loop (MCAO) architecture

The diagram in Figure 4 shows the closed-loop architecture. This architecture can be well suited for narrow science fields and corresponding narrow guidestar constellations. This is essentially the "conventional" architecture, but we'll make the distinction here in that the MCAO system could consist entirely of MEMS deformable mirrors eliminating the large optics needed to feed piezo DMs at the front end, or it can contain a mix of the two technologies, e.g. where the piezo DM acts as the woofer. In either case, the system operates closed loop because the laser and tip/tilt guidestar light reflects off all of the science wavefront-correcting mirrors before being picked off by wavefront sensors.

In spite of the small aperture size, which may introduce optical design problems due to Lagrange Invariant limitations, MEMS are feasible to use on the modest technical fields necessary to probe the cylinder of atmosphere above the Keck's 10 meter aperture with laser guidestars.

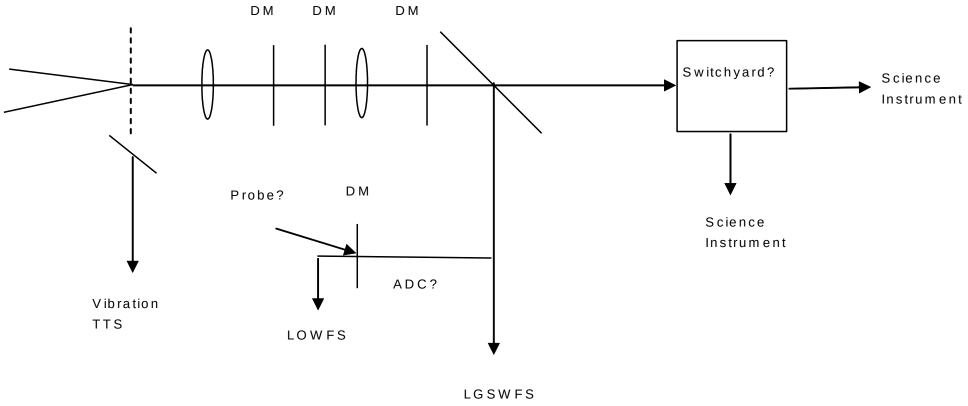


Figure 4 Generic closed loop architecture. The laser and natural guidestar pickoffs occur after the deformable mirrors. In this configuration, the deformable mirrors must pass the entire technical field containing all the guidestars (exception being the bright guidestar used as a telescope vibration sensor).

4.3 Open loop (MOAO) architecture

The diagram in **Figure 5** shows the open-loop architecture, which can be MCAO, MOAO, or hybrid in its wavefront control. The key feature of this approach is that deformable mirrors are driven “go-to” based on measurements from the guidestars which are picked off at the telescope focal plane ahead of the AO system and science path. There are two configuration options that make the open-loop architecture perform closer to a closed loop system. The first is to probe the deformable mirrors with a separate beam. This would be done if the go-to actuation is deemed not sufficiently accurate. Such a probe would most likely be one arm of an interferometer and use sufficient laser light to get a very accurate reading of the DM surface shape. The second option is to make the wavefront sensors closed loop systems so that the Hartmann sensors operate close to null where they are more linear and operate at highest sensitivity. The wavefront is then read out as the sum of the deformable mirror command plus the Hartmann sensor residual. We don’t believe that this second option will be necessary as the required WFS open-loop sensing linearity can be achieved using the radial format CCD design.[12]

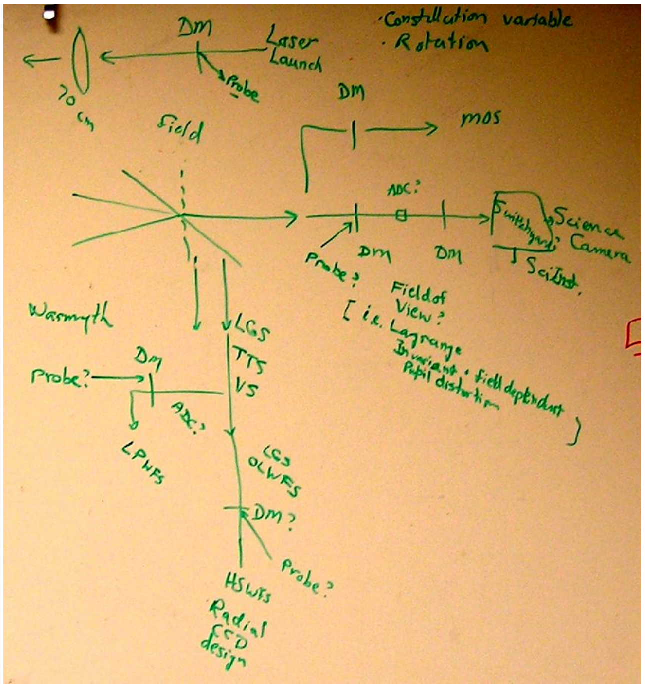


Figure 5 Generic open loop architecture. Laser and natural guidestars are picked off at the telescope focal plane and sent to the various wavefront sensors. On the science leg are multi-conjugate or multi-object deformable mirror paths.

4.4 *Hybrid (MCAO/MOAO) configuration*

The hybrid MCAO/MOAO architecture uses elements from both closed loop and open loop architectures. The “front-end” is an MCAO relay with multiple DMs in series. This is followed by the wavefront sensor pickoffs. The wavefront sensing and control system senses the phase introduced by both the atmospheric and by the front end DMs and uses this information to drive these DMs in closed loop, as well as drive the subsequent DMs associated with multiple science arms in open loop. After the the MCAO relay and WFS pickoff is an MOAO configuration of multiplexed science instrument arms (spectrographs or imagers) each with its own DM.

In this configuration, the system inherits many of the advantages of an MOAO architecture, e.g. the reduced anisoplanatism over a wide field. This configuration also relives the need for woofer DMs in each arm, as the MCAO relay acts as a common woofer.

4.5 *Common elements*

Some components or component choices are common amongst architectures. These are discussed here.

All of the architectures can coexist with an adaptive secondary mirror (AM2), however to use a (presumably single, since they are very expensive) AM2 efficiently in front of all the KNGAO instruments, one must trade off the specifications of this mirror according to its science benefits. E.g. the woofer for a visible wavelength AO system and the main DM for a near-thermal IR AO system will have differing actuator requirements. Further discussion of this issue is beyond the scope of this study but it included in the AM2 study (WBS #3.1.2.1.3).

Each of these systems will need to accommodate the following components:

- Atmospheric dispersion compensator, science leg
- Atmospheric dispersion compensator, tip/tilt sensor
- Field de-rotation – options:
    - At front end (big K-mirror) ahead of all systems
    - At front end ahead of deformable mirrors. Wavefront sensor unit rotates on a turret (open-loop architecture)
    - At back end after the deformable mirrors but before the wavefront sensor pickoff (closed-loop architecture)
    - At back end after the deformable mirrors and after the wavefront sensor pickoff; wavefront sensor unit rotates on a turret (closed loop architecture)
    - At back end in open-loop architecture
    - Instrument specific field de-rotation:
        - K-mirror in instrument
        - Instrument rotates
        - No field de-rotation – instrument reads out fast, rotates images in software, and co-adds images
- Instrument switchyard options:
    - Deployable instruments move into position at output focal plane
    - Multiple instruments are fixed on the platform, but fed via a switchable steering mirror or dichroic.
- Telescope vibration sensor
    - A bright star well off-axis with sensor system tuned to the know spectrum of telescope vibration. Use to feed forward counter-vibration to the AO tip/tilt mirror.
    - Option: use one of the tip/tilt stars instead. This increases the TT sensing bandwidth requirements and reduces sky coverage significantly.

Field de-rotation is the subject of another design-trade study (WBS # 3.1.2.2.3). So is the instrument switchyard (WBS # 3.2.3.3).

5 Concepts for Keck NGAO systems

We now present a few particular configurations that look attractive to carry forward as strawman concepts for the Keck NGAO system, in consideration of the emerging science cases. These are, after some deliberation by the author of this study and with inputs from core team members Brian Bauman and Richard Dekany, and science team lead Claire Max, appearing to be most interesting in terms of science productivity per unit cost. Of course, at this early stage, these are not the only remaining options nor are they deduced quantitatively from the results of this study. Instead, they are the first "strawman" concepts. There can also certainly be some mixing and matching of the generic architecture component options which were described above.

First, we reiterate the baseline science instrument suite as given in the proposal:

Imaging:
- Visible imager
- Near-IR imager
- Thermal near-IR imager

Spectroscopy:
- Near IR IFU
- Visible IFU
- Deployable near IR IFU

More details about the envisioned requirements of these instruments can be found in the NGAO proposal document.[13]

5.1 Narrow-field on-axis closed loop multi-conjugate AO for the visible

Instruments fed: visible IFU, visible imager.

Field: 20 arcsec science (30 arcsec technical) contiguous field.

Wavelengths: 0.6 to 1.1 microns. Must be refocused for individual bands V,R,I

Concept:

The working wavefront control concept here is:

A) 2 or 3-DMs operating in closed loop MCAO configuration passing 5 LGS and correcting TT stars in the visible. Separate DMs in the low-order wavefront sensors, operating open loop, to enhance sky coverage. LOWFS are visible wavelength sensing pyramid sensors measuring up to Zernike n=2.

Two other wavefront control configuration concepts were considered but (tentatively, at this point) rejected:

B) Single DM in science leg. WFS pickoff in focal plane after this DM and DMs in each WFS to compensate for the anisoplanatism. This is more DMs than WFS measurements and so has unobservable modes such that the science DM is not really closed loop. Hence this option is tentatively rejected.

C) Single DM in science leg. WFS pickoff (dichroic) in focal plane after this DM and 2 high-altitude DMs in MCAO configuration in the WFS arm ahead of all the WFS. This does not assure that the science leg DM is optimal for on-axis without some open-loop extrapolation and may operate more like a ground layer AO (GLAO) system. Hence this option is also, tentatively, rejected.

Optical design is optimized for the visible and designed to pass the LGS constellation with a minimum of pupil distortion and aberration of off-axis LGS wavefronts at all zenith distances. Brian Bauman has proposed an on-axis refractive design as one of the outcomes of the AO relay design trade study (WBS # 3.1.2.2.2).

If it is optically feasible, this concept can be combined with the concept for the narrow-field *infrared* MCAO system described below. The low-order wavefront sensors (pyramid sensors) would then be infrared sensors. However, this combination option introduces the considerably increased complexity of an infrared instrument. Carrying the option of a separate visible system would allow for a simplified design making it a quick and cheap first light alternative. But this would be at the expense of perhaps becoming a “throw-away” in favor of a subsequent IR version.

5.2 Narrow-field closed-loop multi-conjugate AO for the infrared

Instruments fed: Near IR IFU, Near IR imager.

Field: 20 arcsecond science field, 30 arcsecond technical, contiguous field

Wavelength range: 1.2 to 2.45 microns. Must be refocused for individual bands J, H, K

Concept:

2 or 3 DMs operating in closed loop MCAO configuration passing 5 LGS and correcting TT stars in the infrared. Separate DMs in the TT sensors, operating open loop, to enhance sky coverage. LOWFS are infrared pyramid sensors sensing up to Zernike n=2. Cooled optics for low IR emissivity.

Optical design is optimized for the infrared and designed to pass the LGS constellation with a minimum of pupil distortion and aberration of off-axis LGS wavefronts at all zenith distances. An on-axis refractive design (see AO relay design trade study WBS # 3.1.2.2.2) keeps these distortions and aberrations low enough that a variable compensator, running open loop, for each WFS is not necessary.

Differences with visible system: optics optimized for the IR. Could be cooled for low emissivity. LOWFS are infrared as opposed to visible.

If it is optically feasible, this concept can be combined with the concept for the narrow-field visible MCAO system described above.

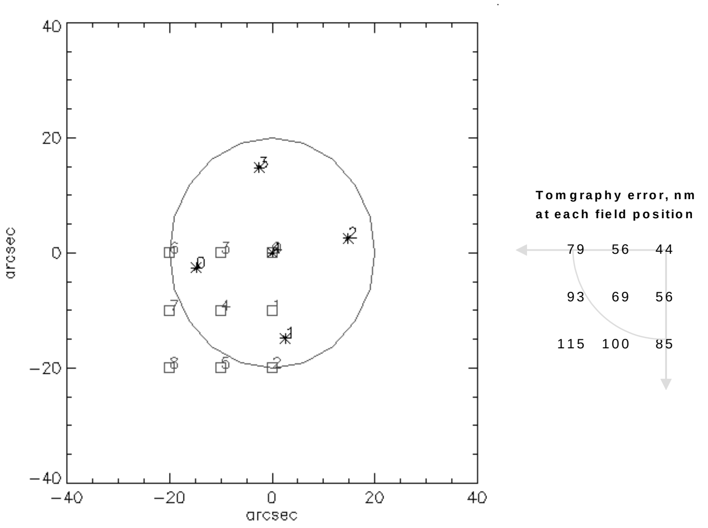


Figure 6 Tomography error in the narrow-field AO system (5 LGS on 30 arcsecond diameter). See Figure 8 for a plot of the generalized anisoplanatism with 3 DMs.

5.3 Wide-field open-loop multi-object AO for the visible and infrared

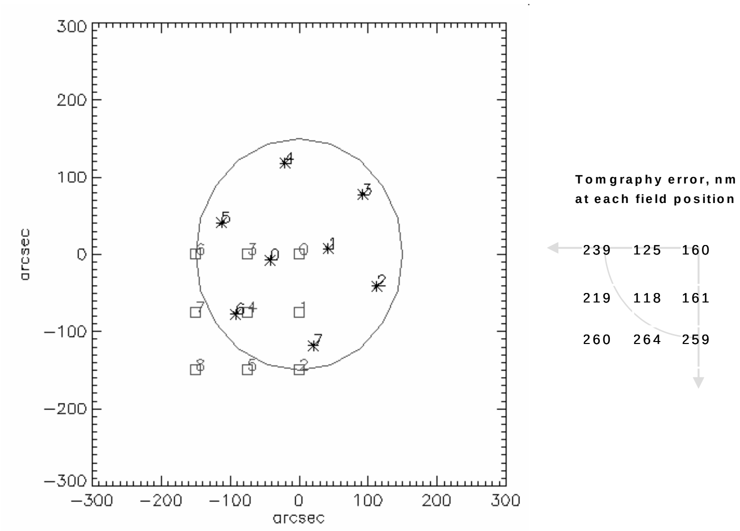
Instruments fed: Near IR IFU, Near IR imager, deployable near IR IFU.

Field: 3 by 3.5 arcsecond rectangular sub fields for each deployable unit. 4 arcminute field of regard for science pickoffs. Up to 6 pickoffs deployable to as close as 20 arcseconds separation. 16 arcsecond science field for single on-axis unit.

Wavelength range: 1.2 to 2.45 microns.

Concept:

Deformable mirrors in each arm of a multi-object system. The DMs could be either A) a woofer-tweeter pair, with the woofer being a low-order large stroke MEMS device and the tweeter being a high-order low-stroke MEMS device, or B) use the highest stroke tweeter MEMS device available and suffer from some percentage of actuators saturating. Note: the present 4k MEMS design from Boston Micromachines for GPI has as baseline 4 micron surface (8 micron wavefront) stroke. See analysis of actuator stroke requirements in section 6. LGS wavefront sensing is open-loop, using radial CCD.[12] Tip/Tilt (LOWFS) sensing is with infrared pyramid wavefront sensors[14] (to Zernike n=2) being fed by DMs operating open-loop and optimized for the tip/tilt direction according to the tomography reconstructor. Three tip/tilt stars. Up to 8-9 LGS variably deployable over the 4 arcminute field of regard. The WFS pick-off is as depicted in the open loop configuration diagram (Figure 5). The WFS unit is on a rotating turret, mounted vertically to minimize flexure. Options for IFU system rotation: vertical, rotating turret; horizontal rotating turret; very big (>180mm) front-end K-mirror.



Tomgraphy error, nm
at each field position

239	125	160
219	118	161
260	264	259

Figure 7 Tomography error in the wide-field AO system (8 LGS on 240 arcsecond diameter).

5.4 Narrow-field thermal near IR AO system

Instrument fed: Thermal near IR imager.

Field: 25 arcsec

Wavelength range: 3 to 5.3 microns.

Concept:

Single MEMS deformable mirror and relay optics in cryogenic chamber. Could use the 6 micron stroke mirror now available from BMC (these are two slow and too low order for the visible and near-IR AO systems). One LGS and one TT star. LGS is sensed closed loop (after reflecting off of DM). For sky coverage, TT star will likely need to be picked off from a >60 arcsec field (correction is not good enough for a near-IR pyramid sensor). Another option is to re-use the near-IR AO systems’ LOWFS and high-order WFS to do high-order wavefront correction of a nearby tip/tilt star; this will need another LGS placed on the TT star for TT wavefront sensing, or the whole laser constellation used in the other AO configurations is reused here. An error-budget study will need to determine if there is important performance improvement to be had by sensing closer tip/tilt stars this way. Question: can we use the science focal plane to get a nearby dim, but corrected TT star, now sensed at the science wavelength?

6 Science advantages and disadvantages of each architecture

We now investigate the advantages and disadvantages, from the science benefit and observing efficiency perspective, of each AO system architecture configurations discussed in section 4. It is best to do this by considering some typical science observing scenarios and then evaluating how well each system would do.

In the following discussion, it is useful to refer to charts (

Figure 8) that illustrate the typical trade-offs in MCAO systems between best Strehl on a field of view versus the extent of the field of view. The main source of wavefront error is generalized anisoplanatism[15] which is due to a finite the number of DMs sampling a continuous atmospheric volume. MCAO design choices include the number and conjugate altitude placement of DMs, plus a choice of corrected field and optimization criteria over that field.

6.1 Observing Scenarios, MCAO

1. The first case is narrow field single object MCAO. This case demands high Strehl, on-axis science operation, similar to that envisioned for TMT's NFIRAOS. Target science programs would be young stellar objects (YSOs), the galactic center, and Solar System planets. The system uses multiple-laser guidestar tomography, and relies on correcting tip/tilt stars on a wide field, using multiple DMs, for good sky coverage, but the science is on-axis. Since the tip/tilt stars must be corrected, there must be sufficient Strehl off-axis, which means that wavefront control cannot be optimized for the narrow field but instead some compromise must be made to achieve reasonable Strehl on a wide field.

2. The next case is wide-field high Strehl imaging. Again, a number of conjugate DMs are needed to get both the science and technical fields. The imaging camera would have a wide field – 1 to 1.33 arcmin in the case of 4096 pixel = 60 arcsec e.g. plate scales of 0.01, 0.02 / pixel. Science programs include photometry of stars in crowded fields, stars in extragalactic bulges or globular clusters, and imaging of fields of hi-z galaxies. The contiguous field allows multiple PSF stars in the field, which is a possible advantage if the number of PSF stars exceeds the number of deployable units that would be available in a comparable multi-object IFU approach. In wide field MCAO, the science field of view is comparable to the technical field, so the wavefront control objectives for science and technical objects are compatible, however, the system design is still led to a compromise of best-possible on-axis Strehl performance to achieve reasonable correction over the wide field.

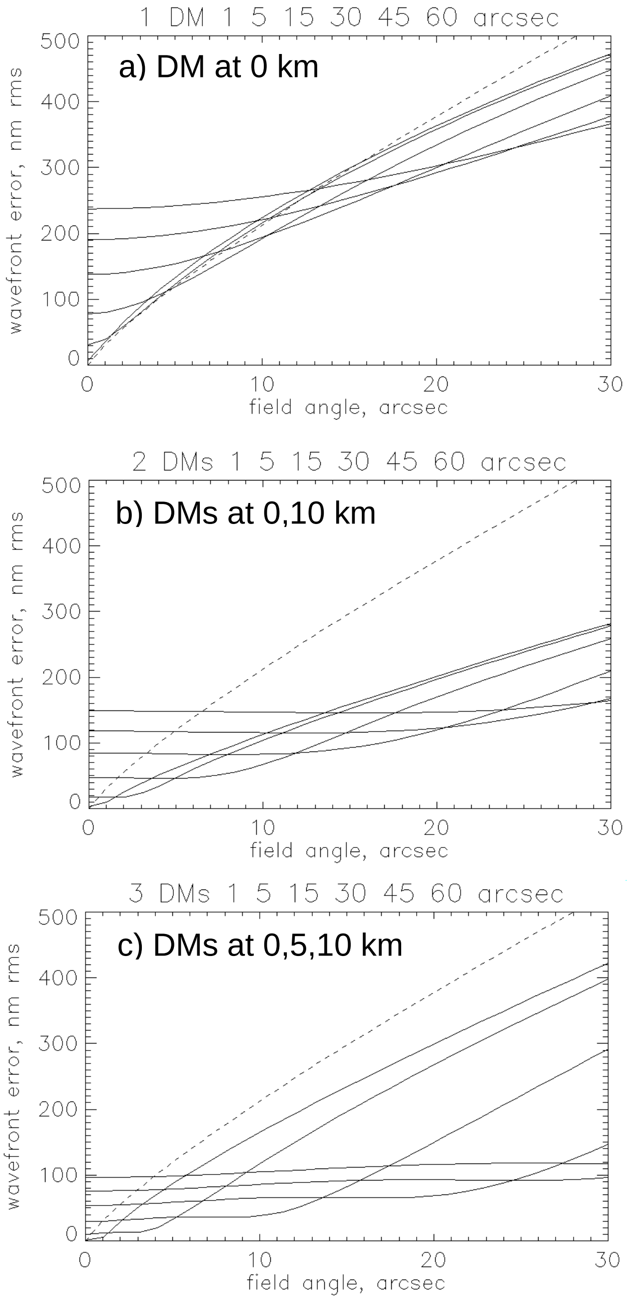


Figure 8 Generalized anisoplanatism error for a) 1-DM, b) 2-DM, and c) 3-DM MCAO system. MCAO correction can be optimized over a sub-region of the field, in this case a disk of radius 1, 5, 15, 30, 45, and 60 arcseconds respectively for each curve in the graphs. Note that as the radius of the optimimizaion field increases, the wavefront error within the field increases. Inside the field the wavefront error is relatively constant. Outside, it rises rapidly. The dashed line is the limiting (infinite aperture)form of the anisoplanatic error, $\sigma^2=(\theta/\theta_0)^{5/3}$. The other curves assume a 10 meter aperture telescope and the 7-layer Cn2 profile given by Flicker [ref] with an r_0 of 15.6 cm and θ_0 of 3.1 arcsec. Uncorrected piston-tip/tilt-removed wavefront error is 933 nm.

From an analysis of these observing scenario cases we can conclude that, although MCAO has reduced anisoplanatism compared to single conjugate AO, it still must sacrifice peak possible on-axis performance in order to correct over the wide field, and in all cases, even the narrow field science case, the architecture demands a wide technical field with AO correction. There are a small number of advantages to the MCAO system passing a wide continguous field, including crowded field photometry, more choices of PSF stars, and packing density of IFU unit pickoffs.

The MCAO architecture allows the deformable mirrors to be controlled in closed loop, which eliminates DM calibration and drift error. If DM solutions can not be found that will driven open loop to commanded shapes reliably, this will become a distinct advantage of the MCAO architecture.

In summary, the science advantages of MCAO are:

1) Contiguous AO-corrected field of view.
    a. Choice of PSF stars in the field
    b. Higher packing density of IFU pickoffs
    c. Very extended objects Jupiter, Saturn, Uranus rings
    d. Long exposure of hi-Z field galaxies
2) DMs in closed loop, eliminating DM calibration error and drift.

The science disadvantages of the MCAO architecture are:

1) Higher field-dependent anisoplanatic error than a MOAO system
2) Extra surfaces in the relay contribute to background emission and reduce throughput.
3) DMs in series could distort the contiguous field randomly resulting in higher astrometric error.

4) Front-end relay adds field and zenith dependent distortion and aberration into the LGS beams, which, even if pre-calibrated, will introduce some amount of wavefront error to the science beams via the closed loop.

6.2 Observing Scenarios, MOAO

1. The first case is on-axis single object MOAO. This would use a single deformable mirror feeding a single imager, spectrometer, or integral field spectrograph, using multiple-laser guidestar tomography to determine the mirror control. Target science programs would be young stellar objects (YSOs), the galactic center, and Solar System planets. Tip/tilt stars on the surrounding wide field will each need their own DM in order to achieve the improved sky coverage enabled by sharpening dim tip/tilt stars. A distinct advantage for MOAO is that the Strehl of these tip/tilt stars will be higher than in the MCAO case since they will have no anisoplanatic correction error.

2. The second case is multiple object MOAO over a wide field of regard using multiple deployable IFUs. Each IFU has its own dedicated wavefront-correcting DM. Some or all deployable units could have an imaging mode capability as an option. Science programs include hi-Z galaxies and spectroscopy of individual stars in crowded fields. In this

approach, the isoplanatic error is reduced to at or near on-axis small-field optimized performance for every deployable unit. For example, Figure 9 shows anisoplanatism error within a typically small field of an IFU field of 2 to 4 arcsec. Optimizing the DM control for best performance over the small field, or simply setting the DM equal to the zero field point correction, results in anisoplanatic error that is less than 50 nm in this example atmosphere. This is to be compared to a 2-DM MCAO system optimized over a 30 arcsec radius field, where the generalized anisoplanatism is nowhere less than 110 nm under the same seeing conditions.

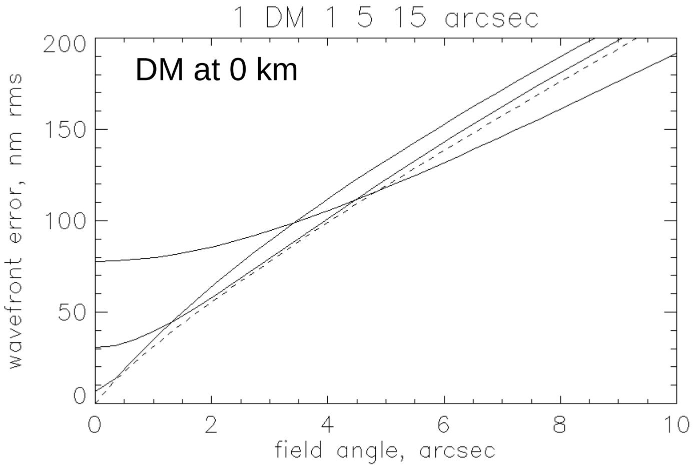


Figure 9 Anisoplanatic error within an MOAO IFU field. Even though there is only a single DM, correction can be optimized for a prescribed field. The example atmosphere with r_0 = 15.6 cm, θ_0 = 3.1 arcsec from Figure 3 is also used here.

MOAO has a number of advantages over MCAO. First is the drastic reduction of generalized anisoplanatic error, which is the field-dependent wavefront correction error associated with using a small number of deformable mirrors to sample a continuous volume of atmospheric turbulence. A second major advantage is that MOAO units are deployable over a wide field of regard, a field is typically much larger than what can be feasibly passed by an MCAO relay. This gives a multiplicity advantage and added flexibility in observing plans. In principle this field is limited only by the telescope’s field of view, which might be tens of arcminutes across compared to only a few arcminutes through an MCAO relay, however this will be practically limited by the *measured* field, as set by the size of the constellation of laser guidestars. Roughly speaking, one laser guidestar is needed for every isoplanatic patch. A further advantage of MOAO is a considerable reduction in the number of optical surfaces between sky and science detector. Extra surfaces needed in a MCAO system to feed the multiple conjugate DMs are eliminated, greatly improving the throughput and emissivity to the science instrument.

In summary, the science advantages of MOAO are:

1) Lower isoplanatic error at the science field points
2) MOAO units are deployable on a wider field of regard than MCAO

3) Sky coverage is enhanced by correcting tip/tilt stars with their own MOAO units, allowing dimmer tip/tilt stars than with MCAO
4) Reduced number of optical surfaces for AO correction, which minimizes emissivity and optimizes throughput.
5) No field distortion introduced by DMs in series

Science disadvantages of the MCAO architecture are:

1) Discontinuous field of view hampers crowded field studies, e.g. contamination by nearby stars' seeing halos which are not imaged and so cannot be PSF-subtracted
2) Cannot image large extended objects
3) DMs are open loop controlled, and so are subject to calibration and drift error.

6.3 Observing Scenarios, hybrid MCAO/MOAO

A hybrid MCAO/MOAO system can provide a path that mitigates some of the challenges, risks, or costs of an MOAO system and still provide a number of its science advantages. The hybrid system, since it dedicates one DM to each channel, will have the same advantage of reduced anisoplanatic error. Deployment of MOAO units however will be limited by the front-end relay's field of view, and will pick up the extra emission and throughput loss of its surfaces.

A science observing scenario using hybrid MCAO/MOAO would involve the deployment of multiple IFUs or imagers over the MCAO-corrected field. Science programs include hi-Z galaxies and spectroscopy of individual stars in crowded fields. Since the science objects are corrected by the MCAO system ahead of the IFU pickoff, they are diffraction-limited in the pickoffs' focal plane, which gives this architecture an advantage in that it allows higher packing density of multiple pickoffs than in a seeing-limited focal plane.

Summary of scientific advantage of hybrid MCAO/MOAO:

1) Operates some DMs in closed loop, eliminating DM calibration error and drift.
2) Allows higher packing density of pickoffs in AO-corrected field
3) Reduced anisoplanatic error over a purely MCAO system

Disadvantages:

1) Limited to the field of view supplied by the front-end relay
2) Extra surfaces in the relay contribute to background emission and reduce throughput
3) DMs in series could distort the contiguous field randomly resulting in higher astrometric error
4) Front-end relay adds field and zenith dependent distortion and aberration into the LGS beams, which, even if pre-calibrated, will introduce some amount of wavefront error to the science beams via the closed loop.

7 Technological feasibility of each architecture, impacts on system design, discussion of cost and risk

7.1 Implementation feasibility of MCAO architecture

MCAO requires a wide field optical relay with accessible positions for deformable mirrors at desired atmospheric conjugates. Typically, one tries to design such a system with the fewest powered optics as possible. The y-ybar approach is a handy way to do initial layout studies of AO relays.[16] Incorporating more than two conjugate mirrors often necessitates having a second “optical space” (space conjugate to the atmosphere), which requires at least one additional powered optic. In a wide field system, the powered optics in the relay must be larger than the deformable mirror, which is at the pupil (ground layer), to avoid vignetting the off-axis beams. Deformable mirrors not at the pupil must also be larger to cover the field, and must have the additional actuators associated with this larger “meta-pupil” so that beam footprints anywhere in the field will see AO correction.

The MCAO architecture will also pass the laser guidestar and tip/tilt guidestar beams. Since the laser guidestars are not at infinity, they will experience aberration from the AO relay, which is designed for best performance at the infinity conjugates. The additional wavefront error introduced on the laser guidestar beam is non-common path, i.e., it must be calibrated and applied as an open-loop offset to wavefront sensor measurements. The pupil is also distorted by the relay, resulting in registration shifts of the corresponding positions of guidestar and starlight rays within the aperture. Both the AO relay aberration and pupil distortion, which were identified as quite important for TMT (30 meter aperture), are considerable less pronounced on a 10 meter aperture. Nevertheless, the Gemini MCAO system takes great pains with very specialized optics designs of the wavefront sensors to counter both these effects. The aberration and distortion effects are field-dependent, meaning that optical mitigation systems must move to accommodate an adjustable LGS constellation. The aberration and distortion effects also change with distance to sodium layer, which forces the optical mitigation systems to continuously be in motions to track the zenith-dependent sodium distance change.

Pupil size in the optical relay design is restricted by physical optics inherent to the wide field of view. In particular, the Lagrange Invarient places a lower limit on the size of DM. For Keck, the limit will be on the order of 100 mm DM size. High order microelectromechanical system (MEMS) mirrors have not yet been built this large. A 1000 actuator (32x32 grid) MEMS device recently developed by Boston Micromachines Corp. has only 10 mm pupil size. Therefore, mirrors in a wide-field MCAO relay will most likely be traditional large piezo DMs, although, there are ongoing MEMS research and development efforts that bear watching over the next few years that might break through to the 100-300 mm mirror diameter range.

In summary, the MCAO architecture has the following implementation advantage:

- AO control of DMs is closed-loop, allowing feedback of mirror shape to the control system.

And disadvantages:

- Powered relay optics and DMs not conjugate to the ground must be larger diameter than the DM.
- The AO relay introduces non-common-path aberration and pupil distortion and may force custom design of the wavefront sensor optics to compensate. The custom optics may need have moving components in order to track sodium layer distance change with zenith angle.
- Pupil size has a lower limit set by physical optics. This size is larger than MEMS DMs produced today.

7.2 Implementation feasibility of MOAO architecture

In the MOAO architecture, Laser guidestar light proceeds directly to the wavefront sensors, without having to pass through AO relay optics. To some extent the rays are somewhat aberrated by the telescope's optics, since the LGS is not at the ideal conjugate, but these effects are very minor and can probably be safely ignored in the case of Keck. It is prudent, however, to calculate and assign an error budget value to this term.

The MOAO deployable units each have their own deformable mirror, which means there will be a premium on size, weight, power consumption, and cost. MEMS devices are ideal for this role, being small, compact, and relatively low-cost (in comparison to piezo mirrors) devices. The pupil size restriction does not apply since the MOAO units have very small fields.

A disadvantage to the MOAO architecture is the need to control the DMs open-loop, i.e. without the benefit of LGS light having reflected off of them, and thus without the benefit of feeding of results of a DM command back to the control system. MEMS DMs show no hysteresis behavior however, and are relatively straightforward to model as deforming thin plates, thus an open loop prediction controller is feasible.

The implementation advantages of MOAO are:

- MEMS are small, enabling the AO systems to be tucked into instruments, and making them ideally suited for making compact MOAO units.
- MEMS are low cost. The marginal cost of scaling to high actuator counts is considerably lower than that for large DMs. For the BMC devices, this number today appears to be around $200-300 per actuator as compared to about $1500 per actuator on a piezoelectric deformable mirror. The low cost makes it practical to have a spare on hand.
- "Go-to" repeatability – A major advantage of an electrostatic actuation over piezoelectric actuation is the absence of hysteretic effects in the displacement to voltage response curves. This implies that the devices could be driven open loop to given surface deflections.

- The low cost and small size of MEMS DMs opens up the possibility of “ubiquitous MEMS,” i.e. devices sprinkled throughout the system to elegantly solve tough optical problems.
    - MEMS DM in each wavefront sensor: This creates a mini closed-loop AO system in which the wavefront detector is kept near null, where its linearity properties are best. The predictable voltage response of the MEMS allows it to be used as the probe of the grosser portion of the wavefront shape, which would be added to the wavefront sensor’s residuals to complete the wavefront measurement. A variant of this is to use MEMS DMs to correct for the slowly varying but known non-common path aberrations of LGS wavefronts.
    - MEMS in the tip/tilt sensors: If there are enough degrees of freedom to form diffraction limited cores at the sensing wavelength, fainter guide stars can be used to sense tip/tilt to a given accuracy because centroid error is proportional to the spot size and inversely proportional to square root of brightness. The ability to use fainter guide stars would give us higher sky coverage.

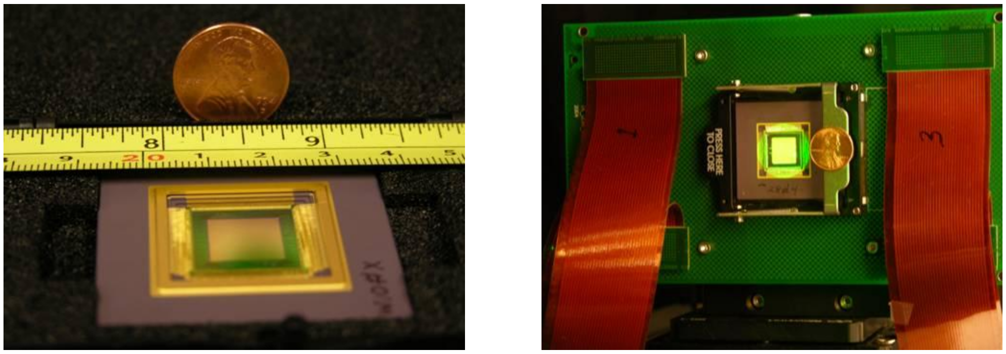

a b

Figure 10 a) 1000 actuator Boston Micromachines MEMS deformable mirror. This is a 32x32 actuator array at 360 microns pitch. b) MEMS mirror plugged into its electrical connector board with cabling shown. The green disk is the 532 nm PSDI interferometer beam.

Practical disadvantages of MOAO are:

- MEMS stroke dynamic range may not be adequate to correct the whole atmosphere, leading to a requirement for dual-mirror “woofer-tweeter” MOAO units. The lastest generation of MEMS mirrors under development (a 4000 actuator mirror for the Gemini Planet Imager AO system) should have just enough mechanical stroke to cover 5-σ wavefront variation for the Keck 10 meter tip/tilt removed wavefront.

- MEMS mirrors have not been shown to work yet in astronomical instruments (this is a risk issue)
- High-order MEMS are presently available from only one manufacturer (another risk issue)

8 Risk reduction and component development efforts

8.1 MCAO/MOAO testbed at UCO/Lick Laboratory for Adaptive Optics

The Laboratory for Adaptive Optics is a component of the University of California Lick Observatory which is charged with the development of new technologies and methods for adaptive optics for ground based observatories. The Laboratory has two main experimental objectives: developing multi-laser guidestar tomography / multi-conjugate adaptive optics for wide-field imaging and developing high contrast "extreme" adaptive optics for imaging extrasolar planets. The laboratory is also evaluating the new components and key technologies needed for future AO systems including MEMS deformable mirrors, high speed low noise detectors, wavefront sensing methods, and fast wavefront control processors. The UCSC location provides a laboratory environment where students and postdocs will be trained in adaptive optics design, modeling, and implementation.[17]

MCAO testbed layout. To perform laboratory experiments relevant to MCAO on a 30-meter telescope, one must scale 60 km of turbulent atmosphere and a large aperture telescope to fit on a room-size optical bench, while retaining similar geometric and diffractive optics behavior. This scaling has been a main consideration in the optical design and layout of the testbed.

Optical path – MCAO mode

The MCAO optical testbed layout is shown in Figure 11. Light enters the system via laser fibers emulating the guide stars, labeled NGS (natural guide star) and LGS (laser guide star) at the lower right of the figure. Here there is an array of sources to simulate a multi-guidestar constellation, plus one deployable source to simulate science objects at arbitrary locations in the field. The guide star and science object light travels through a series of phase aberration plates in the atmosphere section, to emulate multiple layers of air turbulence at different altitudes in the atmosphere. At this point the light is focused, as it would be in an actual telescope, then fed to a series of deformable mirrors (we are using liquid crystal spatial light modulators to perform the function of deformable mirrors). From there, the AO corrected light is sent to a number of Hartmann wavefront sensors, each of which senses an individual guide star.

The AO corrected light also travels to a far-field imaging camera to characterize Strehl ratio and other performance metrics of the corrected imaging. Another path goes to an interferometer to characterize AO corrected wavefront quality. We mentioned this interferometer earlier as one that takes interferograms at high speed. The MCAO testbed is designed to run in "closed loop" at a relatively quick pace (the testbed goal is 5 Hz sample rate) while the phase aberration plates are moved to simulate wind blown turbulence. This allows us to characterize the dynamic behavior of MCAO control algorithms.

The testbed is designed to handle up to 4 deformable mirrors, 8 laser guidestars, 4 tip/tilt guide stars, and a "science object" (point source for testing performance) deployable over the field.

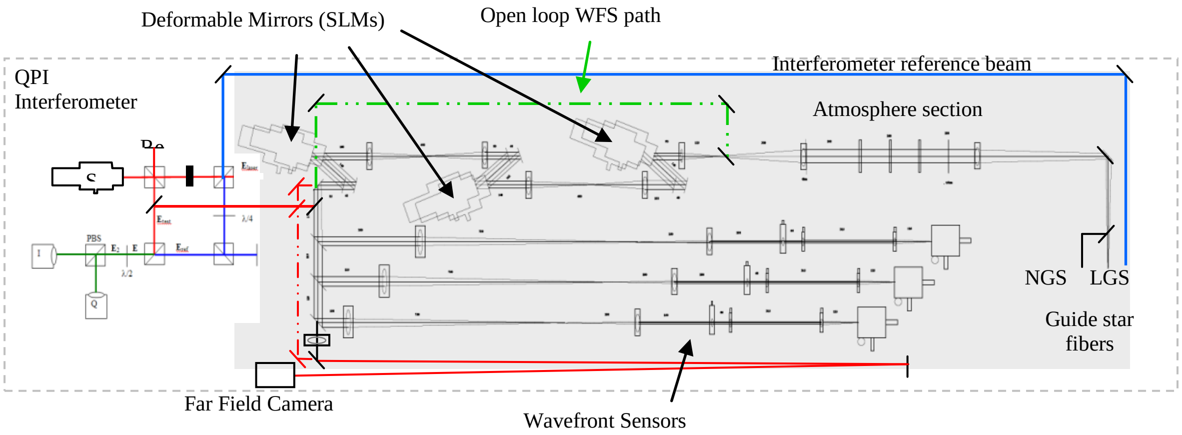


Figure 11 Laboratory for Adaptive Optics MCAO/MOAO testbed layout

MOAO mode

The MCAO arrangement on the optical bench can be switched to an MOAO configuration (the green dotted line path in Figure 11). In MOAO mode, each science object has its own dedicated deformable mirror, so the AO correction is specific to and optimized for the direction the science light comes from. Guide star light is steered to the wavefront sensors directly, without bouncing off any deformable mirrors, where it is detected and processed to form a 3-D estimate of differential optical paths throughout the volume of atmosphere. Deformable mirror commands are derived by summing along ray paths through this volume corresponding to the science object directions.

Experimental results from the LAO testbed

In progress experiments on the LAO testbed are directed to anchoring the multi-guidestar tomography theory and simulation models to laboratory measurements (Keck NGAO system design phase task #3.1.1.2.5). The present configuration of the testbed is 5 laser guidestars on an 83 arcsecond diameter field. Results in this configuration are too preliminary to report on at this time, however an earlier test with a 3 LGS constellation clearly showed the benefit of tomography on a wide field.[18]

8.2 MEMS 4K actuator device development

A consortium consisting of the Center for Adaptive Optics, the UCO/Lick Laboratory for Adaptive Optics, and the Gemini Observatory has begun a development program for a 4000 actuator MEMS deformable mirror which is primarily targeted to the Gemini Planet

Imager (GPI) instrument. GPI is now funded for construction and will be commissioned on the Gemini South telescope in 2010. This mirror, or variants of its design, also will be of great interest for the AO instrumentation now being planned for the Thirty Meter Telescope and for the Keck Next Generation AO systems. Specifications for the device are given in Table 1 below.

Table 1. MEMS Deformable Mirror Specifications for GPI and 30 Meter Telescope AO Systems

Actuator Count	4,000 to 10,000 (64x64 and 100x100)
Actuator Spacing / Clear Aperture Diameter	400 microns / 10 mm to 40 mm
Stroke Range	>3.5 microns surface
Differential Stroke (neighboring actuators)	>1 micron
Bandwidth	>2500 Hz (-3db)
Go to accuracy	<10 nm
Operating Temperature	-30 degrees C
Actuator Yield	99% (MCAO, MOAO), 100% on a 48x48 square area (planet imager)

We have had to compromise on the actuator stroke because of present limitations of the silicon micro machining technology. We are hoping to extend the stroke of actuators through either refinement of the actuator design or the use of new fabrication processes. The tip/tilt removed wavefront on 30 meter apertures requires more than 3.5 micron surface (7 micron wavefront) dynamic range. For the 8-meter Planet Imager, it is important not to saturate any actuators down to the 10^{-6} probability level because it will otherwise severely affect image contrast and hence planet detectability. For the 10 meter, 3.5 microns surface stroke is useful if some saturation is tolerable on the general-use AO instruments, but on the 30-meter 10 microns surface stroke is needed for reasonable performance. Instruments that need more stroke will require a second deformable mirror, a high-stroke low-order “woofer” mirror, to operate in tandem. This is not a strong limitation however because small woofer mirrors that fit these needs are on the market and the overall approach still retains the huge cost savings and size advantage over piezo based systems.

An NRE contract with Boston Micromachines in presently in Phase 2. Phase 1 was the testing and downselect of a number of high stroke actuator designs, with trade offs in actuator stroke, voltage response, and structure print-through to the surface.[19] Phase 2 is proceeding with 2048 actuator device fabrication runs and testing, and Phase 3 will deliver the final packaged device to GPI with a due date in September, 2008.

8.3 Experiments in the open-loop control of MEMS

The MOAO system runs in “open loop,” that is, the effect of AO commands to deformable mirrors are not sensed by the wavefront sensors. This puts additional demands on deformable mirror technology to respond accurately to commands without having to be re-measured.

An accurate open-loop model of any deformable mirror surface is not simply the linear superposition of influence functions of individual actuators. Instead, surface shape is ultimately determined through a non-linear cross-coupling of forces through the continuous mirror surface.[20] At the LAO, we have developed a model for MEMS surface response based on applying a plate equation model of the continuous surface that takes care of all the cross-coupling and a set of non-linear lookup tables that are decoupled amongst the actuators (Figure 12). The empirical look-up tables are determined from a calibration procedure performed while actuating the MEMS in an interferometer. To date we have achieved ~15 nm accuracy in computing the command voltages to achieve an arbitrary surface shape of ~500 nm amplitude, using the Boston Micromachines 1024 actuator MEMS device.[21] A similar process has apparently also been successfully applied to the OKO membrane mirror.[22]

Plate Equation PDE:

$$D\,\nabla^4 z(x) = f_p(x) = \sum_{i=1\ldots n} f_{p_i}(x - x_i)$$

Non-linear voltage-force-displacement relation for each individual actuator (decoupled)

$$f_p(z_i) = f_E(v_i, w_i) = f_s(w_i)$$

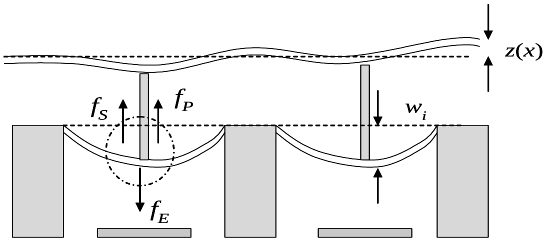


Figure 12 Open-loop modeling of MEMS displacement in response to command voltages.

8.4 Piezo Actuator development

Ongoing development of piezo actuator deformable mirror technology has shown a steady improvement in actuator performance. A Cilas SAM (Stack Array Mirror) prototype with 57 actuators has recently been tested for the Thirty Meter Telescope project.[23] This mirror achieved >10 microns of surface actuation with <10% hysteresis. This low amount of hysteresis makes it conceivable that an open-loop go-to actuation with this mirror is possible. DMs made with piezo stack actuators are still macro in scale, with 5 mm actuator spacing, implying a 64-across device will have a diameter of 320 mm. Also, the cost scaling is still likely close to the $1000/actuator regime, making it an expensive option relative to MEMS.

8.5 Woofer deformable mirror options

Woofer deformable mirrors will be necessary if it is determined that the high-order DM (the "tweeter") does not have sufficient stroke to correct the wavefront under a specified range of seeing conditions.

These are the basic options for a woofer deformable mirror:

1. Adaptive secondary.

   An adaptive secondary mirror such as the one employed on the Monolithic Mirror Telescope and being developed for the Large Binocular Telescope, can function as a low-order common woofer mirror. This mirror would have up to 300 degrees of freedom and would relegate the residual high order and field dependent AO correction to the MEMS mirrors in the downstream AO system.

   Advantages of this approach are:

   a) Each MOAO channel would only need one DM, and a minimum of associated relay optics, which maximizes throughput, minimizes emissivity, and reduces overall system complexity.

   b) Wavefront sensors would see a partially corrected beam, which lowers the dynamic range required on open-loop wavefront sensing. Knowledge of the exact AM2 wavefront correction is necessary, but prior adaptive secondary mirror designs have included position sensors on the actuators to provide this information.

   c) The common woofer would enable MEMS devices with limited stroke to perform the residual correction. This residual could be handled by present day available 2 micron stroke 1K MEMS devices as well as by the 3.5 micron stroke 4K MEMS under development.

   A *disadvantage* of this approach is that an adaptive secondary is likely to have a very high dollar cost.

2. Common woofer in a front-end AO relay.

   A common woofer would be a single low-order DM that provides partial correction over the entire diameter of the largest field of regard envisioned for Keck NGAO instruments.

   The *advantages* of this approach are similar to those of an adaptive secondary

   Disadvantages of this approach are

   a) It introduces from 3 to 5 additional optical surfaces in the science path, which negatively impacts emissivity and throughput.

   b) It requires building a relatively expensive conventional (piezo actuator) DM so that it is large enough to address NGAO's large field of regard.

   c) It requires large optical elements in its relay design, e.g. >300mm relay parabolas, and consequently a long optical path, which makes servicing and stability an issue.

   d) If the laser guidestar wavefront sensing is relegated to after this relay, the LGS wavefronts will suffer from a non-common path aberration introduced by the relay. This is due to the fact that the relay is designed to image optics at infinity rather than the LGS focus (up to 250 mm behind telescope focus). This aberration is large enough that it would have to be calibrated out rather precisely in order to perform adequate AO correction.

3. Woofer tweeter pair in each science leg

   In this configuration, each MOAO channel has one woofer DM and one MEMS DM (the "tweeter"). The woofer DM needs to be small in physical size to keep the overall size of a multi-object spectrograph manageable. There are a number of commercial options for small low-order DMs, falling into four basic categories: piezo stack, piezo bimorph, silicon membrane, or magnetic actuator. Since each MOAO channel has a small field of view, it is not necessary to have a separate pupil relay for the woofer – it can live in the same optical space as the MEMS mirror.

   An MCAO system would have a field limited to about 2 arcminutes, according to the latest studies of AO relay designs (task 3.1.2.2.2). This would be enough to pass a small laser guide star constellation but not enough tip/tilt stars for reasonable sky coverage. Thus each AO corrected tip/tilt leg would also need a woofer-tweeter pair.

   Advantages of this option are

   a) It precludes the need for using a large common woofer relay, saving the extra reflections and corresponding negative impact on emissivity and throughput, and saving the extra cost of the relay.

   b) It allows the wide field of regard for MOAO.

   c) The LGS wavefront sensors have very little non-common path aberrations introduced by a relay.

   Disadvantages are:

   a) Extra cost of woofer DMs for each channel in an MOAO system, and each tip/tilt star path.

   b) If the woofer DM used is a piezo-bimorph, its "go-to" shape will need to be sensed with an interferometer for precise open-loop wavefront control. A small interferometer system has been designed to handle this (LAO's "mini-QPI"), but this adds complexity and cost.

Woofer device options (exclusive of an adaptive secondary)

1. Piezo-stack actuator – any of the common designs from Xinetics or Cilas. Advantages: well established suppliers. Disadvantages: Hysteresis will demand a separate surface figure monitor for open-loop architectures, high per unit cost.
2. Piezo-bimorph – available from Cilas. Advantages and disadvantages similar to those of the piezo-stack. Possible lower cost than piezo stack however.
3. Electrostatic membrane – available from OKO Tech and Agileoptics. Advantages: low cost, small size, go-to with no hysteresis. Disadvantages: operating bias voltage gives a nominally powered surface, limited stroke with stroke reducing drastically with correction order, low mechanical resonance frequency may interfere with desired temporal control bandwidth.
4. Magnetic membrane – available from ALPAO/LOAG. Advantages: small size, go-to with no hysteresis, very high stroke, Disadvantages: new device with uncertain market may mean future problems with availability. A woofer-tweeter testbed using this mirror has been set up at the University of Victoria.[24]

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