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Keck Observatory
Next Generation Adaptive Optics (NGAO)
Capability/Architecture Options

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Abstract

This document describes the top-level advantages and disadvantages of several distinct high-level architecture options for a Keck Observatory (Keck) Next Generation Adaptive Optics (NGAO) Program. We consider architecture options to support multiple specialized science instruments for the execution of leading-edge science cases, guided by the Keck Observatory Strategic Plan. The Keck Adaptive Optics Working Group (KAOWG), with broad involvement of the science community, is concurrently developing formal key science case documents for NGAO. The architecture issues raised in this document are intended to be input to the iterative discussions to be held between the KAOWG science case teams and the KAOWG Technical and Science Instruments Subcommittee (TSIS).

Revision Sheet

Release No.	Date	Revision Description
Rev. 0.1	1/17/06	Initial draft by R. Dekany
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1 GENERAL

1.1 Acronyms and Definitions

AM2	Adaptive M2
AO	Adaptive Optics
CARA	California Association for Research in Astronomy
$C_n^2(h)$	Atmospheric Turbulence Phase Structure Function (a description of the vertical distribution of turbulence above a site)
$C_n^2(h,t)$	Explicit notion indicating $C_n^2(h)$ is an evolving function of time
CW	Continuous Wave
d-IFU	Deployable IFU
DL	Diffraction-limited
DM	Deformable Mirror
ELT	Extremely large telescope
FA	Focal ansioplanatism
FoV	Field of View (the field observed by a single detector array)
FoR	Field of Regard (the field over which objects may be selected)
HOWFS	High-Order Wavefront Sensor (used for either NGS or LGS sensing); see LBWFS
IFS	Integral Field Spectrograph
IFU	Integral Field Unit (optical re-formatting feed to an IFS)
IR	Infrared
K1, K2	The Keck 1 and Keck 2 Telescopes
KI	Keck Interferometer
LAO	Laboratory for Adaptive Optics (at UC Santa Cruz)
LGS	Laser Guide Star
LGSF	Laser Guide Star Facility
LBT	Large Binocular Telescope
LBWFS	Low-Bandwidth Wavefront Sensor (an NGS HOWFS run at low frame rates used for quasi-real-time wavefront calibration
LOWFS	Low-Order Wavefront Sensor (almost always used for NGS sensing (only))
M1	Keck primary mirror
M2	Keck secondary mirror
M3	Keck tertiary mirror
M6	The sixth mirror in the telescope train, typically used to describe the deformable mirror in architectures having a dedicated AO optical relay
mas	Milli-arcsecond (units)
MEMS	Micro-electro-mechanical systems
MCAO	Multi-conjugate AO
MOAO	Multi-object AO (an architecture having at least one DM per IFS)
MOEMS	Micro-opto-electro-mechanical systems (for some reason, in the adaptive optics world, MEMS is more often used than MOEMS)
Na	Sodium
NDL	Near-diffraction-limited

NIR	Near Infrared (typically 1-2.5 microns wavelength)
NSF	National Science Foundation
OCDD	Operation Concept Definition Document
OIWFS	On-Instrument WFS using NGS (see also TTF)
PSF	Point Spread Function
P-V	Peak-to-Valley
RMS (also rms)	Root Mean-Squared
RTC	Real-Time Controller
SLAO	Single-Laser Adaptive Optics
SLGLAO ("Sly-Go")	Single-Laser Ground Layer Adaptive Optics
SNR	Signal-to-Noise ratio
Spaxial	The focal plane sampling defined by the IFU
SRD	Science Requirements Document
SSC	Science Steering Committee
TSIS	The KAOWG Technical and Science Instrument Subcommittee
TTF	Tip/Tilt/Focus
WFE	Wavefront Error
WMKO	W.M. Keck Observatory

1.2 Purpose

The purpose of this document is to describe the key features, compromises, and benefits of different top-level NGAO architectures as applied to a variety of AO science observing modes.

The audience for this document is the KAOWG, including its TSIS and science case subcommittees, the SSC, WMKO management, and interested members of the Keck science user community.

1.3 Scope

This document describes the relative, qualitative science compromises and benefits of different options. As such it provides the "sign of the effect" without fully quantifying certain complex tradeoffs. In some situations where fundamental issues arise, limiting cases are given quantitative basis.

1.4 Assumptions

1.4.1 Technology State-of-the-Art

In this document, we assume successful implementation of the following technologies as establishing a baseline for comparison among component technologies[1]:

- 672 actuator, 0.911m diameter, large-stroke glass AM2 by Arcetri University on LBT (undergoing telescope I&T)
- 3,517 actuator, 1.8mm pitch, 1.5 microns stroke electrostrictive DM by Xinetics, Inc. on Palomar (fabrication beginning in 2006, expected completion in 2008)
- 4,096 actuator, 400 micron pitch, 2 micron stroke MEMS DM by Boston Micromachines at LAO (ongoing development, expected completion in 2008)

[1] Stroke numbers here indicate P-V stroke for the entire device, not interactuator stroke which is typically less

1.4.2 Laser Guide Star Facility

We assume here a laser projection architecture that consists of a single axially-mounted 50cm diameter projector behind the secondary mirror of the telescope. No assumption is made whether the projector is reflective/transmissive/catadioptric, is centrally obscured/unobscured, or on the nature of the beam transport to the projector. Off-axis laser projection (as is currently implemented) would not invalidate any of the architecture issues addressed herein, and the cost/benefit analysis for the choice of NGAO projection scheme remains TBD.

We assume here a multiple sodium beacon projection architecture that may support different LGS asterisms for potential use in different observing modes (e.g. narrow-field vs. MOAO vs. GLAO). We further assume that total delivered laser power is a major cost driver (typically $100K/W on extant systems), but that no other physical constraints exist, and that appropriate human, aircraft, and satellite safety systems will allow for routine operation.

1.4.3 Number of NGAO Systems

To control the potential number of configuration concepts, we here assume that only one telescope will be configured with an NGAO system, although this contradicts "twenty-year" Goal #2 from the Keck Strategic Plan. It is entirely possible that the science case development will identify desirable asymmetries in the K1 and K2 AO and instrument complements, but these should be revisited by the KAOWG TSIS after the science case is complete.

1.4.4 Interferometry

We assume for this purpose that NGAO must support Keck Interferometer (KI) AO compensation of both K1 and K2, but that either or both of the existing first generation AO systems could be retained, operated, and maintained should resource limits require it. Although interferometry may be revisited in future revisions of this document, for the time we'll consider interferometry as congruous with the MIRAO capability described herein, a reasonable assumption for KI's nulling mode. (e.g. KI would benefit from architecture choices that also benefit MIRAO).

1.5 Related Documents

- The Keck Strategic Plan, as of September 2005, can be viewed at http://www.astro.caltech.edu/~lah/keck.science.2005/Current.pdf
- See the collection at: http://www2.keck.hawaii.edu/optics/kpao/
- The KAOWG is concurrently drafts an NGAO Science Case

2 NGAO

Next Generation AO (NGAO) is the name generically describing the future WMKO Adaptive Optics Program, which itself is a collection of multiple adaptive optics and instrumentation projects, in alignment with the Strategic Plan of the WMKO. NGAO includes all activities necessary for successful execution of the NGAO science cases, including work that may not be normally considered within an instrument development program, such as necessary primary or tertiary mirror engineering activities.

2.1 Guidance from the WMKO Strategic Plan

The Keck Strategic Plan, most recently revised in September 2005, identifies four major 20-year Strategic Goals (page 10):

#1. Achieving highly efficient operations
#2. Maintaining scientific leadership through state-of-the-art instrumentation
#3. Maintaining world leadership in high angular resolution astronomy
#4. Achieving complementarity with Extremely Large Telescopes

NGAO is part of all of these themes, targeting new high angular-resolution instrumentation, synergistic with upcoming ELT activities and capabilities (particularly with TMT), while providing the opportunity for improving observatory efficiency (both operational efficiency and photon efficiency).

The Strategic Plan also lays out "twenty-year" Goals supporting a vision of the Observatory in 2024 that include (page 11):

(1) 90% efficiency for clear weather open-shutter time;
(2) diffraction-limited performance from 10 microns to 400nm with Strehl>0.6 a significant fraction of the time on both telescopes;
(3) faint-object capability for the Keck Interferometer;
(4) pan-chromatic, hard mirror coatings on all optics;
(5) data pipeline reduction codes for all instruments; and
(6) a complete archive.

Most relevant to us here is Goal (2), which necessitates adaptive optics capabilities not available today. The Strategic Plan further notes that, in the area of ELT synergy (page 12),

> "Wide-field imaging and multi-object spectroscopy will likely remain the domain of 10m-class telescopes into the next era and the selection of targets at the forefront of TMT astronomy will require the capabilities of 10m telescopes."

The discussion in the Plan of twenty-year goal (4), deployment of pan-chromatic, hard mirror coatings on all optics, explicitly cites improved photon transmission as a major thrust for the Observatory. Thus, in considering NGAO, we must also explore the architectural trades for transmission losses (and by extension optical emissivity).

Thus, we begin our consideration of the architecture options for NGAO with both (as short as) 400 nm wavelength diffraction-limited operation and wide-field and multi-object spectroscopy in mind as the key strategic elements.[2]

2.2 AO Observing Modes

Over the past 5 years, considerable research, design, and analysis in adaptive optics, prompted by the initiation of ELT projects around the world, has led to a expansion and refinement of a number of distinct adaptive optics observing modes. Each has it's own tradeoff between AO performance (as measured by RMS residual wavefront error or ensquared energy), reflecting both the fundamental physics underlying the three-dimensional nature of the Earth's turbulence atmosphere, and science case specific optimizations that reflect the success of the first-generation AO systems on Keck and elsewhere.

The basic parameters describing each of these AO observing modes is shown in Table 1.

FoR		Observing Mode	Primary Science Objective(s)	Typical Wavelength Range (microns)	Typical Spatial Resolution	Key Issue
Narrow	0" - 20"	EXAO	High Contrast	0.8 - 5	n/a; 10^7 contrast	Control of systematics
		LTAO	High IR Strehl, Photometric Precision Visible Resolution and Sensitivity	0.4 - 5	λ/D	Voracious for laser power
Moderate	20" - 2'	SLAO	Balanced Efficiency and Spatial Resolution	0.6 - 5	λ/d_0 (note 1,2)	Performance compromise
		MCAO	Uniform PSF, Astrometric Precision	0.6 - 5	λ/D	Complexity
		MIRAO	High Spatial Resolution	5 - 14	λ/D	Control of emissivity
Wide	2' - 10'	GLAO	Improved SNR	0.31 - 2.4	$r_0 / (D\ \alpha)$ (note 3)	Performance compromise
		MOAO	Balanced Efficiency and Spatial Resolution	0.6 - 2.4	λ/D - 0.15"	Open-loop control

Table 1. Modern classification system for AO observing modes. Notes: 1) $d_0 \propto \lambda^{6/5}$, and is typically ~4m at 0.5 microns on Mauna Kea, and is a strong function of $C_n^2(h)$, 2) the fraction of energy in the λ/D core is $(d_0/D)^2$, 3) the GLAO FHWM correction factor, denoted here by α, is a function of λ, and is believed to be ~1.2 at visible wavelengths, ~1.3 in J-band, and perhaps 1.5 in K-band. GLAO correction depends strongly on the $C_n^2(h)$ profile. New data from Mauna Kea (by Gemini) are expected within several months.

The only architecture, to date, that has been successfully deployed to date is single-laser AO (SLAO), but on-going projects at Gemini Observatory, and elsewhere, are proceeding with the

[2] One additional goal, maintaining excellent UV performance (between 310 and 380nm wavelength), we shall not emphasize for diffraction-limited capability, as they are specifically excluded from the "twenty-year" goal (2) which specifies a wavelength limit of 400 nm.

construction of new MCAO and EXAO capabilities, whereas several groups have proposed LTAO and GLAO systems.

A common need among all AO system architectures, when driven toward shorter wavelength, visible-light correction is the development of new (and likely more sophisticated) natural guide star sensing strategies to overcome limitations imposed by the atmosphere and available star counts. Primary among these is the use of compensated NGS for low-order wavefront sensing (which may include between 2 (tip/tilt) and ~8 spatial modes, depending on choice of architecture).

2.2.1 Narrow-field, High-contrast Extreme AO (EXAO)

EXAO intends to maximize high-contrast science, such as direct planetary companion detection, brown dwarf companion spectroscopy, and circumstellar material spectroscopy. It is characterized by DM and WFS component technology that pushes the state-of-the-art. Engineers must manage static calibration wavefront errors and understand the detailed spatiotemporal spectrum of wavefront errors arising from both telescope and instrument. Offsetting this, because EXAO has typically been considered as an NGS-only architecture (e.g. the proposed Keck XAOPI instrument or the funded Gemini Planetary Imager (GPI)), no laser guide stars are needed for operation, a significant simplification.

2.2.2 Narrow-field, Diffraction-limited Laser Tomography AO (LTAO)

LTAO seeks to provide the best wavefront control for a narrow field of regard, over a large sky fraction, using an asterism of laser guide stars and sophisticated tomographic reconstruction algorithms. The role of the multiple LGS is primarily to overcome focal anisoplanatism present when using a single laser beacon, to regain diffraction-limited performance. Natural anisoplanatism is allowed to degrade the quality of correction as one moves away from the 'sweet spot' target direction. This sweet spot can be moved (algorithmically) interior to the LGS asterism.

2.2.3 Moderate-field, Near-diffraction-limited Single-laser AO (SLAO)

SLAO is the traditional architecture for AO deployed on existing telescopes, including Keck. SLAO can provide diffraction-limited performance on 8-10m telescopes, but rarely with high Strehl ratio[3]. Typically using a single Na LGS beacon, SLAO suffers the consequences of focal anisoplanatism (FA), also known as laser cone effect. FA results in a particular non-Kolmogorov spatial spectrum for the residual wavefront error, unlike that of most other AO residual errors (such as DM fitting error or finite servo bandwidth error). SLAO correction concentrates light into a tighter core (of typical diameter d_0/D, where d_0 scales as $\lambda^{6/5}$ and is typically 4 meters in K-band at Keck.) In most cases, SLAO on 8-10m telescopes can reach the diffraction-limit at K-band, but high Strehl in J-band is less likely (though ensquared energies in J-band may still be quite respectable.)

[3] On 20-30m telescopes, SLAO (also known as SLGLAO) provides a low-risk non-diffraction-limited observing mode that can nevertheless produce good ensquared energy fraction over a moderate field of regard. Because the geometric nature of FA allows for good sampling of low-altitude turbulence, the behavior of SLGLAO on increasingly large telescopes is analogous with that of GLAO (thus the historic genesis of the single-laser GLAO acronym).

A second variant of SLAO, known as Synthetic SLAO, takes advantage of multiple LGS beacons to tomographically synthesize a residual wavefront error spectrum equivalent to the FA error induced by a single beacon at an arbitrary altitude (not just the 90km sodium layer altitude). This allows an algorithmic 'dialing-in' of the tradeoff between level of compensation and compensated field of view. Typically, synthesis of beacons in the 200-300 km altitude range produces near-diffraction-limited performance over a ~1 arcmin FoV. (The limiting case of synthesizing a laser beacon to be at infinity, eliminating FA error altogether, is in fact LTAO.)

2.2.4 Moderate-field, Diffraction-limited Multiconjugate AO (MCAO)

MCAO employs multiple deformable mirrors, at different optical conjugate distances into the atmosphere, to emulate a three-dimensional correction of the Earth's three-dimensional atmosphere. By doing so, normal (angular) anisoplanatism is overcome, increasing the compensated, contiguous FoV by linear factors of about 3-4 (for 2-mirror correction, thereafter increasing approximately linearly for more mirrors) depending on atmospheric conditions. MCAO requires multiple LGS and tomography as well as sensing of multiple NGS, which is additionally required in order to resolve the ambiguity induced by tilt anisoplanatism which can otherwise confuse the distribution of certain spatial correction modes between the multiple DMs.

MCAO is expected to improve the spatial uniformity of the AO point spread function within the compensated FoV, though performance still varies toward the edge of the FoV, and with time.

2.2.5 Moderate-field, Diffraction-limited Emissivity-optimized Mid-IR AO (MIRAO)

MIRAO takes an otherwise straightforward AO system, which because of its long wavelength subject need be no more complex than existing first generation AO systems, and drives it in the direction of minimizing total system emissivity and optimizing background stability. We can satisfy these goals by minimizing the number of and/or reducing the temperature of optical surfaces in the science path.

Increasingly, the goal of minimizing AO system emissivity is being extended to near-IR AO systems (where systems temperatures in the -30 to -40 C range typically suffice to reduce instrument emissivity well below levels established by the telescope and atmosphere.)

2.2.6 Wide-field, Seeing-enhanced Ground-layer AO (GLAO)

GLAO aims for partial compensation over wide, contiguous field of view, using a single conjugate AO system that attempts to correct only the (common) low-altitude atmospheric turbulence. The extent of compensation depends strongly on both the fraction of turbulent energy present at low-altitudes and ones ability to disentangle the low-altitude turbulence from the high. Systems have been conceived that use either Na or Rayleigh LGS asterisms spread over typically 10', or using NGS-only systems selecting the brightest stars within a somewhat larger FoV (20'). NGS GLAO, however, cannot obtain a large sky fraction and is restricted to moderately low galactic latitudes or specific target fields known to have appropriate field stars.

GLAO has the potential for correcting telescope and dome-induced wavefront errors over the entire telescope FoR.

2.2.7 Wide-field, Near-diffraction-limited Multiobject AO (MOAO)

MOAO is envisioned using a 'one AO system per object' implementation, wherein each field object is separately corrected by an independent wavefront corrector. Control signals are provided to each deformable mirror (DM), based upon a tomographic reconstruction of the atmosphere using multiple laser beacons. These N separate correctors might or might not share a global woofer mirror (which could be an adaptive telescope secondary.) The advantages of MOAO include a reduction in the number of science reflections (which increases throughput and can reduce emissivity), more compact packaging (due to the relatively small field of view (FoV) seen by each DM), and better potential performance (as each DM can be tuned to optimize the wavefront correction in each particular direction in the sky). On the other hand, MOAO as currently envisioned requires that each DM operate in open-loop, namely that the corrections applied to each science field are at no time directly measured by the wavefront sensors. Instead, the wavefront sensors operate in a non-null-seeking mode which relies on exquisite calibration of the wavefront sensor and deformable mirrors. Thus, MOAO requires sensors and actuators of unusually high linearity and dynamic range. The experimental validation of the MOAO concept, at the required level of accuracy, is a near-term necessity before TMT endorses such an implementation in its baseline.[4]

2.3 Basic NGAO Architecture Elements

Given our current understanding of the adaptive optics observing modes described above, and the state-of-the-art in wavefront sensing and control technology, we enumerate 3 fundamental correction architectures for NGAO, which we will consider individually and in combinations. These are: an adaptive secondary mirror, a dedicated AO relay employing a common-mode DM, and MEMS DMs deployed within science instruments. We will find that in order to truly maximize the science return in all AO observing modes, we require an NGAO program that utilizes all three of these correction elements at different times and in different ways. To the extent that NGAO will be resource-limited, however, it is informative to consider the science compromises made when selecting various subset architectures. The remainder of this note addresses these compromises and the technical risks that arise when selecting from among these subset architecture combinations.

2.3.1 AO Relay

The traditional first-generation AO system, such as that in use on Keck I and II today, involves the use of a dedicated optical relay to form an optical space conjugate to atmosphere, providing an appropriate optical location for deformable mirror compensation[5]. Science light and guide star light (whether NGS or LGS) all enjoy compensation of turbulence, allowing the HOWFS to operate in a closed-loop control scheme. The iterative nature of closed-loop control provides 'forgiveness' to an AO relay system, compensating for nonlinear effects in the WFS, DM and elsewhere that might otherwise corrupt the instantaneously applied wavefront correction.

First-generation AO relays were designed with modest FoR, typically 2 arcminutes, a choice made to correspond with typical single-conjugate anisoplanatism limits in the K-band. Designs

[4] This subsection taken verbatim from Dekany, R., et al., "Initial concepts for CELT adaptive optics," Proc. SPIE Vol. **4839**, p. 1165-1174.

[5] The large majority of astronomical AO systems have chosen to place a single DM conjugate to the telescope entrance pupil. Gemini's ALTAIR system originally conjugated 1 DM to 6.5km, but subsequently reconjugated to nearer the primary mirror. Gemini South MCAO will have 3 DMs conjugated to 0, 5, and 10km altitude.

for optical relays passing larger FoV, however, do exist. Eventually physical size constraints on the Nasmyth platform restrict the FoV, but 6-8 arcmin is likely practical.

AO relays (even large ones) can be easily tested in a laboratory environment and have minimal impact on routine operations during installation and commissioning (depending e.g. on Nasmyth platform footprint).

2.3.1.1 Limitations

The primary scientific penalties associated with a dedicated AO relay are lower transmission and higher system emissivity. These can be controlled via good coatings, clean optics environment, and cooling of optical surfaces, but these all increase cost and complexity.

Large FoR AO relays can require large space volume on the Nasmyth platform, although not necessarily a large platform footprint (for vertically oriented relay concepts).

2.3.2 AM2

An adaptive secondary mirror similarly provides a convenient conjugate altitude for AO correction (typically near the ground; some 130 m below ground for Keck). This subterranean conjugation is typically not an issue for near-IR correction over modest FoV (the practical effect, if any, on visible-light or wide-FoV AO systems has not been sufficiently explored). Furthermore, by not forming a new optical space, several fewer reflections are necessary, increasing optical transmission and reducing system emissivity. AM2 correction is made to both the science and WFS light.

A WFS package is still needed in the vicinity of the Nasmyth platform.

2.3.2.1 Limitations

Most difficulties surrounding AM2 involve in the technical challenge of fabricating the mirror itself. A mirror for Keck would exceed the largest diameter AM2 fabricated to date (by about 50% linearly), although the facesheet technology itself is not unprecedented. Several potential AO observing modes require of order 3-5 times the maximum number of actuators demonstrated to date (672 at LBT). Moreover, the relationship between actuator count and effective number of modes of wavefront control for existing AM2's does not appear sufficiently well understood Thermal control of dissipated heat is a challenge for voice-coil actuator mirrors, requiring on-telescope glycol or similar cooling schemes.

Convex AM2 systems are difficult to test, requiring large test fixtures and null optics to simulate use of the AM2 in the actual telescope.

Installation of an AM2 would likely require moderate amounts of telescope down time.

2.3.3 Open-loop MEMS Correction

To be explicit, we use the terminology "Open-loop MEMS correction" here to mean correction applied to science path light only and not to the guide starlight[6]. This requires that all high-order

[6] More strictly, "Go-to Correction" may be more appropriate, but for historical reasons most practitioners use the "Open-loop" terminology.

wavefront sensors operate in an open-loop control mode, deriving wavefront information for use by the AO system, but never seeing the feedback of that correction applied to the sensor wavefronts.

Because this architecture can provide multiple independent corrections to a number of DMs, the approach has historically been associated with multiobject AO (MOAO) and very small diameter mirrors (driven by multiobject packaging), but this is not strictly necessary. We can consider single-channel, open-loop correction of FoR's set only by packaging constraints and conservation of AΩ product, which restricts the plausible FoR for small DMs. With a pupil demagnification of ~400:1, even a 25 mm diameter DM could reasonably pass 1 arcmin Keck FoR (limited by practical optical design).

Open-loop correction can be implemented with either MEMS or traditional electrostrictive actuator DMs. However, because open-loop control relies on accurate knowledge of true actuator placement, MEMS devices, being more linear and potentially athermal, appear today more appropriate.***Limitations***

Past experience with adaptive optics open-loop control[7] indicates that it should be relatively straightforward to reduce incident wavefront errors to 10% of their initial amplitude using open-loop correction. Thus, architectures that use only open-loop MEMS correction can reduce a typical 1.0 micron (tip/tilt removed) RMS wavefront error to 100 nm RMS. While this is encouraging for some IR science goals, the inclusion of a (new) order of 100nm error term into the visible light AO observing mode error budget (which may target 140nm total error) appears troublesome. Use of open-loop MEMS correction behind a common-mode AO relay or AM2, which has already reduced the wavefront error to only the anisoplanatic residuals (order of 100nm rms), greatly reduces the performance risk (to typically 10's of nm, which can be absorbed into LTAO error budgets).

2.4 Observing Mode vs. Architecture Comparison

In considering the implementation of various observing modes, we will need to perform substantial analyses and trade studies to quantify the performance, risks, and costs of different architectural choices. What we can say today, however, is that the development of an AM2 sufficient for performing EXAO or visible-light LTAO is a high-risk option (and may also have performance issues for these modes). Similarly, although we have reason to believe that open-loop MEMS control can reduce wavefront errors to 10% of the initial P-V wavefront amplitude, we believe that reduction to 1% of initial amplitude is also high-risk.

These two statements lead form the basis for a classification of performance-to-risk ratio for implementing each AO observing mode using various architecture combinations, as shown in **Table 2**. Often use of two architectures in combination is not beneficial for a particular observing modes; in these cases we assume an implementation using only the more favorable architecture option.

[7] Independent personal communications with Don Gavel, UCSC and Chris Shelton, JPL.

2.4.1 Architecture costs

Table 2 does not attempt to incorporate the relative financial cost of these options; significant analyses and design development will be required to produce accurate cost estimates. In general terms, however, we can say that the cost of developing an appropriate AM2 for NGAO is likely to be comparable to the cost of building an AO relay. To within 50% error bars in each of the following *single-telescope* estimates, either an AM2 or an AO relay is likely to cost ~$10M (although interesting new large DM technologies are maturing). The cost of further developing MEMS DM and open-loop WFS technologies to the point needed for MOAO may be comparable to somewhat less than an AM2 or dedicated relay, though this assumes significant on-going commercial and/or military investment into MEMS mirror development. Finally, the cost of either an AM2 or AO relay is likely to be *less* than the cost of the laser guide star facility (LGSF), which could be $10-15M, driven by the high cost of sodium laser power needed for precision wavefront control. Thus, the full complement of a single telescope AM2 + AO relay + MEMS development + LGSF would total of order $40-50M.

To this must be added the cost of new instrumentation designed to fully exploit each of these AO modes. Based on scaling from Gemini and TMT instrument feasibility studies, a near-DL MOAO spectrograph may cost $20M, a mid-IR spectrometer perhaps $10M, and implementation of GLAO for a currently seeing-limited instrument (using an AM2) could be another $5-10M.

Thus, although these instrument issues must clearly await the results of the NGAO science case prioritization, the ballpark cost of the full NGAO program, providing the many different kinds of AO system architecture described in Table 1 is crudely likely to be of order $75-100M, depending on the instrument compliment to exploit the NGAO implementation(s).

Observing Mode	Instrument Example	NGAO Program Architectures Available						
		Relay (only)	AM2 (only)	Open-loop MEMS (only)	Relay + AM2	Relay + Open-loop MEMS	AM2 + Open-loop MEMS	Relay + AM2 + Open-loop MEMS
EXAO	XAOPI	Excellent	Poor	Poor	Excellent	Excellent	Poor	Excellent
LTAO (IR)	OSIRIS or NIRC2	Excellent	Excellent	Good	Excellent	Excellent	Excellent	Excellent
LTAO (Visible)	20” Imager or 20" FoR Multi-IFU	Excellent	Poor	Poor	Excellent	Excellent	Poor	Excellent
SLGLAO	2' FoR Multi-IFU	Excellent	Good	Good	Excellent	Excellent	Good	Excellent
MCAO	2’ DL Imager	Excellent	--	Poor	Excellent	Excellent	Poor	Excellent
MIRAO	1’ DL Imager or 1' High Resolution Spectrograph	Poor	Excellent	Good	Excellent	Good	Excellent	Excellent
GLAO	DEIMOS or MOSFIRE	Good	Excellent	--	Excellent	Good	Excellent	Excellent
MOAO	8' FoR Multi-IFU or Multi-FoV Imager	--	--	Good	--	Excellent	Excellent	Excellent
Seeing-limited	DEIMOS or MOSFIRE	--	Good	--	Good	--	Good	Good
Principal Architecture Deficiency		No MOAO	No MOAO or MCAO	High LTAO Risk; No GLAO	No MOAO	No Seeing-limited	High LTAO Risk	None

Table 2. Performance-to-risk ratio summary of AO observing modes for various NGAO architectures. Combination columns should be interpreted as the capability provided to the Keck science user community by investments in multiple architectural development paths. From R. Dekany, "Keck Observatory Next Generation Adaptive Optics (NGAO) Capability/Architecture Options", Caltech Instrumentation Note #601.

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2.5 Key Points

The following details supports the performance-to-risk comparisons made in **Table 2**.

- ExAO and LTAO (visible) require small error budget (of order 80nm or 140nm rms for all error sources, respectively) - uncertainty regarding the residual errors of open-loop MEMS control make meeting ExAO and LTAO error budgets high risk.
- The combination of open-loop MEMS with AM2 reduces the wavefront error that must be compensated open-loop, while MEMS can reach the required actuator count, making the combination more attractive for LTAO (visible) than either alone. Because EXAO requires careful control of systematics, any open-loop component to the architecture appears difficult to implement.
- ExAO and LTAO (visible) require on order 4,000 actuators to overcome atmospheric fitting error - achieving this with AM2 is considered high risk.
- MCAO with AM2 (only) is precluded as at least 2 conjugates are required.
- MCAO with AO relay + AM2 could provide 2 conjugates with greater photon efficiency that an AO relay alone (assuming sufficient actuator count within AM2)
- MCAO using only open-loop MEMS combines the unproven concept of MCAO with that of open-loop compensation - this double risk is unfavorable.
- MCAO using AM2+MEMS requires that all but one of the MCAO DM's operate in open-loop, with the same double risk as identified above.
- MIRAO with an AO relay can be optimized up to and including the development of an entirely cryogenic AO system. Although conceptually straightforward, we believe an all-cryo AO system has to be considered high risk.
- MIRAO with open-loop MEMS is an intriguing possibility due to the small physical volumes required within a cryostat and the relatively large (order 500 nm rms) allowable MIRAO wavefront error.
- GLAO with MEMS (only) is precluded due to constraints on the FoV that could be passed through a highly demagnified pupil (assuming 25-50mm diameter MEMS DMs)
- MOAO as currently envisioned requires open-loop MEMS compensation.
- MOAO using only open-loop MEMS compensation requires excellent correction of large initial wavefront errors. MOAO with open-loop MEMS becomes considerably easier when used in combination with an AM2 or AO relay.
- AM2 is the only option that can feasibly improve the performance of DEIMOS (due to its very wide FoV) and MOSFIRE (due to its forward Cass placement).

2.6 Conclusions

At the bottom of **Table 2**, we call out the greatest performance-to-risk deficiency among the various architecture options. Comparing these issues against the guidance provided by the Keck Strategic Plan in Section 2.1, we make the following conclusions:

1. Due to the high Strategic importance of moving AO science toward 400 nm observing wavelength, the NGAO program should baseline use of an AO relay, the options without an AO relay deemed too high risk. To maximize the versatility of this relay for MOAO and GLAO upgrade paths, it should be designed to pass as large a field of view as allowed by practical volume constraints at Nasmyth (incl. for vertical orientations).
2. To enable MOAO capability, open-loop MEMS correction techniques must be developed and proven in the laboratory. (This may also help other observing modes via open-loop sharpening of NGS used for low-order wavefront sensing).
3. The addition of an AM2 to an NGAO program having both an AO relay and open-loop MEMS development has the benefits of improved MIRAO performance through emissivity reduction, options for AM2+MEMS implementations of MOAO, and possible GLAO compensation of seeing-limited instruments (though this may drive AM2 to impracticable actuator count).

Finally, we reiterate a ballpark program cost for a full AO relay + AM2 + MEMS development + LGSF + one new MOAO spectrograph + one new MIRAO spectrograph + seeing-limited instrument support program to be order of $75-100M. Although this is likely to evolve in the next few months as the NGAO science case matures, this scale of investment by our community, necessary to realize the vision of the Strategic Plan, is unlikely to diminish.