Keck Adaptive Optics Note 510

NGAO System Design Phase
Technical Risk Evaluation

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ABSTRACT

This note is intended to summarize the significant technical risks associated with the NGAO system as identified during the system design phase. The current version represents the fourth iteration on the risks. Tthe first iteration was included in the proposal (KAON 400), and iterations were performed during and after the system architecture phase of the system design (these are included as Appendix I). The risk evaluation methodology is described in section 1. Section 2 identifies and ranks the technical risks, including risk mitigation options, and presents the resultant risk matrix. The final section provides more specific risk mitigation plans for the remaining design phases.

1. Methodology

The JPL risk evaluation matrix approach used for the Keck Interferometer was selected to track the significant technical risks. This matrix ranks each risk by the consequences and likelihood of the risk occurring. A scale of 1 to 5 is used with higher numbers representing higher risk.

Likelihood of Occurrence:

Level	Definition	
5	Very High	> 70%, almost certain
4	High	>50%, more likely than not
3	Moderate	>30%, significant likelihood
2	Low	> 1%, unlikely
1	Very Low	<1%, very unlikely

Consequence of Occurrence
(replaced JPL's usage of "mission return" with "science return")**:**

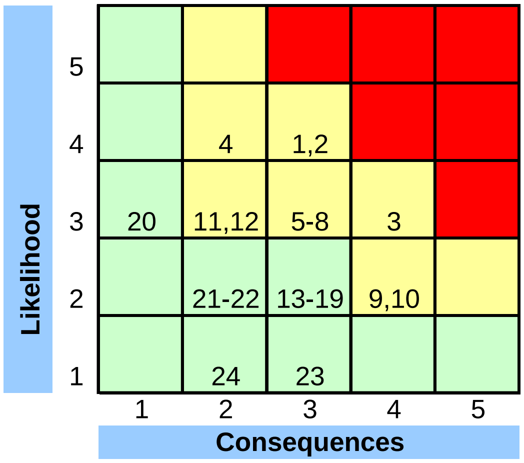
Level	Performance Risk Definition
5	Project Failure
4	Significant reduction in science return
3	Moderate reduction in science return
2	Small reduction in science return
1	Minimal or no impact to science return

A JPL-format technical risk matrix using these definitions is shown in the next section. In this risk matrix red represents high risks that require implementation of new processes or a change in the baseline plan, yellow represents medium risks that need to be aggressively managed including considering alternative approaches, and green represents relatively low risks that should at least be monitored.

2. Technical Risks Identification and Ranking

2.1 Technical Risk Matrix

The current risk matrix is shown in the following Figure.



Likelihood	Consequences 1	2	3	4	5
5					
4		4	1,2		
3	20	11,12	5-8	3	
2		21-22	13-19	9,10	
1		24	23		

2.2 Significant Technical Risks

The following table lists the significant technical risks that have been identified. The risks have been sorted in descending order by highest combined consequences and likelihood scores, followed by highest likelihood and highest consequence. Each risk has a unique number, a trend column which will be used for tracking which way the risks are moving, a consequence ranking, a likelihood ranking, a description, the status of the risk and plans for mitigation.

#	Trend	Conse-quence	Like-lihood	Description	Status	Mitigation
1		3	4	Inadequate PSF calibration to support precision astrometry, photometry and companion sensitivity science.	The importance of PSF calibration and approaches to this calibration are documented in KAONs 474, 480 and 497. Based on thes KAONs, NGAO team members wrote a 2-year PSF reconstruction proposal to the CfAO that was funded; work began in Nov/07. Science cases for which high accuracy PSF calibration has the most impact are: Galactic Center General Relativistic effects astrometry, narrow-field proper motion astrometry, and two target sets for detection of planets around low mass stars.	1) Participate in and monitor the CfAO funded effort, including support for PSF reconstruction tests & demonstrations with the existing Keck AO systems. 2) PSF calibration system-level preliminary design and design of the PSF calibration sequences and pipeline. 3) Collaborate with others to implement an atmospheric profiler for Mauna Kea, in support of PSF calibration.
2		3	4	Inadequate sky coverage to support the wavefront error budget and hence science cases.	All of our evaluations have assumed AO corrected low order wavefront sensors using low noise near-IR detectors. These evaluations are documented in KAONs 470, 487, 492 and 504.	1) Prototype a near-IR tip/tilt sensor to demonstrate that adequate detectors are available and that the AO correction is adequate. 2) Demonstrate the technique in the lab and/or on-sky.
3		4	3	Required lasers unavailable	Performance budget assumes return from a single frequency laser system. We would need more laser power from a mode locked laser system.	1) See discussion in programmatic risk KAON 566.

4		2	4	Wavefront error budget not achieved due to inadequate assumptions and calculations	The largest issues are addressed in this table as separate risks. In addition, we anchored our assumptions through site monitoring (KAONs 303, 415, 496, 503), sodium return measurements (KAONs 416, 417, 419), comparison to the Keck II AO performance (KAON 461), and understanding of the telescope wavefront error contributions (KAONs 468, 469, 482)	1) Anchor to Keck II NGWFC results. 2) Revisit all the assumptions and calculations during the preliminary design phase.
5		3	3	Inadequate tomographic reconstruction accuracy to support the wavefront error budget and hence specific science cases.	Laser tomography of the atmosphere has not yet been demonstrated or used for AO science. Tomography experiments with natural guide stars (ESO, Palomar & MMT) have begun to set limits on tomographic measurement error. We have compared multiple tomography codes as part of the system design phase (KAON 475); our NGAO tomography predictions have been made using one of these codes (KAON 429). The NGAO error budget assumes 50 nm rms of residual tomography error versus the 164 nm of focal anisoplanatism in the Keck II LGS AO system error budget. The consequence ranking was selected for the case of not reducing the tomographic error below 120 nm rms. Our design includes a flexible asterism generator to optimize for the science case & conditions (as we learn about what is optimum).	1) Closely monitor the results of tomography experiments being performed by other groups (Gemini, MAD, MMT). 2) Continue to perform lab experiments at the LAO directly in support of NGAO tomography issues. 3) Maintain a flexible LGS asterism architecture to allow for optimally LGS positioning to optimize for each science case & to minimize tomography error.
6		3	3	Astrometry performance requirement not achieved	Astrometry error budget not yet adequately understood. Current understanding and recommendations are summarized in KAON 480.	1) We will continue to work with the UCLA Galactic Center team and with the CIT proper motions team to understand the limitations imposed by the existing Keck AO system and science instrument. 2) A full error budget will be developed during the preliminary design phase.

7		3	3	Tomographic reconstruction computer architecture not yet tested in hardware	The proposed architecture is is a new, untried concept for astronomy. Massively parallelized architectures are assumed for cost and performance reasons.	1) Monitor the progress of other projects (i.e., P3K). 2) Benchmark on a software simulator. 3) Benchmark on a scaled subset of hardware.
8		3	3	Keck Interferometer needs not met.	Needs & options documented in KAONs 428 and 483. Conceptual design for implementation partially addressed in the optical relay system design report (KAON 549). A complete layout of the interferometer feed and an analysis of the polarization impact needs to be developed next.	1) Complete the preliminary design with the interferometer requirements in mind.
9		4	2	Complexity and instability of interactions in the overall software control system	NGAO will be significantly more complex than the existing Keck AO system with many more potentially interacting control loops and significantly more motion control. We are addressing this issue with significant attention to the final science operations product and utilization of significant operational "lessons learned" experience from the current LGS AO system.	1) Good system-level design with attention to science observing sequences and operations. 2) Employ a hierarchical control structure and test each level comprehensively before integration.
10		4	2	Adequate wavefront sensor CCDs not available	Fast low-noise high pixel count (256x256) detectors required. A CCID-56 with more pixels is a prime candidate. CCID-56d (160x160 pixels) devices are available, and being tested for GPI.	1) Monitor the progress of the AODP-funded CCID-56 project. 2) Evaluate alternative options.
11		2	3	Photometry performance requirement not achieved	Error budget not adequately understood. Current understanding and recommendations summarized in KAON 474.	1) Develop a more complete understanding of this performance budget, which will be closely tied to the quality of PSF determination (listed as a separate risk item).
12		2	3	Inadequate tip/tilt performance for 1st relay DM mounted on a tip/tilt stage	1st stage DM is ~100 mm in diameter. We do not yet know whether the required tip/tilt bandwidth can be achieved.	1) Evaluate BW requirement for the 1st stage DM given that tweeter MEMs may be on their own tip/tilt stages. 2) Determine achievable tip/tilt bandwidth performance during preliminary design. 3) Develop options for a separate tip/tilt mirror (either use existing fold or redesign).

13		3	2	Inadequate performance of multiple LGS projection and sensing system.	An ~ 9 LGS system is needed to achieve the requirements. Design and packaging of both the laser projection and LGS wavefront sensor package to meet the performance requirements (including measurement error, reliability & observing efficiency) will be challenging.	1) Complete the preliminary design. 2) Consider prototyping one LGS WFS during DD phase.
14		3	2	No workable design for deployable near-IR integral field spectrograph (d-IFS).	This instrument will be key to the future of extragalactic science with NGAO. A conceptual design has been developed for the object selection mechanism for NGAO's low order wavefront sensors, which could also apply to the d-IFS heads.	1) Plan to start d-IFS system design during NGAO preliminary design, including the pickoff design. 2) Complete a preliminary design for the low order wavefront sensor pickoff heads during the NGAO preliminary design phase and consider d-IFS pickoff requirements where possible.
15		3	2	Rayleigh-scattered background on LGS WFS cannot be calibrated out.	A first-order Rayleigh rejection trade study has been performed (KAON 490)	1) Learn from Gemini MCAO experience. 2) Perform additional modeling during preliminary design phase.
16		3	2	K-band background requirement not achieved.	The background performance budget was evaluated in KAON 501 with the conclusion that the AO optics need to be cooled to 260 K.	1) Re-evaluate expected K-band background based on conceptual & preliminary optical designs. 2) Develop enclosure design. 3) Revisit science requirement, especially for narrow field NIR instruments.
17		3	2	Inadequate MEMS performance	Good lab experience, but little on-sky performance data and no on-sky lifetime data yet. Impact of windows on throughput could be an issue. Degradation of actuators and coatings an issue.	1) Monitor VILLAGES on-sky experiments and LAO lab experience. 2) Evaluate pros/cons of various window options (including no window) on MEMS.
18		3	2	Woofer-tweeter performance inadequate.	Woofer-tweeters are used for the science instruments & the low order wavefront sensors. The tweeters are used open loop. Such systems have not yet been demonstrated on-sky.	1) Need to design servo control. 2) LAO & others (i.e., U. Vic) are doing woofer-tweeter demonstrations. Need to quantify the performance results.

19		3	2	Space command shutdowns	Recently US Space Command has been requiring frequent blackout periods. Keck is already actively pursuing this issue in collaboration with other Observatories.	1) Monitor progress of current discussions with Space Command.
20		1	3	Low mass star companions sensitivity science requirement not achieved	Current requirements & understanding of companion sensitivity documented in KAON 497. Current low mass stars companion sensitivity requirements are only partially met by a simple coronagraph (unlikely to have an advanced coronagraph in 1st generation instruments).	1) Revisit science requirements in light of KAON 497. In particular, re-evaluate the three target sets discussed in the SCRD.
21		2	2	Science requirements inadequately understood and/or defined.	Science cases requirements are defined in KAONs 455 and 456. All Key Science Drivers are complete. Case development for four of the Science Drivers is not yet complete; work is ongoing.	1) Complete the science case requirements for the last four Science Drivers. 2) Revisit Key Science Drivers and Science Drivers as needed during preliminary design.
22		2	2	Required dichroic performance not achieved	Multiple large dichroics with excellent performance are required to meet the throughput, background and wavefront performance budgets. Dichroic changers must be repeatable.	1) Discuss with vendors. 2) Evaluate whether coating tests are valuable. 3) Design dichroic changer.
23		3	1	Impact of telescope vibrations on wavefront error budget higher than predicted.	Measurements and impact documented in KAON 482. Tip/tilt vibrations from Keck II experience added to performance budget tool.	1) Improve tip/tilt vibration model in the wavefront budget during the preliminary design. 2) Reduce tip/tilt vibrations.
24		2	1	LOWFS-based tip/tilt correction for narrow field science instruments inadequate	Tip/tilt errors from the 2nd AO relay or opto-mechanical drifts will not be sensed by the low order wavefront sensors.	1) Evaluate the error budget impact. 2) Design a stable system. 3) Design a metrology system if needed

4. Technical Risk Mitigation Plans

4.1 Preliminary Design Phase

Many of the above technical risk items will be addressed during the preliminary design phase. Specific actions planned for the preliminary design phase, on the medium to high risk items, include the following (the numbers below correspond to the first column in the above risk table):

1. PSF calibration.
   - Collaboration and support for the CfAO-funded PSF reconstruction proposal. Support the effort for 2nd year funding for this project.

- Produce a system level design for PSF calibration. This includes defining the requirements for the hardware and software that will be needed to support PSF calibration, including such things as implications for observing and calibration sequences, the real-time control system design and data products, atmospheric profilometry and data post-processing.
- Investigate options for collaborative implementation of an appropriate atmospheric profilometer on Mauna Kea including the Chun et al. proposal to the Mauna Kea Directors and reuse of the TMT monitoring equipment.

2. Sky coverage.
    - Initial plans included prototyping of a tip/tilt sensor and object selection mechanism (as proposed in KAON 565) during the preliminary design. For budget reasons we have reduced the available preliminary design phase budget for this work and hence the scope. However, Caltech and HIA are collaborating on a TMT IRIS LOWFS study and we have recently started investigating whether a TMT/NGAO collaboration is possible on this design/implementation. Some cost sharing, if available might allow us to get further in this prototyping.
    - If the above collaborative prototyping is not feasible we will determine whether we can move the fabrication of the first LOWFS assembly into the detailed design phase in order to identify problems early.
    - We will continue with the preliminary design of the LOWFS assembly including investigating the availability of the required sensors.
3. Lasers.
    - See the Programmatic Risks KAON 566.
4. Wavefront error budget.
    - Revisit the assumptions and calculations.
5. Tomographic reconstruction.
    - Monitor and summarize the results of tomographic experiments, and compare with our simulation codes as appropriate.
    - Define and implement appropriate experiments at the LAO. See Appendix II for a letter of intent to perform these experiments from Don Gavel, LAO Director, who is also a member of the NGAO Executive Committee.
6. Astrometry performance.
    - Develop a full astrometry performance budget.
    - Work with the UCLA Galactic Center team and CIT proper motions team to develop and anchor this budget.
7. Tomographic reconstruction computer architecture.
    - Monitor the progress of similar designs and implementations.
    - Proceed with the preliminary design and analysis.
    - Design a benchmark experiment to be performed during the detailed design phase.
8. Interferometer needs.
    - Complete the optical relay design for the interferometer feed.
    - Evaluate the polarization and field/pupil rotation implications of this design, and redesign as appropriate, including consideration of the option of modifying the existing Keck AO or interferometer optics to work with NGAO.
9. Software control complexity.
    - Complete the preliminary design of the overall software architecture.
10. Wavefront sensor CCDs.
    - Monitor the progress of suitable CCDs developments.
    - Explore collaboration with TMT on development of low noise sensor, also needed for their NGS wavefront sensor.
11. Photometry performance.
    - Develop a better understanding of the photometry performance budget.
12. Inadequate woofer tip/tilt performance.
    - Develop a preliminary design that includes discussions with vendors.
    - Use experiments at LAO to anchor modeling.

Appendix I. Preliminary Technical Risk Evaluation Results dated August 15, 2007

As of August 15, 2007 the NGAO system architecture down select process was still on going. Five possible architectures were identified during the team work shop at UC Santa Cruz in early July (see KAON 499). The risk table shown in this Appendix was compiled to assist in the down-selection process for NGAO system architecture and as a repository for risk evaluation for the final system design report.

This appendix explains our initial methodology for risk evaluation. It also included a risk table with about 70 items. These are organized by system level risks, component risks, and architecture specific risks.

Methodology

Risk areas in the project were identified. Each risk was evaluated for its impact and likelihood. Impact level was assigned in one of the following 4 categories:

- Major - Project objectives at risk (mandatory change to one or more of project scope, schedule, or resources)
- Moderate - Project objectives can still be met, but would require significant changes to plan
- Low - No major plan changes required; the risk is an inconvenience or it will be addressed through minor allocation of contingency resources
- Unknown - Impact is not quantifiable at this time

These categories are broad and include cost and schedule risk as inclusively. Each risk was also assigned a likelihood of occurrence based on the following 3 categories.

- Likely - 50% or higher
- Unlikely - 10% to 50%
- Very unlikely - 10% or less

Using these criteria the following risk table was developed, see **Table 1**.

Table 1: Risk evaluation for NGAO as of August 15, 2007.

Ref. #	Description	Impact	Likelihood	Mitigation Plans	System Design Phase Mitigation
	System Level Risks				
1	Achieving science requirements				
a	Long exposure time performance	Moderate	Likely	On instrument metrology	
b	(add other parameters?)				
2	Science requirements inadequately understood & changing	Major	Unlikely	Talk to the astronomers a lot	Science Core Requirements document and flowdown
3	Delivered PSF too variable (spatially and temporally) to satisfy astrometry and photometry requirements	Moderate	Likely		CfAO funded PSF study (2008-2009)
4	Adequately meeting interferometer needs	Unknown	Likely	Review proposed performance with KI team	KI support trade study and KAON
5	Achieving contrast performance budget	Unknown	Unlikely	(Need to verify science requirements)	Contrast trade study & KAON
6	Achieving defined photometry budget	Unknown	Unlikely	(Need to verify science requirements)	Photometry trade study & KAON
7	Achieving defined astrometry budget	Unknown	Unlikely	(Need to verify science requirements)	Astrometry trade study & KAON
8	Achieving desired SNRs	Unknown	Unlikely	Managing throughput in optical design, making provisions for long exposure stability	Throughput and background trade study & KAON
9	Achieving polarimetry requirement	Unknown	Unlikely	Control effects that rotate or scramble polarization	Polarimetry trade study
10	Wavefront error budget assumptions & accuracy				
a	Bandwidth error assumptions. Assumption that closed loop bandwidth is 1/15 of sample rate. The rate of ~1/20 has been demonstrated, but would significantly impact error budget.	Moderate	Unlikely	Investigate and simulate control loop impact.	
b	Sodium return expectations not met	Major	Likely	Refine and adjust assumptions based on data from current systems	See LAO web page for current info
c	low noise CCDs for WFS.	Major	Unlikely	Another design turn for CCID-56, more laser power	AODP CCD project
d	Impact of telescope vibration	Moderate	Likely	Reduce telescope vibrations	Vibration trade study & KAON
e	Tomography. No sky demonstration.				MAD, MMT, LAO bench experiment
i	Codes contain assumptions that are untested in actual operating conditions	Major	Likely	Refine and adjust assumptions based on testing	
ii	Alignment and registration - beacons and WFS	Moderate	Unlikely	Design opto-mechanics for closed loop beacon positioning and stability. Implement test procedures during I&T to ensure proper alignment and registration.	
f	Tip/tilt tomography. No sky demonstration of benefits of multiple TT stars	Moderate	Unlikely	LAO laboratory experiments	
g	Rotating LGS constellation limits performance for long exposures	Moderate	Likely	De-rotate, configurable add beacons?	

h	MCAO mirrors are not at proper conjugates or correct "statistical position" for the actual Cn2 profile	Moderate	Unlikely	Get MASS/DIMM data for Mauna Kea before detailed design phase	Collate TMT and other Mauna Kea seeing measurements
11	Risk of not being able to find adequate tip/tilt stars for certain science cases	Low	Likely	System provides gradual degradation, TT stars AO corrected	
12	Rayleigh background on LGS WFS cannot calibrated out	Major	Likely	Issue for GS MCAO, will be tested by them. Use long period pulsed laser and electronic shutter on HOWFS CCD to gate out Rayleigh	Rayleigh Rejection trade study
	Component Risks				
13	Availability of required lasers	Major	Likely	Continue to pursue laser development	
14	Fiber transport. Mitigation is conventional beam transport	Moderate	Likely	Testing programs underway for fibers	Keck I LGS experiment with Gemini Laser, Subaru Fiber; ESO & Subaru experience
15	Availability DM with small pitch and adequate stroke	Major	Unlikely	Use 48 x 48, 5 mm, add a second DM	
16	MEMs mirror window/no window	Moderate	Likely	Account for windows in budget or develop MEMs without windows	
17	MEMs mirror lifetime	Major	Likely	Work with MEMs vendors, other AO project	
18	DM on a tip/tilt stage	Major	Likely		
a	DM incompatible with operation on TT stage	Major	Unlikely	Use a separate TT mirror	
b	Problems with DM interface cabling on TT stage	Major	Likely	Address in DM design	
c	Insufficient TT rejection	Moderate	Unlikely	Add a second TT mirror	
19	Switchyard approach:				
a	Dichroics. Size and performance.	Major	Likely	(at report we will not have this level of risk). Test coating samples to confirm performance before completing design	
b	Performance and reliability of dichroic changers.	Moderate	Unlikely		
20	K-mirror. Size, performance.	Moderate	Unlikely	Other architectures for derotation, better coatings	
21	Achieving real-time control performance requirements	Major	Unlikely	Benchmark tests, simulations anchored to RTC hardware performance, prototype testing	
22	Fitting system on telescope	Major	Unlikely	Design process will ensure compatible system	
23	Thermal/mechanical performance of AO system environmental enclosure	Moderate	Unlikely	Careful design, thermal performance modeling including FEA	
24	Design & cost of interfacing with existing instruments exceeds value of doing so	Unknown	Unlikely	Replace those instruments	
25	MOAO not demonstrated.	Moderate	Likely	MCAO gives reasonable sky coverage, VILLAGES testing planned. Other testing programs, perhaps on existing	

				Keck AO system.	
26	Fast LOWFS IR based camera				
a	Detector performance	Moderate	Unlikely	Some performance data on hand. Testing continues.	
b	Detector availability	Major	Unlikely	Two sources of supply	
27	Calibration unit with LGS simulators				
a	Finding space for it	Major	Unlikely	Will be designed-in from the beginning as an essential capability	
b	Achieving required level of performance	Moderate	Unlikely	On-sky calibration can substitute at greater expense	
28	Rayleigh Laser				
a	Complexity of pulse tracker or other range gate method	Unknown	Unlikely		
b	Additional background light	Major	Unlikely		

Table 2: Architecture specific risk for NGAO, as of August 15, 2007.

Ref. #	Description	Impact	Likelihood	Mitigation Plans	System Design Phase Mitigation
	candidate 1 split relay				
	Unclear that dNIRI can fit close enough to elevation journal	Major	Likely		
	Unclear if there is enough space for dNIRI & narrow field at same time	Major	Likely		
	Calibration: the non-common path accuracy between the TT location and narrow field science instruments (This is particularly true due to the adoption of rotators over a single k-mirror field de-rotator)	Major	Likely		
	candidate 2 AO secondary				
	Development of AM2 is costly and uncertain	Major	Likely		
	Actual tip/tilt performance of the AM2 is Unknown	Major	Likely		
	Fitting error for AM2 worse than expected	Major	Likely		
	candidate 3 large relay				
	Large instrument that needs to be cooled	Major	Likely		
	Unclear if the instrument will fit on the platform	Moderate	Unlikely		
	MCAO option only provides 60” field fully corrected (50% EE)	Moderate	Unlikely		
	MCAO requires 2 DMs, one at ground and one at 5km	Moderate	Unlikely		
	candidate 4 Keck I upgrade				
	Higher background	Moderate			
	Parts not designed for Low Temp operation	Major	Likely		
	dNIRI feed hard to fit in front of AO	Moderate	Likely		
	Some of the hardware will be obsolete by the time of NGAO	Moderate	Likely		
	candidate 5 cascade relay				
	Cannot be packaged	Major	Likely		
	Cannot support interferometer	Moderate	Unlikely		
	High emissivity	Major	Unlikely		
	Complication of woofer-tweeter control	Major	Likely		
	Lower transmission for both the LGS path (loss of laser return) and instruments path (reduced sensitivity, but potentially offset by higher Strehl with less risky architectural approach)	Major	Likely		
	LOWFS away from science instruments, though all are not rotating	Moderate	Likely		
	Potentially more scintillation, static aberrations due to large number of surfaces that need to be controlled	Moderate	Likely		

Appendix II. Letter from LAO Director.

Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

Adaptive Optics Experiments in the Laboratory for Adaptive Optics in Support of Risk Reduction for Keck Next Generation Adaptive Optics

Donald Gavel, Director, Laboratory for Adaptive Optics
March 17, 2008

1. Introduction

The charter for the Laboratory for Adaptive Optics (LAO) is to develop innovative adaptive optics technology, concepts, and instruments for astronomy, particularly with three main instrumentation thrusts: Multiconjugate Adaptive Optics (MCAO), Extreme Adaptive Optics (ExAO), and AO component testing. All three are aimed at improving the ability of ground-based astronomical telescopes to correct for the blurring due to the Earth's atmosphere, so that telescopes on the ground can make diffraction-limited images as clear as can be achieved by space-based telescopes.

Within the Laboratory for Adaptive Optics, we have been able to pursue the higher risk experimental projects that otherwise would not have been funded by the giant telescopes. This has only been possible because of the independent nature of the funding for the Moore Foundation grant and is consistent with the Moore Foundation's goal of advancing cutting edge scientific research.

The LAO is an ideal place to explore the concepts envisioned for the Keck Next Generation Adaptive Optics system using real light and real equipment not unlike that which would be used in an on-telescope system. The "MCAO" testbed is a reconfigurable system that simulates the AO process from the point of guidestar production at the sodium layer to the point of wavefront sensing, tomographic correction, and control. This testbed can be configured to mimic the conditions at the Keck telescope, including the Mauna Kea ridge model layered atmosphere, 10 meter scalloped aperture, 5+3 and 6+3 laser guidestar constellations, and tip/tilt stars. We have both woofer and tweeter DM's which can both be positioned at the ground conjugate, as is envisioned for NGAO's MOAO architecture.

2. Issues for NGAO Risk Reduction

The tomographic error in the Keck NGAO high Strehl error budgets is on the order of 40 nm rms for the on-axis 5-LGS constellation. This is much more accurate than what has been demonstrated with on-sky experiments such as ESO's Multiconjugate Adaptive Demonstration (MAD) experiments (~350 nm total wavefront error) or the Palomar Multi Guide Star Unit (MGSU) experiments (~200 nm tomography error). Recent measurements on the LAO testbed with a 5 LGS constellation configured like the Gemini South MCAO system have shown 80-90 nm rms tomography error, which is consistent with simulations and perhaps a predictor for Gemini South, but is not at the finer precision goal of NGAO with its more compact guide star constellation.

Some of the risk issues we can address for NGAO are:

- Can the 40 nm tomography error be reliably achieved, given the assumptions of the Mauna Kea ridge model seeing conditions?
- How important are the tip/tilt/focus/astigmatism measurements in achieving this precision?
- How stable is the PSF and how does it vary with field position as a result of tomographic reconstruction?
- What are the noise propagation properties of the tomographic reconstructor?
- How precisely calibrated do the Hartmann wavefront sensors have to be, and how stable do they have to be, to achieve this precision, and how would systematic errors propagate into the result?

3. Testbed Setup

To do these tests, the experimental testbed would be set up as follows:

- Assign similarity parameters so that the testbed 20 mm beam size represents 10 meters of telescope diameter, and we can place multiple aberrator plates in the 0-15 km atmospheric section of the testbed. The similarity parameters map lateral and transverse dimensions to physical sizes on the bench.
- Construct constellations of 5+3 and 6+3 LGS for the front-end. Position at 90 km (or higher to simulate zenith dependent distance) conjugate height. The 5 and 6 central guidestars are compacted into a 30 (-ish?) arcsecond diameter field. The +3 guidestars are on the wide field for tip/tilt star tomography improvement or "point-and-shoot".
- Construct a constellation of natural stars – three tip/tilt stars on the field and a central science "scoring" star – to be positioned at infinity conjugate height. Light from the constellations of the two stars are combined with a beam splitter positioned before the atmosphere space.
- Arrange multiple aberrator plates in a model layered atmosphere.
- Place a woofer DM and a tweeter DM at 0 km conjugates. The woofer DM is a 52 actuator magnetically actuated LAOG mirror. The tweeter DM is a 768x768 pixel Hamamatsu liquid crystal programmable phase modulator. These do not correspond exactly to the woofer/tweeter pair envisioned for NGAO, but the combination will have sufficient degrees of freedom to model the NGAO pair's correction of a full atmosphere without wrapping phase.
- Note: there is no provision for additional tweeter mirrors assigned to each of the tip/tilt stars as they are in KNGAO. We have two additional Hamamatsu PPMs that might be applied for this purpose, but at considerable pain of reconfiguring light paths on the testbed. As a work-around, the following procedure can be used:
  - For each tip/tilt star, one at a time, apply the tomographically measured but tip/tilt removed wavefronts along the tip/tilt star direction to the woofer/tweeter pair.
  - Measure the tip/tilt of the star as seen in the tip/tilt star's far field image.
  - After all the tip/tilts have been measured, feed this result to the tomography reconstructor as additional data.
  - Now calculate the tomographically determined wavefront, which incorporates the tip/tilt information, along the on-axis direction to the science target, and apply this correction to the woofer/tweeter pair.
  - Analyze Strehl performance accordingly.
- As a second note, the wavefront sensors on the bench can be "super sampled" with more Hartmann samples across the aperture than the 64 across KNGAO arrangement. This, in combination with super sampling across the DM using the bench's programmable phase modulator, allows us to suppress fitting error. This allows us to further isolate the tomography error contributor, which is the term of interest.
- Photon error is suppressed by using sufficiently bright sources and/or co-adding wavefront sensor measurements. Photon noise can be simulated in experiments designed to investigate noise propagation.

One of the ongoing efforts at the LAO is to continue to automate and build scripts for standardized experiments. We are employing an Electrical Engineering graduate student (Luke Johnson) to do this work.

4. LAO Staff

The following staff members can assist with the Keck NGAO risk reduction experiments:

- Donald Gavel, Director, LAO
- Renate Kupke, LAO Staff Optical Scientist
- Mark Ammons, Astronomy Graduate Student
- Luke Johnson, Electrical Engineering Graduate Student

5. Relevant Articles

1. Gavel, D., *Laboratory for adaptive optics at UC Santa Cruz: project status and plans*, Advances in Adaptive Optics II, **Proceedings of the SPIE**, Volume 6272, pp. 62721U (2006). link

2. Gavel, D., *Progress with Adaptive Optics Testbeds at the UCO/Lick Observatory Laboratory for Adaptive Optics*, **Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference**, held in Wailea, Maui, Hawaii, September 12-15, 2007, p.E65**.** link

3. Ammons, S. Mark; Kupke, Renate; Laag, Edward A.; Gavel, Donald T.; Dillon, Daren R.; Reinig, Marco R.; Bauman, Brian J.; Max, Claire E.; Johnson, Jess A., *First results from the UCSC Laboratory for Adaptive Optics multi-conjugate and multi-object adaptive optics testbed*, Advances in Adaptive Optics II. **Proceedings of the SPIE**, Volume 6272, pp. 627202 (2006). link

4. Laag, Edward; Gavel, Don; Ammons, Mark, *Open-Loop Woofer-Tweeter Control on the LAO Multi-Conjugate Adaptive Optics Testbed***, arXiv**:0710.0405**,** 10/2007. link